

Advances in Science, Technology & Innovation
IEREK Interdisciplinary Series for Sustainable Development

M. Sumesh · João Manuel R. S. Tavares ·
S. C. Vettivel · Mario Orlando Oliveira *Editors*

2nd International Conference on Smart Sustainable Materials and Technologies (ICSSMT 2023)

Innovations in Engineering
and Smart Sustainable Technologies
(Volume 2)

Advances in Science, Technology & Innovation

IEREK Interdisciplinary Series for Sustainable Development

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ASTI series has now been accepted for Scopus (September 2020). All content published in this series will start appearing on the Scopus site in early 2021.

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We are honored to dedicate the proceedings of ICSSMT 2023 to all the participants, organizers and editors of ICSSMT 2023.

Preface

The Second International Conference on Smart Sustainable Materials and Technologies (ICSSMT 2023) held between August 30 and 31, 2023 in Trichy, India, continued as a series of conference events targeting the design and implementation of engineering solutions for minimizing the negative impact on the environment. The theme of the conference includes the sustainable engineering practices, environmental protections, waste management, sustainable construction, and analysis of various materials to enhance sustainability are considered.

With the innovation of sustainable solutions, engineers are now playing a pivotal role in mitigating the emerging environmental challenges. The initiatives undertaken by engineers become paramount in building a greener future. From developing renewable materials to building a smart sustainable infrastructure, engineers are more involved in exploring the state-of-the-art technologies to shape the future of sustainable engineering. To contribute more towards this goal, ICSSMT 2023 conference was initiated to establish an international forum to emphasize the critical need for establishing sustainable engineering for addressing the environmental challenges and balance the global economic growth. The conference brought together the academia and industry professions to explore the recent advancements in renewable technologies and showcased the design, development, and implementation of various sustainable engineering solutions.

The conference has welcomed technical contributions that highlight the importance of sustainable engineering processes and eco-friendly materials. A total of 102 submissions were received, and from that 20 papers were accepted by the technical committee members.

Finally, we take this opportunity to thank all the members of the 2nd ICSSMT 2023 Technical Program Committee as well as the reviewers. Conducting a high-quality conference program would not have been possible without their involvement. We also thank all the authors who dedicated much of their time and efforts to contribute to 2nd ICSSMT 2023. We are equally grateful to the members of the 2nd ICSSMT 2023 organizing committee for their help in handling all the event-related work to make this meeting a success.

Trichy, India
Porto, Portugal
Chandigarh, India
Posadas, Argentina

Dr. M. Sumesh
Prof. João Manuel R. S. Tavares
Dr. S. C. Vettivel
Dr. Mario Orlando Oliveira

About the Conference

Conference Scope

Sustainable materials science and engineering is one of the important characteristics of the existing high-tech revolution. The advances of materials science pave way for technical advancements in materials science and industrial technologies throughout the world. Materials are regarded as critical component in all emerging industries. Exquisite preparation and manufacturing must be carried out before a new material may be used. Nevertheless, electronic materials are undeniably important in many aspects of life. Smart Materials and Structures is a multi-disciplinary platform dedicated to technical advances in smart materials, systems, and structures, including intelligent materials, sensing and actuation, adaptive structures, and active control. Recently, sustainable materials and technologies reshape the electronics industry to build realistic applications. At present, without the impact of sustainability, the electronics industry faces challenges. Researchers are now more focused on understanding the fundamental science of nano-, micro-, and macro-scale aspects of materials and technologies for sustainable development with a special attention towards reducing the knowledge gap between materials and system designs. The main aim of this international conference is to address the new trends on smart sustainable materials field for industrial and electronics applications. The main purpose of this conference is to assess the recent development in the applied science involving research activity from micro- to macro-scale aspects of materials and technologies for sustainable applications. In such a context, particular emphasis will be given to research papers tailored in order to improve electronic and industrial applications and market extension of sustainable materials.

Call for Papers

Prospective authors are encouraged to contribute to shape the conference through the submissions. Also, high-quality research contributions describing novel and unpublished results of conceptual, experimental, or theoretical work in all areas of sustainable materials, structures, and systems are cordially invited for presentation at the conference.

Track-1

Nanomaterials
Bio and bio-degradable materials
Electronic, optical and magnetic materials
Computational materials science

Composite materials
Smart materials and Sustainability
Emerging technologies in materials science
Energy storage and conversion
Functional materials for renewable energy applications
Environmentally-adaptable materials
Material, structural reliability, and durability applications
Intelligent, bio-inspired materials
Adaptive structural stability
Durability and corrosion of materials

Track-2

3D materials
Hydrogels and Phase Change Materials
Nano materials for sustainability
Sustainability of materials processes
Testing and diagnostics
Energy Storage and conversion materials
Synthesis of electronic materials
Battery energy storage and analysis
Fabrication of nanomaterials and Nano devices
Numerical analysis and optimization
Process modeling and simulation
Surface process control
Optics and photonics
Structure materials and applications

Important Dates

Paper Submission Deadline: 22 April 2023
Revision/Rejection Notification: 25 May 2023
Notification of Acceptance: 28 June 2023
Registration Deadline: 30 July 2023
Conference Dates: 30–31 August 2023

Guest Editors

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Synergistic Modelling and Analysis: Unravelling Optimal Ammonia Manufacturing via the Haber Process Using DWSIM and Microsoft Excel for Material Balance Integration

Sunil Sable and Mitesh Ikar

Abstract

Ammonia manufacturing through the Haber process is a critical industrial operation with substantial environmental and economic implications. Achieving optimal process performance necessitates a comprehensive approach that combines dynamic simulation, precise material balance analysis, and advanced integration techniques. In this research paper, we present a novel framework that leverages the capabilities of DWSIM, a sophisticated process simulation software, and harnesses the analytical power of Microsoft Excel for seamless material balance integration. The methodology involves developing a detailed process model in DWSIM, incorporating intricate thermodynamic properties and reaction kinetics specific to the Haber process. The integration of Microsoft Excel enables real-time tracking and analysis of material balance throughout the ammonia manufacturing cycle, accurately assessing reactant consumption, product yield, and process efficiency. Through extensive simulations and sensitivity analyses, we investigate the intricate interplay between various operating parameters, catalyst performance, and energy consumption. The results provide invaluable insights into process optimization, identifying critical areas for improvement. Furthermore, the developed framework facilitates exploring alternative process configurations, catalyst formulations, and reactor designs, enabling the identification of novel strategies to enhance ammonia production efficiency. The integration of real-time data acquisition from plant operations offers potential for continuous monitoring and control, further improving process performance. This research presents a comprehensive and sophisticated approach to optimize

ammonia manufacturing via the Haber process. The integration of DWSIM and Microsoft Excel for material balance analysis establishes a powerful synergy enabling accurate process evaluation, dynamic optimization, and potential real-time control. The findings have profound implications for sustainable ammonia production, resource conservation, and the advancement of process engineering practices.

Keywords

Ammonia manufacturing • DWSIM simulation • Haber process • Material balance analysis • Microsoft excel integration

1 Introduction

Ammonia production through the Haber process is a highly intricate and interconnected industrial operation that encompasses multiple essential process units. These units work in harmony to achieve efficient and sustainable manufacturing of ammonia. This paper focuses on the synergistic modelling and analysis of the Haber process, employing DWSIM, a sophisticated process simulation software, and Microsoft Excel for seamless integration of material balances. The objective is to uncover the optimal design and operation of ammonia manufacturing, considering critical stages such as desulfurization, primary and secondary reforming, high-temperature shift (HTS), low-temperature shift (LTS), CO₂ removal, methanation section, ammonia synthesis, vapor–liquid separator, and storage. Desulfurization holds a pivotal role in ammonia production as it involves the elimination of sulphur compounds from the hydrocarbon feedstock, typically natural gas. This step is indispensable to prevent catalyst poisoning and ensure the efficiency of downstream reactions. The primary reformer assumes a key position in ammonia production, where the

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hydrocarbon feedstock undergoes primary reforming to convert it into a synthesis gas primarily composed of hydrogen (H_2) and carbon monoxide (CO). Steam methane reforming (SMR) is commonly employed for primary reforming, entailing the reaction between the feedstock and steam to enhance the production of a hydrogen-rich gas. The synthesis gas generated from the primary reformer undergoes a series of purification steps to eliminate impurities, including sulfur compounds, carbon dioxide (CO_2), and other trace contaminants. Effective removal of CO_2 is crucial for producing high-quality synthesis gas, which significantly influences the efficiency of ammonia synthesis. Following purification, the synthesis gas flows into the high-temperature shift (HTS) reactor, where a shift catalyst facilitates the conversion of carbon monoxide (CO) and water (H_2O) into additional hydrogen (H_2) and carbon dioxide (CO_2).

The HTS reaction is exothermic and typically occurs at lower temperatures. Subsequently, the shifted gas enters the low-temperature shift (LTS) reactor, which further promotes the conversion of CO to CO_2 and H_2 . The LTS reaction is also exothermic but takes place at even lower temperatures, leading to the desired equilibrium conversion. The next vital unit is the methanation section, where any remaining traces of CO and CO_2 are reacted with hydrogen to produce methane. This step plays a critical role in minimizing the presence of CO and CO_2 , as their presence can adversely affect the efficiency of subsequent processes. Following purification and methanation, the synthesis gas is prepared for ammonia synthesis. The gas, along with nitrogen (N_2) feedstock, enters the ammonia synthesis reactor, where it interacts with an iron-based catalyst under high pressure and temperature. This catalytic process facilitates the conversion of the synthesis gas into ammonia (NH_3), the desired end product. After ammonia synthesis, the reaction mixture enters the vapor–liquid separator, where the ammonia vapor is separated from unreacted gases and any liquid byproducts. The ammonia vapor is then cooled and condensed, resulting in the formation of liquid ammonia. The collected liquid ammonia is subsequently stored in appropriate storage facilities for future utilization. By integrating these process units and utilizing tools like DWSIM and Microsoft Excel for modelling and material balance analysis, we can optimize the design and operation of ammonia manufacturing via the Haber process. This comprehensive approach allows for a thorough understanding of the intricate interplay between different units, optimization of process parameters, and ensures the efficient and sustainable production of ammonia.

2 Recent Advances in Haber Process for Ammonia Manufacturing

This section presents an experimental study of ammonia absorption under conditions relevant to the Haber process (Chaban & Prezhdo, 2016; Failed, 2016, 2020; Leigh, 2004; Modak, 2004) for ammonia synthesis. The authors describe the experimental apparatus used in the study and the reaction conditions tested, including temperature, pressure, and ammonia concentration. They report on the rate of ammonia absorption and the equilibrium concentrations of ammonia in the gas and liquid phases. The implications of their findings for the design and optimization of industrial Haber process reactors, including the importance of considering the rate of ammonia absorption in the liquid phase. The paper concludes that the rate of ammonia absorption under Haber process conditions is significantly affected by factors such as temperature and ammonia concentration, and that further research is needed to better understand the kinetics of the process. The paper provides insights into the behaviour of ammonia under Haber process conditions and highlights the importance of considering the rate of ammonia absorption in the design and optimization of industrial reactors (Huberty et al., 2012). The paper presents an experimental study of the use of the absorbing pervaporation technique for ammonia recovery after the Haber process for ammonia synthesis. The authors describe the experimental setup used in the study, which consists of a pervaporation membrane module and an ammonia absorption column, and the conditions tested, including temperature, feed flow rate, and ammonia concentration. They report on the efficiency of the pervaporation process in separating ammonia from the reaction mixture, as well as the effects of various operating parameters on the performance of the process. The authors also evaluate the energy requirements and cost-effectiveness of the pervaporation process compared to traditional ammonia recovery techniques. The paper concludes that the absorbing pervaporation technique is a promising approach for ammonia recovery after the Haber process, with potential for reducing energy consumption and improving process efficiency. However, the authors note that further research is needed to optimize the process and to evaluate its long-term reliability and durability. The paper provides insights into a novel approach for ammonia recovery after the Haber process and highlights the potential for using membrane-based separation techniques in the ammonia production industry (Atlaskin et al., 2018). A modelling study of the reliability of fixed bed reactors for ammonia production, based on statistical analysis

and Monte Carlo simulations. The authors describe the model used in the study, which includes several factors that can affect the reliability of fixed bed reactors, such as catalyst ageing, fouling, and thermal stress. They use the model to evaluate the impact of these factors on the performance and reliability of the reactor over time, and to predict the probability of failure or downtime. The implications of their findings for the design and maintenance of fixed bed reactors in the ammonia production industry. The model can provide valuable insights into the performance and reliability of fixed bed reactors, and can be used to optimize the design and maintenance of these reactors for improved efficiency and reliability. The paper provides valuable information on the use of statistical analysis and Monte Carlo simulations for predicting the reliability of fixed bed reactors in the ammonia production industry (Ukpaka & Izonowei, 2017).

A simulation study of the Haber–Bosch process for ammonia synthesis using an Aspen Plus model. The authors describe the model used in the study, which includes several reaction steps, including nitrogen and hydrogen purification, compression, and reaction in the reactor. They report on the effects of various operating parameters, such as temperature, pressure, and reactor design, on the efficiency and performance of the process. The authors also evaluate the environmental impact of the process, including greenhouse gas emissions, and discuss the implications of their findings for the optimization and design of industrial Haber–Bosch reactors. The Aspen Plus model can provide valuable insights into the performance and environmental impact of the Haber–Bosch process, and can be used to optimize the design and operation of industrial-scale ammonia production reactors. The paper provides insights into the use of process simulation for the optimization of the Haber–Bosch process for ammonia synthesis (Aguirre-Villegas et al., 2014; Amin et al., 2013; Aparicio & Dumesic, 1994; Baboo & Reddy, 2012; Baboo, 2022a, 2022b; Bartels, 2008; Charles, 2005; Gilbert et al., 2014; IFA Technical Committee, 2009; Lan et al., 2012; Patil et al., 2014).

3 Methodology

3.1 Process Modelling

The first step is to develop a detailed process model using DWSIM software. This involves creating a digital representation of the Haber process, including all essential process units and their interconnections. The process model encompasses stages such as desulfurization, primary and secondary reforming, high-temperature shift (HTS), low-temperature shift (LTS), CO₂ removal, methanation section, ammonia synthesis, vapor–liquid separator, and storage. Each process unit is represented by its corresponding equipment and specifications, such as reactors, heat

exchangers, and separators. The model also incorporates thermodynamic properties and reaction kinetics specific to the Haber process, ensuring accurate representation of the chemical reactions and equilibrium conditions.

3.2 Data Collection

The next step is to gather relevant data necessary for the simulation and analysis. This includes data on process parameters such as temperature, pressure, and flow rates, as well as thermodynamic properties of the involved substances. The data collected from literature sources, industry databases, experimental studies, or previous research works. It is crucial to ensure the accuracy and reliability of the collected data to obtain reliable simulation results and meaningful analysis.

3.3 Simulation

Using the process model and the collected data, simulations are performed in DWSIM software. The simulations replicate the behaviour of the Haber process under different operating conditions, allowing for the assessment of process performance and efficiency. The software solves the mass and energy balance equations based on the specified process conditions and thermodynamic properties, providing insights into the dynamic behaviour of the process and the interactions between different process units.

3.4 Material Balance Analysis

To analyse the material flow within the system, Microsoft Excel is employed for material balance integration. Material balance calculations are performed to track the consumption of reactants, generation of intermediates, and production of ammonia at each stage of the process. The material balance analysis ensures accurate tracking of mass flows, composition changes, and process efficiency throughout the ammonia manufacturing cycle. The integration of material balance calculations with the DWSIM simulations allows for a comprehensive understanding of the process dynamics and quantification of key performance indicators.

3.5 Sensitivity Analysis

Sensitivity analysis is conducted to evaluate the impact of variations in key process parameters on the performance of the Haber process. By systematically varying parameters such as feedstock composition, operating temperature, pressure, or catalyst activity, the sensitivity of the process to

these variations can be assessed. Sensitivity analysis helps identify critical parameters that significantly influence process performance and guides the optimization efforts by focusing on improving those parameters.

3.6 Alternative Process Configurations

To explore potential improvements in ammonia manufacturing, alternative process configurations are examined. Different reactor designs, catalyst formulations, or operating conditions are considered and simulated using DWSIM. The performance of these alternative configurations is evaluated based on key metrics such as ammonia yield, selectivity, energy efficiency, and process economics. This analysis enables the identification of novel strategies or configurations that offer improved process performance and efficiency.

3.7 Real-Time Data Acquisition

The methodology also explores the potential for real-time data acquisition from plant operations. Real-time data, such as temperature, pressure, flow rates, and composition, can be collected from sensors and integrated into the simulation and analysis process. This real-time data acquisition enables continuous monitoring and control of the ammonia manufacturing process, allowing for dynamic optimization and performance tracking.

4 Energy Balance

Feedstock Energy – The energy required to produce the primary feedstocks for ammonia production, namely hydrogen (H_2) and nitrogen (N_2), needs to be accounted for. Hydrogen is typically produced from natural gas through steam methane reforming (SMR), which involves a reaction with steam to produce hydrogen and carbon dioxide. Nitrogen is sourced from the air through an air separation unit (ASU), which consumes energy for compression and separation.

Synthesis Gas Generation – The reactants, hydrogen and nitrogen, are combined in the synthesis gas generation stage to produce ammonia (NH_3). This step involves the exothermic Haber–Bosch reaction, which releases heat. The energy released is typically recovered and utilized within the process.

Compression and Cooling – The synthesis gas, consisting of ammonia, unreacted hydrogen, and nitrogen, is compressed to increase the pressure and subsequently cooled to remove excess heat. Both compression and cooling steps require energy input.

Separation and Purification – The synthesized gas is then subjected to separation and purification processes to extract ammonia and remove impurities. These separation and purification steps involve additional energy inputs for separation techniques such as distillation, absorption, or adsorption.

Product Conditioning – The produced ammonia is further processed and conditioned to meet specific quality and purity requirements. This may involve additional energy-intensive steps, such as liquefaction, refrigeration, or compression.

Byproduct Utilization – Ammonia production may generate byproducts, such as heat or excess hydrogen, which can be utilized within the facility or for other purposes, reducing the overall energy demand.

By considering these factors and quantifying the energy inputs and outputs at each stage, an energy balance for ammonia production can be established. This analysis helps assess the energy efficiency of the process and identify potential opportunities for energy optimization and waste heat recovery. It is crucial for evaluating the sustainability and economic viability of ammonia production methods.

5 The Amount of Ammonia at Equilibrium

The amount of ammonia at equilibrium in the Haber–Bosch process is primarily influenced by three factors:

Temperature: The equilibrium constant of the Haber–Bosch reaction, which determines the extent of ammonia formation, is temperature-dependent. According to Le Chatelier's principle, an increase in temperature favours the endothermic forward reaction, resulting in a decrease in the amount of ammonia at equilibrium. Conversely, a decrease in temperature promotes the exothermic reverse reaction, leading to an increase in the amount of ammonia at equilibrium. However, it is important to note that excessively high temperatures may also negatively impact the catalyst's performance and overall process efficiency.

Pressure: The pressure also impacts the equilibrium position of the Haber–Bosch reaction. Increasing the pressure shifts the equilibrium towards the side with fewer moles of gas, which, in this case, is the forward reaction to produce ammonia. Therefore, increasing the pressure promotes the formation of more ammonia at equilibrium. However, there is a practical limit to the pressure that can be employed due to economic and safety considerations.

Reactant Concentrations: The concentrations of reactants, namely nitrogen and hydrogen, play a crucial role in determining the amount of ammonia at equilibrium. According to

the law of mass action, an increase in the concentration of reactants favours the forward reaction, resulting in an increase in the amount of ammonia at equilibrium. Conversely, a decrease in reactant concentrations shifts the equilibrium towards the reactant side, resulting in a decrease in the amount of ammonia at equilibrium.

It is important to note that the Haber–Bosch process operates under specific conditions of temperature, pressure, and reactant concentrations to optimize the production of ammonia. These conditions aim to achieve a balance between achieving a high yield of ammonia while considering practical and economic constraints. By manipulating these factors, it is possible to adjust the amount of ammonia produced at equilibrium.

6 The Equilibrium When Ammonia is Removed

According to Le Chatelier’s principle, when a component of a chemical equilibrium is removed or decreased, the equilibrium will shift in the direction that replaces or replenishes the removed component. In the case of the Haber–Bosch process and the equilibrium involving ammonia (NH_3), removing ammonia from the system will cause the equilibrium to shift to the right, favouring the forward reaction to produce more ammonia.

When ammonia is removed from the reaction mixture, the system recognizes the decrease in ammonia concentration and tries to compensate for the loss. To do so, the equilibrium position shifts in the direction that produces more ammonia to restore the balance. This shift occurs because the forward reaction, which generates ammonia, is favoured to replace the removed ammonia. In practical terms, the increased forward reaction leads to the production of more ammonia until a new equilibrium is reached. The equilibrium will continue to shift until the concentrations of reactants and products once again establish a new balance. It's important to note that the specific extent of the shift in the equilibrium position will depend on various factors, including the temperature, pressure, and concentrations of the reactants and products. Altering these conditions can influence the magnitude of the shift and the final equilibrium composition. Overall, when ammonia is removed from the system, the equilibrium responds by favouring the forward reaction, resulting in an increase in the production of ammonia to compensate for the loss.

7 Microsoft Excel Ammonia Material Balance

Figures 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18 and 19 explain the Material Balancing of Ammonia using Microsoft Excel.

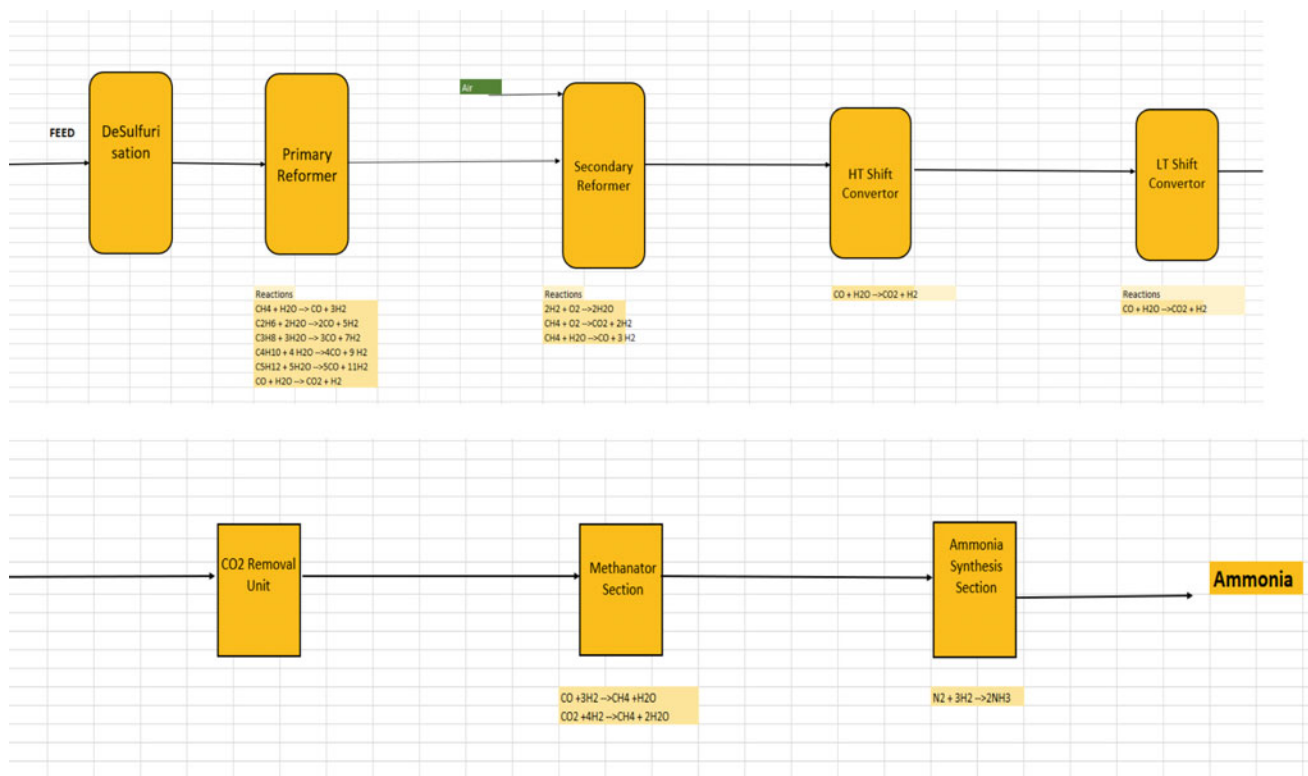


Fig. 1 Process block diagram

Feed		1936.18 Kg/hr							
				FEED		100 K moles/hr.			
	Mass flow(kg/hr)	Mole flow(kmol/hr)		FEED	Mole flow(k mol /hr)	Molar Flow	Mass Fraction	Mole Fraction	
	1385.6	86.6		CH4	86.6	5.4125	13.856	0.938660763	
	177.9	5.93		C2H6	5.93	0.197666667	1.779	0.034280267	
	172.04	3.91		C3H8	3.91	0.088863636	1.7204	0.015411142	
	45.24	0.78		i – C4 H10	0.78	0.013448276	0.4524	0.002332262	
	59.16	1.02		n – C4H10	1.02	0.017586207	0.5916	0.003049881	
	29.52	0.41		i – C5H12	0.41	0.005694444	0.2952	0.000987557	
	29.52	0.415774648		n – C5H12	0.41	0.005694444	0.2952	0.000987557	
	29.92	0.68		CO2	0.68	0.015454545	0.2992	0.002680199	
	7.28	0.26		N2	0.26	0.009285714	0.0728	0.001610371	
Total	1936.18	100.0057746		Total	100	5.766193934	19.3618	1	
				Steam Fed		427.595 Kg moles			

Fig. 2 Feed to primary reformer

↓
Primary Reformer
↓

Gross product	Mole flow(K moles/hr)	Molar flow	Mole Fraction
H2	268.3990537	134.1995269	0.862385898
CO	36.51820652	1.304221661	0.00838112
CO2	46.75111573	1.062525357	0.006827944
CH4	38.90067775	2.431292359	0.015623842
N2	0.26	0.009285714	5.96714E-05
H2O steam	298.933	16.6073889	0.106721524
Total	689.7620537	155.6142408	1

Reactions

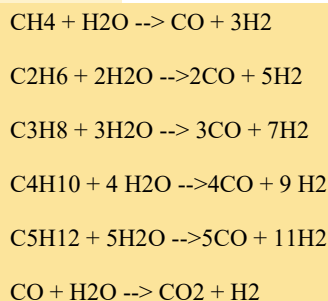


Fig. 3 Product from primary reformer

8 DWSIM Simulation

Figures 19, 20, 21, 22, 23 and 24 shows the process simulation of Ammonia by Haber's Process in DWSIM Software.

8.1 Overview of Results

Our study aimed to optimize ammonia manufacturing via the Haber process by utilizing DWSIM for dynamic simulation and Microsoft Excel for material balance integration. Through comprehensive simulations and material balance

↓
Secondary Reformer
↓

Gross product	Mole flow(K moles/hr)	Molar flow	Mole Fraction
H2	308.6127927	154.306396	0.849936456
CO	72.9315268	2.60469739	0.014346957
CO2	47.85996827	1.08772655	0.005991316
CH4	1.378504937	0.08615656	0.00047456
N2	136.6958718	4.88199542	0.026890563
Ar	1.645672637	0.04120362	0.000226954
H2O	333.762	18.5423333	0.102133194
Total	902.8863371	181.550509	1

Reactions

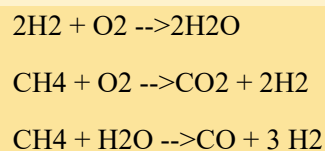


Fig. 4 Product from secondary reformer

↓
HT Shift Converter
↓

Gross product	Mole flow(K mol)	Molar flow	Mole Fraction
H2	364.4705894	182.235295	0.886139615
CO	17.07373011	0.60977608	0.002965105
CO2	103.717765	2.35722193	0.011462257
CH4	1.378504937	0.08615656	0.000418946
N2	136.6958718	4.88199542	0.023739252
Ar	1.645672637	0.04120362	0.000200357
H2O	277.9042033	15.4391224	0.075074469
Total	902.8863371	205.650771	1

Reactions

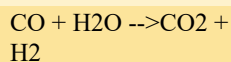


Fig. 5 Product from HT shift converter

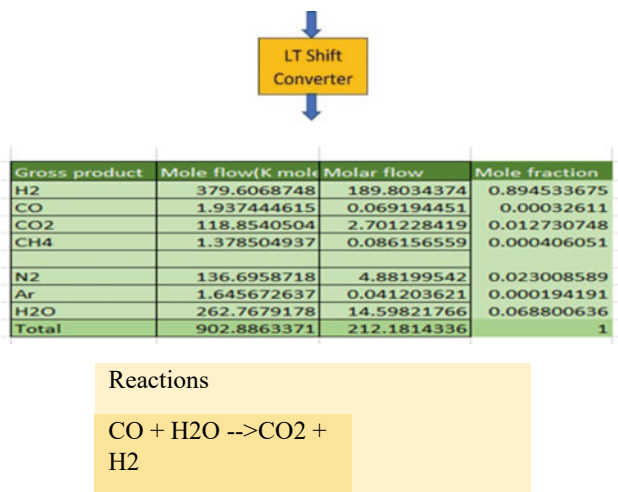


Fig. 6 Product from LT shift converter

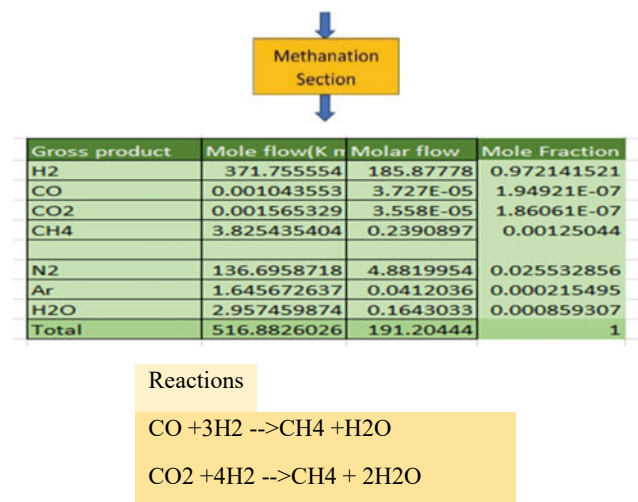


Fig. 8 Product from methanation section

analysis, we obtained valuable insights into the performance and efficiency of the process.

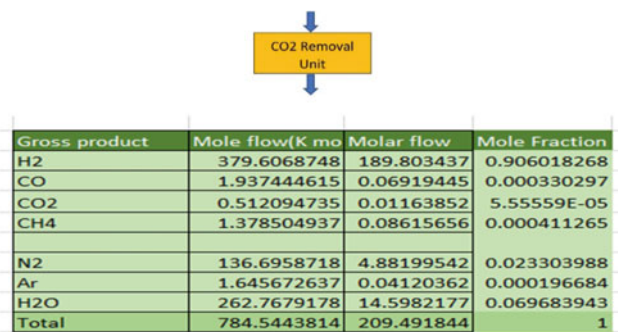


Fig. 7 Product from CO2 removal unit

8.2 Simulation Results

The simulations conducted using DWSIM provided a detailed understanding of the behavior of the Haber process under different operating conditions. We observed the effects of temperature, pressure, and catalyst loading on process performance. The simulations revealed optimal operating parameters that resulted in increased ammonia production

Fig. 9 Total ammonia

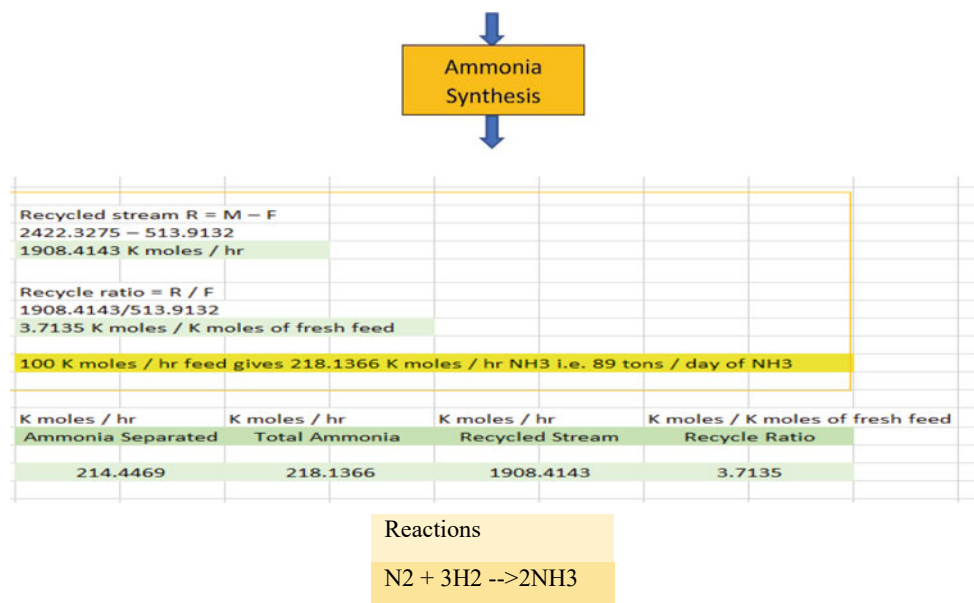


Fig. 10 Material balance for primary reformer

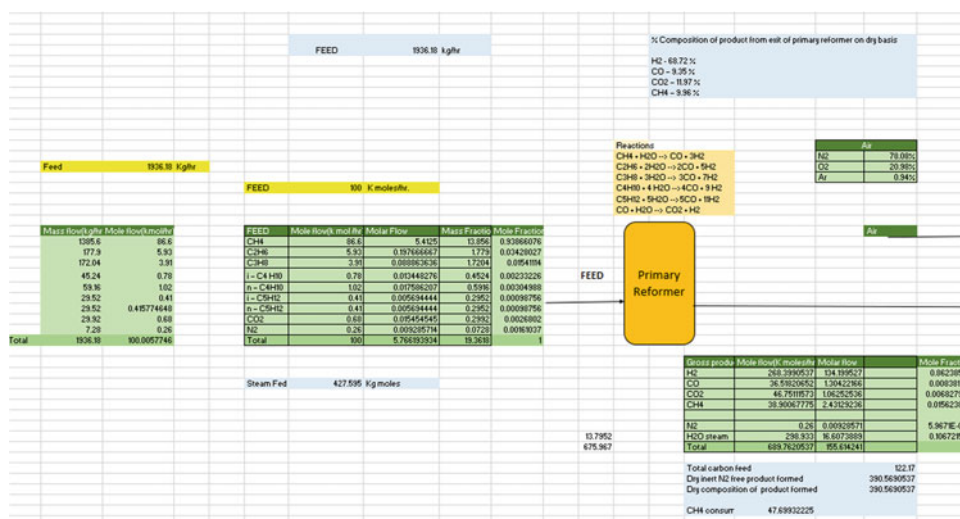
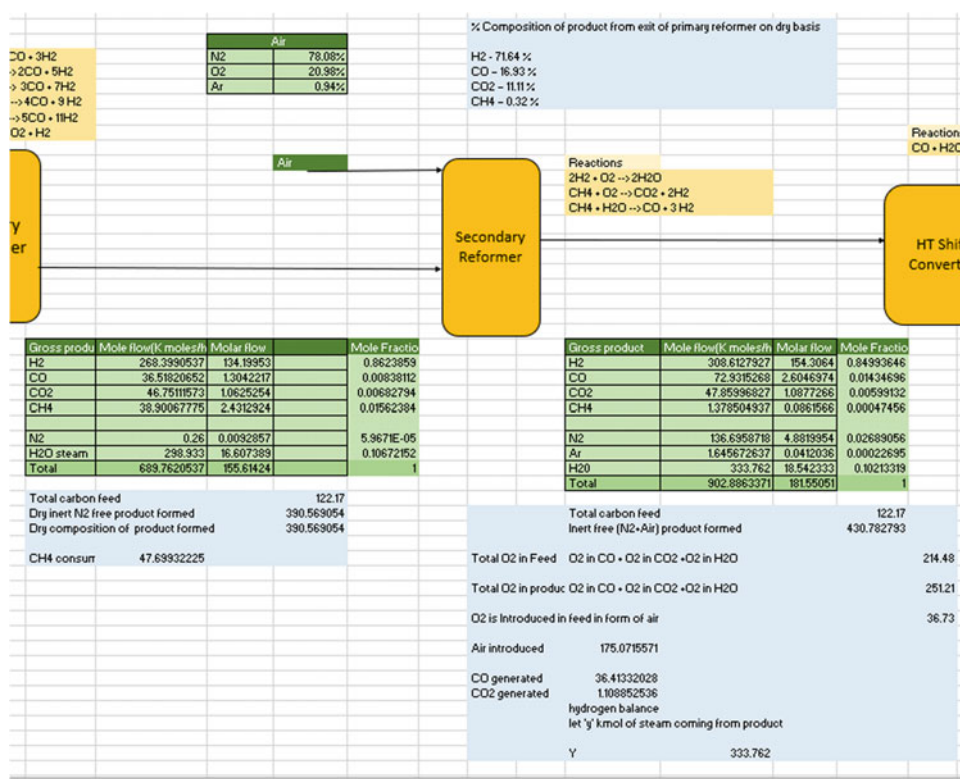


Fig. 11 Material balance for secondary reformer

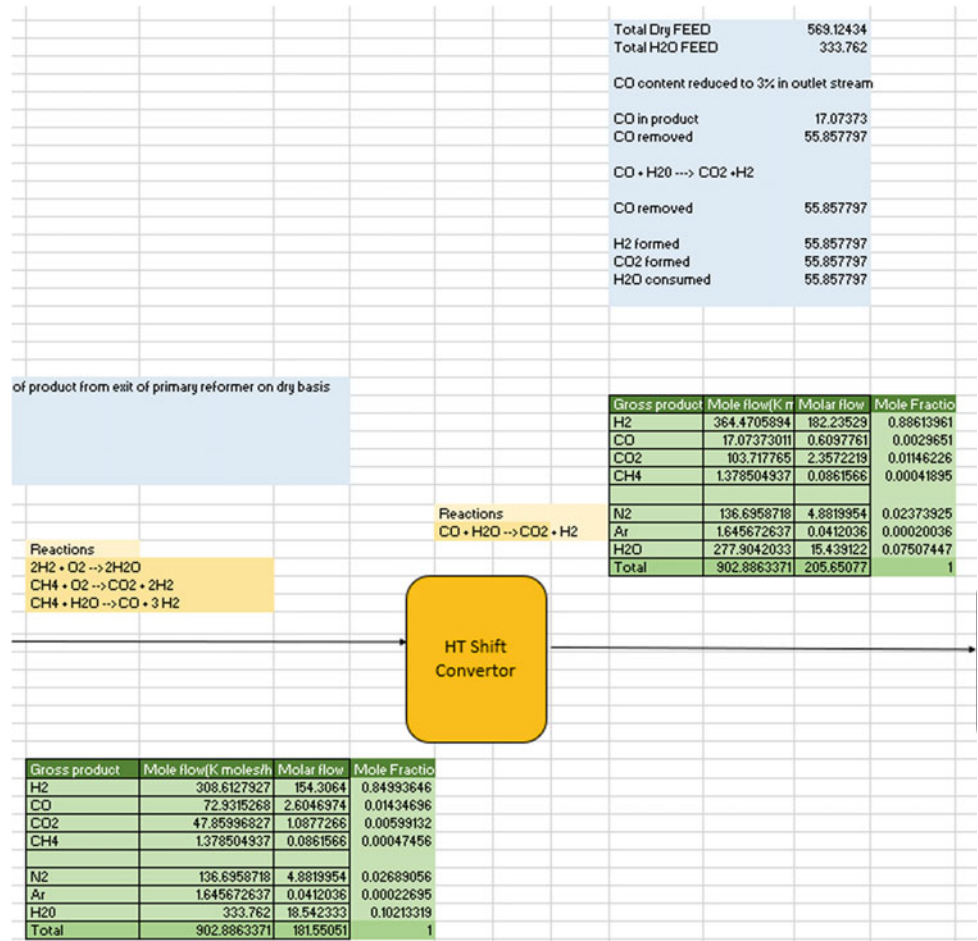


and enhanced process efficiency. We identified key reaction zones within the process where adjustments to operating conditions could lead to improved yield and reduced energy consumption.

8.3 Material Balance Analysis

The material balance analysis, conducted using Microsoft Excel, allowed for real-time tracking and analysis of reactant consumption, product yield, and process efficiency. Accurate

Fig. 12 Material balance for HT shift convertor



material balance calculations provided insights into the optimal utilization of resources and identified areas for process optimization. The analysis revealed the impact of various process units, such as desulfurization, reforming, shift reactors, and ammonia synthesis, on overall material balance and product quality.

8.4 Sensitivity Analysis

Sensitivity analyses were performed to assess the influence of important parameters on process performance. The analyses revealed the sensitivity of the process to changes in catalyst performance, energy consumption, and reactant feed composition. By identifying the most influential parameters, we were able to focus on optimizing those aspects to maximize process efficiency.

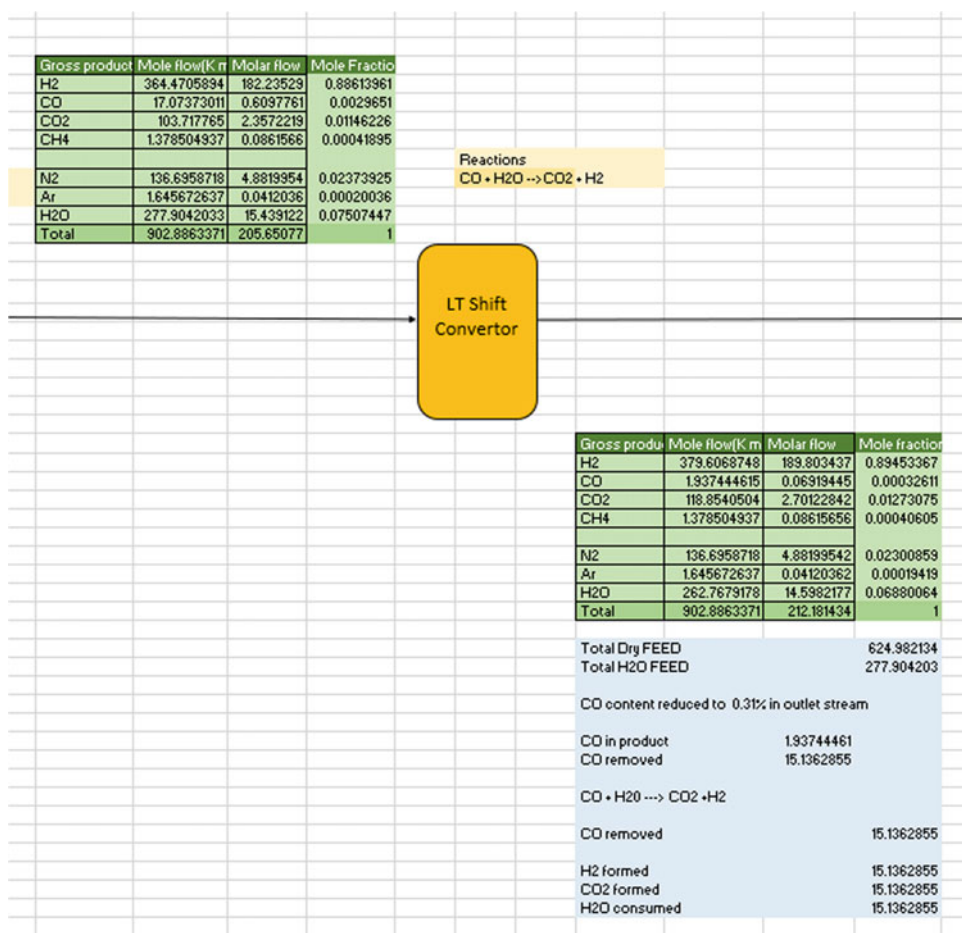
8.5 Alternative Process Configurations

Through the developed framework, we explored alternative process configurations, reactor designs, and catalyst formulations. Comparative analysis of different configurations allowed us to identify novel strategies for improving ammonia production efficiency. Alternative configurations showed promising results in terms of enhanced yield, reduced energy consumption, and improved sustainability.

8.6 Real-Time Data Acquisition

The integration of real-time data acquisition from plant operations offers the potential for continuous monitoring and control. By incorporating real-time data, we can further optimize process performance and ensure long-term

Fig. 13 Material balance for LT shift convertor

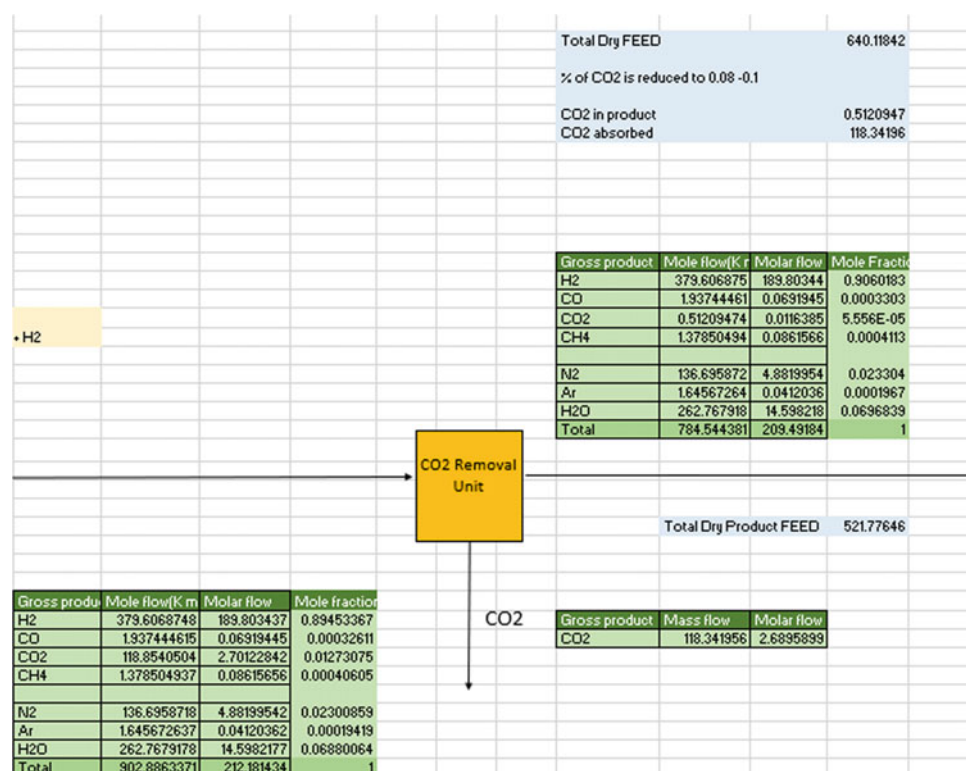
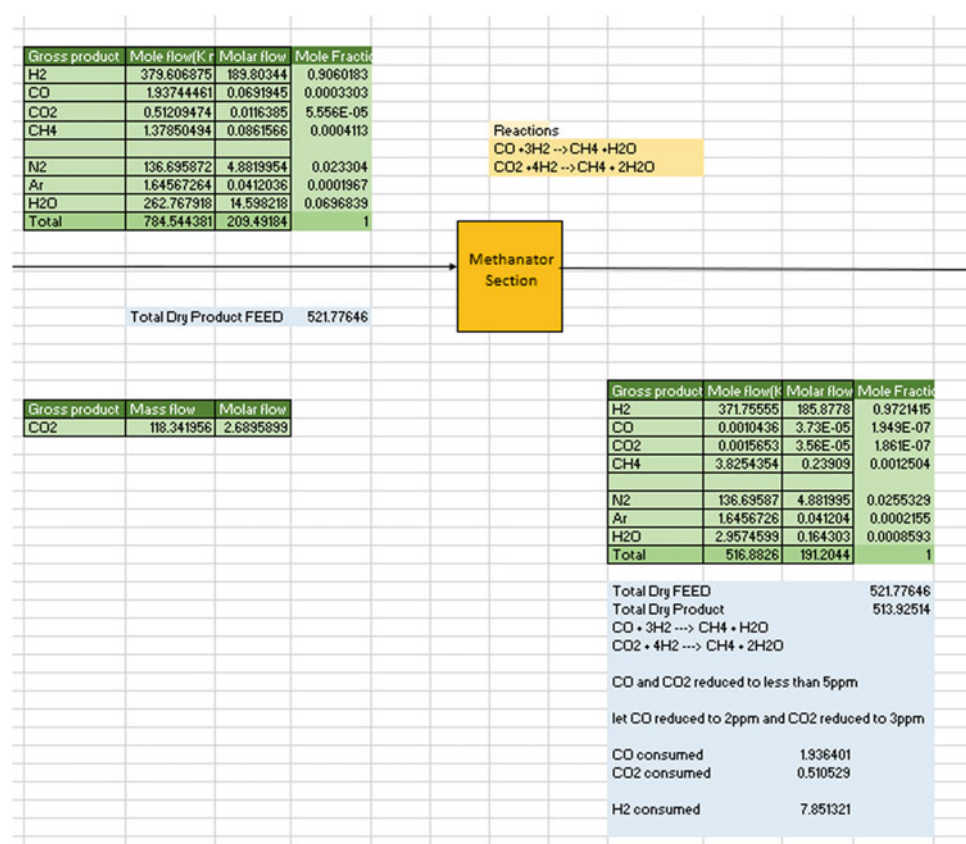


sustainability. These results collectively demonstrate the effectiveness of our approach in optimizing ammonia manufacturing via the Haber process. The findings provide valuable insights into process optimization, resource conservation, and the advancement of process engineering practices.

9 Conclusion

The research has presented a sophisticated and comprehensive approach to optimize ammonia manufacturing through the Haber process, utilizing the synergistic modelling and analysis

capabilities of DWSIM and Microsoft Excel for material balance integration. The integration of these powerful tools has enabled a deeper understanding of the intricate dynamics and performance of the ammonia production process. Through extensive simulations, sensitivity analyses, and material balance calculations, the interdependencies between various operating parameters, catalyst characteristics, and energy consumption have been explored in detail. The obtained insights have provided valuable guidance for process optimization, enabling the identification of critical factors influencing reactant consumption, product yield, and overall process efficiency. The utilization of real-time data acquisition from plant operations, facilitated by the integration of DWSIM

Fig. 14 Material balance for CO₂ removal unit**Fig. 15** Material balance for methanation section

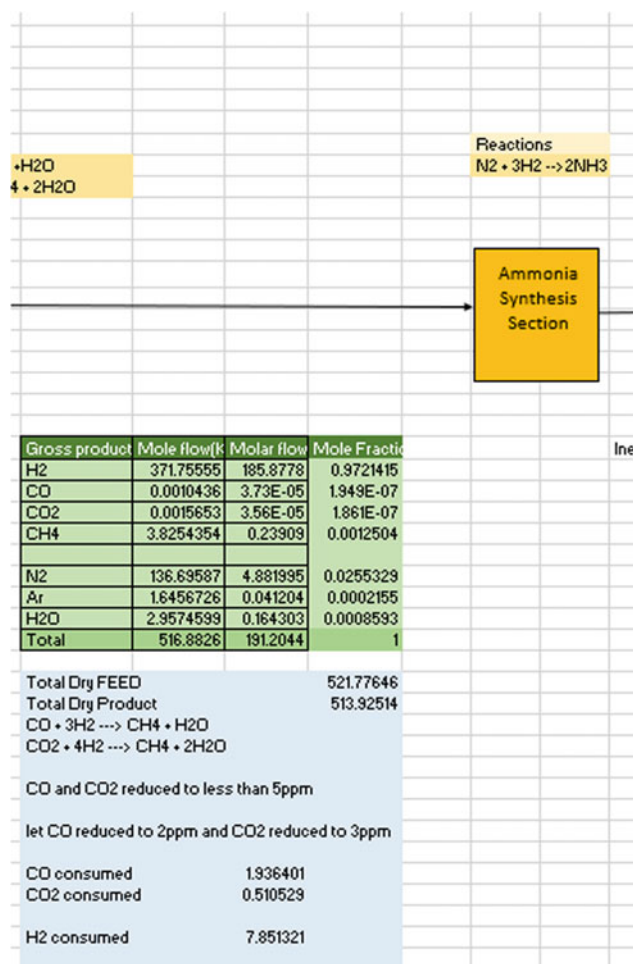


Fig. 16 Material balance for ammonia synthesis section

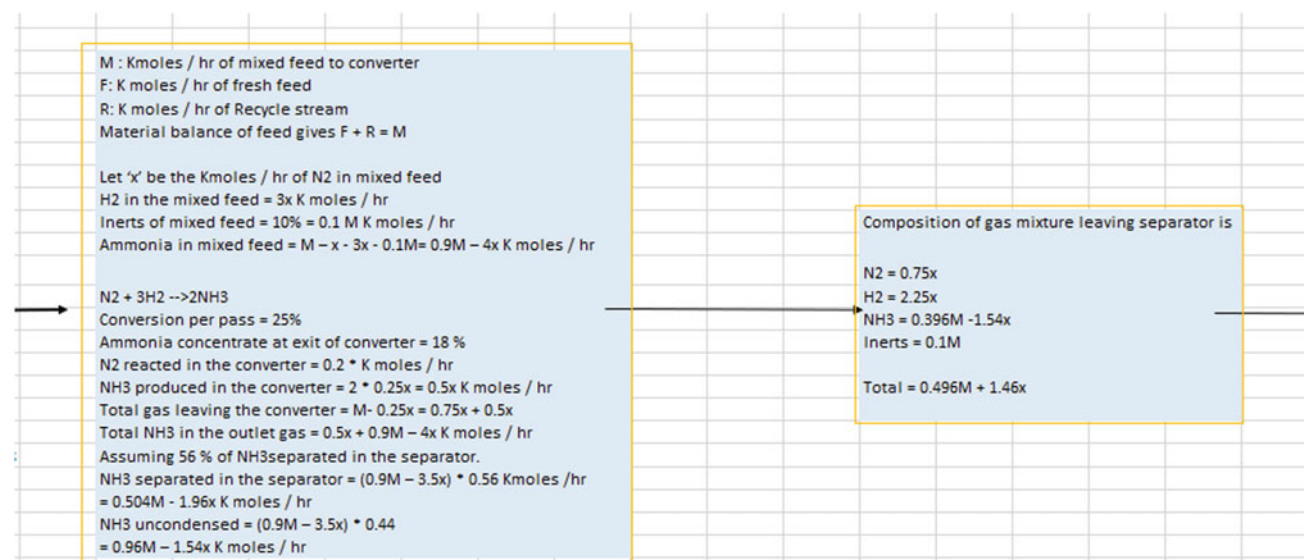


Fig. 17 Calculations for mix feed

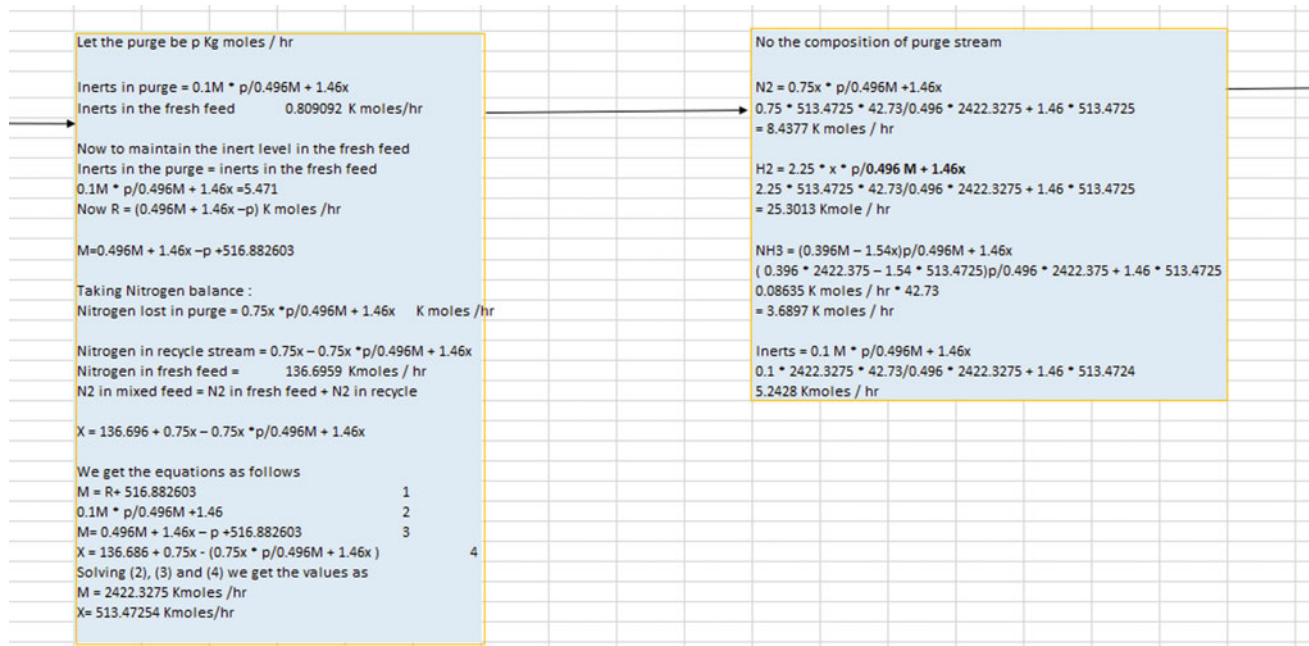


Fig. 18 Calculations for purge and recycle

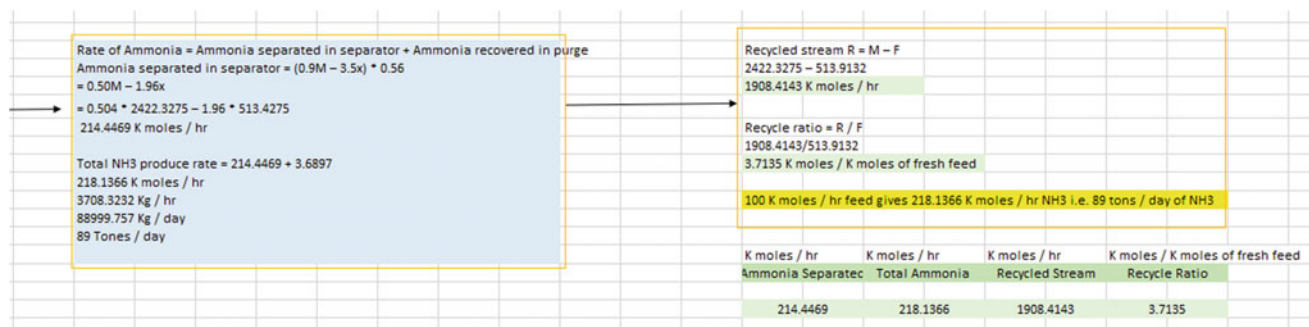


Fig. 19 Calculations for total ammonia

and Microsoft Excel, has further enhanced process monitoring and control capabilities. This integration has enabled the continuous evaluation and adjustment of process parameters, leading to improved performance and operational efficiency. The outcomes of this research underscore the significance of catalyst selection and design in ammonia manufacturing. By considering catalyst activity, impurity tolerance, and start-up agility, the study highlights the importance of catalysts that can operate efficiently under low operating conditions, thereby

minimizing energy requirements and enhancing process flexibility. Furthermore, the developed framework provides a solid foundation for exploring alternative process configurations, reactor designs, and catalyst formulations. The ability to analyse and evaluate the impact of these modifications on material balance, process performance, and overall sustainability offers exciting prospects for future advancements in ammonia manufacturing. This research paper represents a significant contribution to the field of ammonia production via

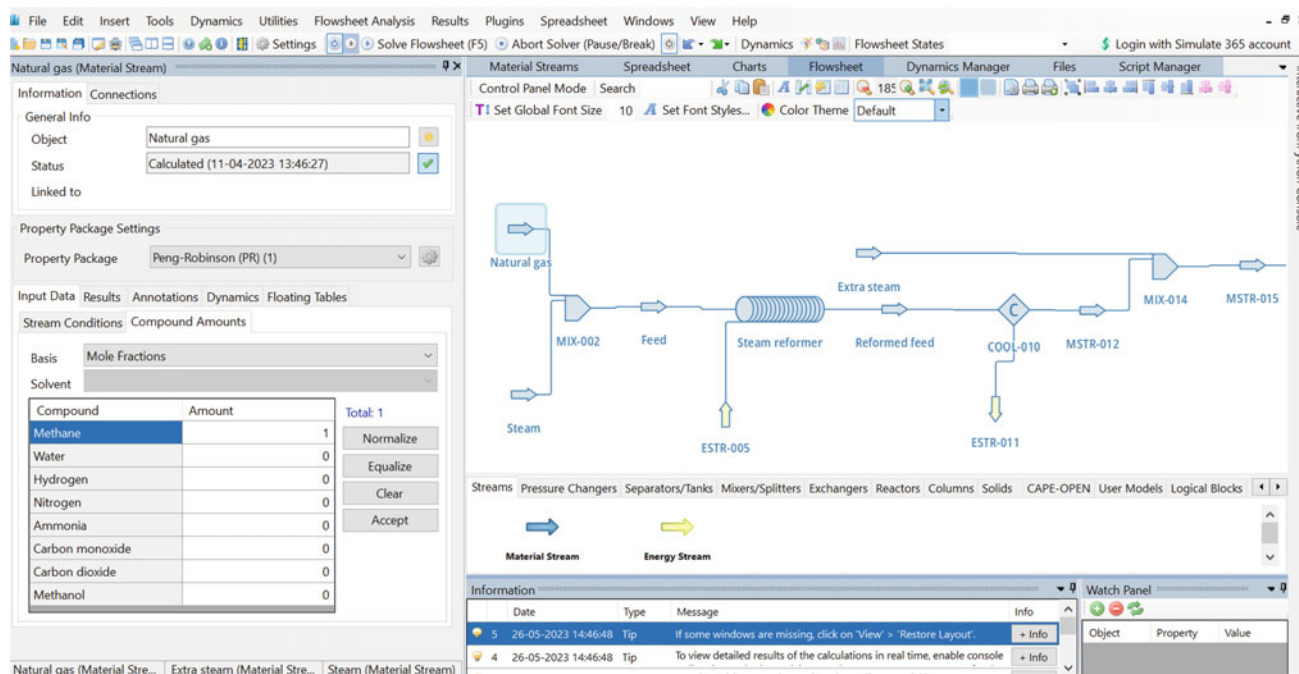


Fig. 20 Natural gas converted into hydrogen gas by steam reformer

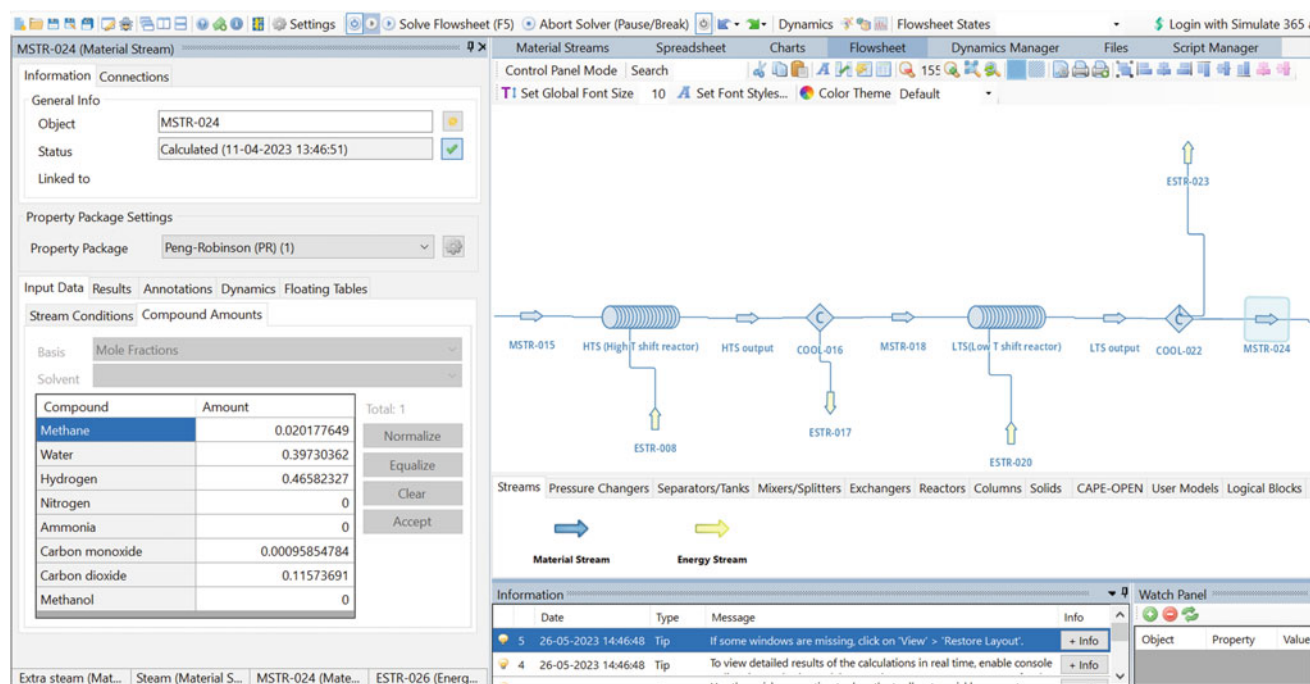


Fig. 21 HTS and LTS reactor convert carbon monoxide (CO) and water vapor (H₂O) into additional hydrogen gas (H₂) and carbon dioxide (CO₂) through water–gas shift reaction

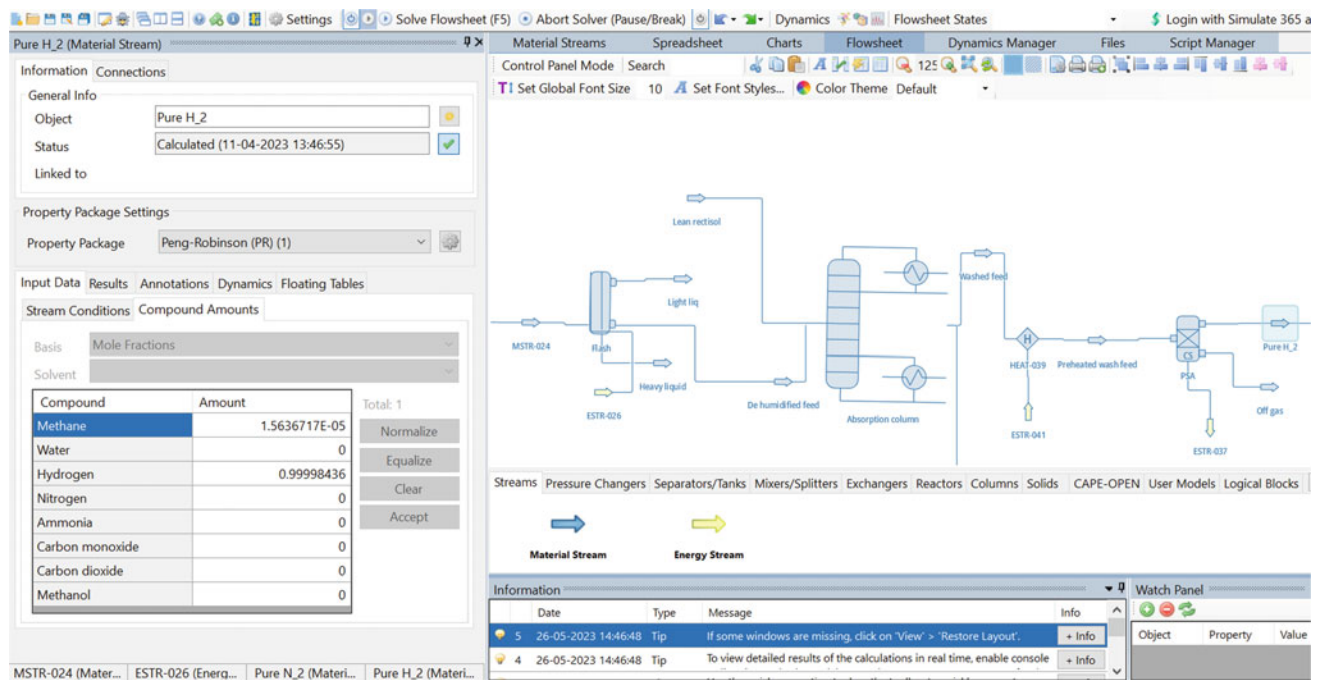


Fig. 22 Hydrogen gas separated using vapor liquid separator, adsorption column and compound separator

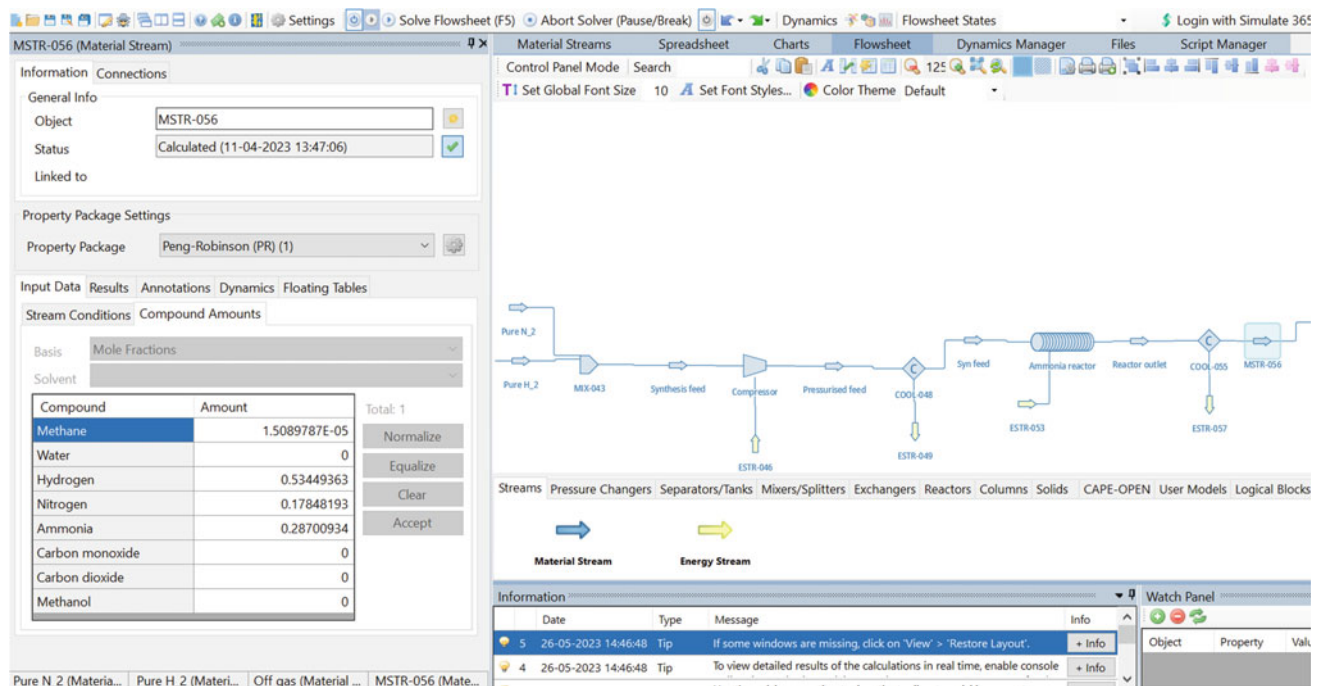


Fig. 23 Ammonia synthesis section where N2 gas reacts with H2 gas to produce Ammonia

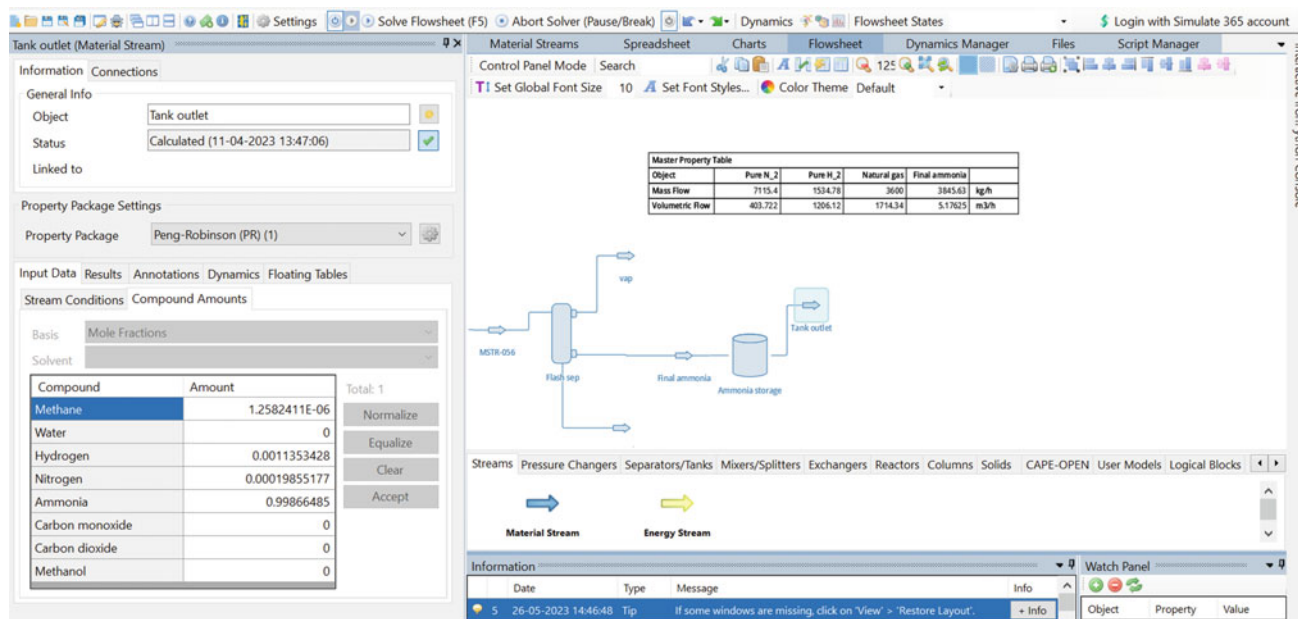


Fig. 24 Ammonia separated using flash liquid separator and stored in ammonia storage tank

the Haber process. The utilization of DWSIM and Microsoft Excel for material balance integration, combined with comprehensive simulations and analyses, offers a powerful toolset for optimizing the process, reducing environmental impact, and improving overall efficiency. The findings of this study pave the way for further research and innovation in the field of ammonia manufacturing, driving towards more sustainable and resource-efficient production practices.

10 Future Scope

While our study has provided valuable insights into the optimization of ammonia manufacturing via the Haber process, there are several avenues for future research and exploration. The following areas offer potential for further investigation and development:

Advanced Catalyst Development – Future studies can focus on the development and characterization of novel catalyst materials for ammonia synthesis and shift reactions. The exploration of advanced catalyst formulations can lead to improved catalytic activity, selectivity, and stability, thereby enhancing process efficiency and reducing energy consumption.

Process Intensification – Investigating process intensification techniques, such as reactor design modifications and integration of novel process units, can further enhance the efficiency of the Haber process. Exploring innovative reactor configurations, such as microreactors or membrane reactors,

can improve reactant conversion, reduce reaction time, and enhance product selectivity.

Renewable Feedstocks – With the growing interest in sustainable and renewable resources, future studies can explore the feasibility of utilizing renewable feedstocks for ammonia production. Investigating the use of biomass-derived gases, hydrogen from renewable sources, or electrochemical synthesis of ammonia can contribute to the development of greener and more sustainable ammonia manufacturing processes.

Process Optimization and Control Strategies – Advancements in optimization algorithms and control strategies can further optimize the Haber process. Implementing model predictive control (MPC) or advanced control techniques can enhance process stability, maximize ammonia production, and minimize energy consumption. Additionally, real-time optimization strategies can be developed to adaptively adjust process parameters based on changing operating conditions.

Integration of Renewable Energy Sources – Incorporating renewable energy sources into the ammonia production process can contribute to sustainable manufacturing. Future studies can explore the integration of solar, wind, or biomass-based energy systems to power the Haber process, reducing reliance on fossil fuel-based energy sources and minimizing the carbon footprint of ammonia production.

Environmental Impact Assessment – Conducting a comprehensive environmental impact assessment of the Haber process can help identify potential areas for improvement

and address environmental concerns. Evaluating the life cycle impact, carbon emissions, and water consumption can guide efforts towards more sustainable and environmentally friendly ammonia manufacturing.

Scale-Up Studies – Scaling up the optimized process from laboratory scale to industrial scale is a crucial step for commercial implementation. Future research can focus on conducting scale-up studies, considering factors such as reactor design, heat integration, process dynamics, and safety considerations, to ensure the viability and efficiency of the optimized process at a larger scale.

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Author Contributions Statement

Acquisition of data: Mitesh Ikar; Writing of the manuscript: Sunil Sable and Mitesh Ikar; Supervision: Sunil Sable

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Comparison of Fins in IC Engine Using CFD Analysis

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Abstract

The purpose of this study is to compare the impact of fin shapes on the basis of effectiveness for better heat transfer characteristics of engine. In this study computational fluid dynamics (CFD) is used to simulate different fin shapes during running condition (40 km/h) after applying boundary conditions of an IC engine (temperature is 873 K). The observation demonstrated how temperature and heat transfer coefficient are going to change according to different fin shapes that will help in obtaining better fin shape for an IC engine. Four types of fin profiles (Rectangular, Circular, Triangular and Trapezoidal) are analyzed in this study for two cases. In case 1, base area and the length of fins are equal for all profiles and in case 2, base area and surface area of all fins are equal. In this study, effectiveness of different fin profiles is calculated and compared in two cases.

Keywords

Fins • IC engine • CFD • K- ϵ model • ANSYS • Fluid fluent model

1 Introduction

Generally, in various applications, solids generate or conduct heat through walls or boundaries, causing it to be released to the surrounding environment to maintain a steady state. However, due to the limited heat dissipation area, it becomes challenging to transfer a large amount of heat efficiently. By attaching the metal plates to the surface heat transfer through

convection and conduction between surface of IC engine and surrounding can be done which is known as 'fins'. Fins manifest as pointed extensions gracing the contours of cylinder blocks and cylinder heads. Their purpose is to amplify the exterior points of contact between a cylinder and the ambient air. These fins are commonly forged seamlessly with the cylinder, forming an integral unit. Alternatively, they can also be affixed onto the cylinder surface (Mhatre et al., 2020). Primary purpose of fins is to serve as a fundamental tool to amplify the dispersion of heat and improve the cooling efficacy of objects or systems. This is accomplished by expanding the available surface area, thereby enhancing the capacity for heat exchange. Fins are a common feature on components that either generate heat or act as conduits for heat, including engines, electronic devices, heat exchangers, and radiators. Their principal role revolves around expeditiously eliminating surplus heat from these components, effectively averting the risk of overheating and guaranteeing an optimal level of performance. When the surface area of an object is increased, the heat transfer also increases. This can be achieved by either raising the convection heat transfer coefficient or increasing the temperature difference between the object and its surrounding environment. Fin material has high thermal conductivity and so they are made up of materials like aluminium, iron, and copper (Vipin et al., 2022). Fins are widely recognized as an effective method to enhance heat dissipation in IC engines. The demand for high-performance, lightweight, compact, and cost-effective heat transfer components is on the rise. Fins are generally employed to achieve optimal heat transfer enhancement, with increased fin area leading to higher heat transfer rates. For specific applications, materials with high thermal conductivity should be utilized. The high thermal conductivity of fins allows for rapid heat transfer to or from the body, particularly in applications where the fin is surrounded by a fluid in motion, which quickly cools or heats the fin due to its extensive surface area. Therefore, the heat transfer rate is increased by extending the surface area of the fin (Sharma et al., 2018). The fins present on the engine cylinder are

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determined by the engine's capacity. Fins help to not let the engine to burn out. For higher capacity of engine, there are many fins provided on the engine. Maximizing the thermal efficiency of an engine and ensuring its proper operation is highly dependent on the temperature distribution within the IC engine (Manikandan et al., 2021). Heat produced during combustion should be maintained thermal efficiency at highest level in IC engines. There are many types of extension that can be provided on fins like triangular extension, trapezium extension, rectangular extension, and circular extension (Mhatre et al., 2019). In numerous engineering applications, significant amounts of heat need to be dissipated from confined spaces. Fins are primarily utilized to achieve cylinder cooling by facilitating contact between the cylinder and air. Fins are manufactured in different geometries depending upon different applications. Fins find utility in cooling various electrical components, motorcycles, compressors, electric motors, refrigerators, and automobile radiators (Madhu et al., 2015). Fins are utilized to the management of heat in electrical applications like computer power supplies or sub-station transformers and utilized in trailing edges regarding blades of the gas turbine, and aerospace industry. There are various industry applications in the pin fin because of their good heat transfer efficiency, for instance in cooling regarding electronic components like heat exchangers (Ghyadh et al., 2021). Engine is a very complex machine that is designed to convert the heat from burning fuel into the force that turns the wheels of vehicles because the engine is the heart of the vehicle. The quantity of heat transferred from an object is determined by the amount of convection, radiation, and conduction. It is a well-established fact that heat always flows from hotter objects to colder objects. There are three modes of heat transfer from the IC engine to the surrounding. Three modes are like conduction, convection, and radiation of the heat transfer (Sharan et al., 2022). A novel technique is developed for heat transfer through fins based on FEM. The function of heat transfer through materials is dependent on their thermal conductivity (Dasore, et al., 2021). In all combustion engines, the majority of the heat, 40%, is dissipated through the exhaust and not through a liquid cooling system another 12% of the heat is cooled through metal fin engines with the help of air. Additionally, approximately 8% of the heat energy is transferred to the oil (Kumar et al., 2016). IC engines are capable of converting roughly 25–35% of the chemical energy present in fuel into mechanical energy at best. Around 35% of the heat generated is lost to the environment of the combustion space, while the remainder is dissipated through exhaust and radiation from the engine. The burning gases within the engine cylinder can reach temperatures of about 2000–2500 °C, which are absorbed by the engine components such as the cylinder head, cylinder wall, piston, and valves. However, such high temperatures are undesirable for various reasons (Suresh et al., 2014).

1.1 CFD Analysis

Computational fluid dynamics (CFD) visualizes the motion of a gas or liquid and its impact on nearby objects by combining applied mathematics, physics, and computer software. Analytical solutions to fins are essential. Analytical solutions for fins with arbitrary shapes are quite impractical. Thus, they may be examined using computational fluid dynamics to prevent this. Up until the answer converges, the simulation process continues. Correct boundary condition specification is crucial. The velocity-related boundary conditions must be specified at the inlet in fin situations. Any pressure-based boundary condition is an acceptable outlet. Correct fluid property import is also essential. Temperature boundary conditions need to be provided in this instance for the fins example. The choice of fin material is also very important. The ANSYS FLUENT module is used to perform the heat transfer study (Balashowry et al., 2020).

1.2 K-epsilon

The K-epsilon agitation model is widely used in computational fluid dynamics to replicate the mean inflow characteristics of turbulent flows. This popular model is a two-equation model that employs two transport equations to provide a comprehensive explanation of turbulence. As a commonly used turbulence model, the K-epsilon model is well-established. In cases of significant negative pressure stents, its performance is impaired. It is a two-equation model, which means that two added transport equations are included to depict the turbulent characteristics of the flow. This enables two-equation model to take literal factors like convection and turbulent energy proximity into consideration. There are two major expressions of K-epsilon models. K-epsilon was initially created as an alternative to algebraically prescribing turbulent length scales for moderate to highly complex overflows, with the aim of improving the mixing-length model (Alamos, 1968).

1.3 Type of Fins

- (A) Longitudinal Rectangular profile fin
- (B) Longitudinal Trapezoidal profile fin
- (C) Pin fin- Cylindrical
- (D) Radial fin- Rectangular profile
- (E) Pin fin- Tapered profile
- (F) Pin fin- Concave parabolic
- (G) Longitudinal fin- Concave parabolic (Zaidshah & Yadav, 2019).

In the pursuit of analyzing the heat transfer through fins of an IC engine, the author took a novel approach by employing computational fluid dynamics (CFD) in their study. Unlike past studies which were primarily experimental and time-consuming, the author simulated the IC engine's fins under various air velocities surrounding the fins. The results of the study were found to be comparable, thus highlighting the effectiveness of the CFD approach through fins of an IC engine in investigating heat transfer (Mote et al., 2016).

The effectiveness of cooling performance in IC engines can be improved through an in-depth analysis of engine fins. One way to achieve this is through the use of numerical simulation methods to optimize both fin material and geometry. By changing the geometry of fins, the cylinder heat transfer rate can also be increased, resulting in even greater improvements to engine cooling performance. Effectiveness of fins is determined by evaluating their ability to enhance heat transfer and dissipate heat from a system. There are several factors that are used to determine the effectiveness of fin: thermal performance, temperature distribution, fin efficiency, and pressure drop (Vyas & Parikh, 2022).

For IC engine heat transfer analysis of fins can increase vehicle thermal efficiency as it increases heat transfer rate and cooling rate by using proper fin dimensions. Proper enhanced heat transfer in IC engines can save fuel in future. The main aim of the research work is concentrated on the maximization of the amount of heat transfer rate (Shivam et al., 2019). Through a research study utilizing computational fluid dynamics, the impact of heat transfer on arbitrarily shaped fins was investigated. The study compared the performance of two types of fins—one with a regular shape, and the other with an arbitrary shape—that had an equivalent surface area. The analysis focused on heat transfer, and the findings shed light on the effectiveness of arbitrarily shaped fins in comparison to their regularly shaped counterparts (Balashowry et al., 2020). A range of perforated fin geometries, including slotted fin, inclined perforated fin, taper with inclination fin, and spline fin, have been designed through CFD analysis. Using ANSYS CFX, these fin designs were analyzed under constant heat flux to evaluate their respective performances (Mhatre et al., 2020). The study involves a comparative evaluation of the heat transfer rate and cost-effectiveness of fins with varying geometries. Various fin profiles are examined to determine the impact of their geometrical parameters on heat transfer rate. To calculate heat transfer parameters, finite element-based heat transfer analysis is performed on the fin structures (Vipin et al., 2022). In their research, the author conducted a thorough analysis and comparison of various types of fins in natural convection using Ansys workbench. The aim of this study was to determine the most effective configuration for convective heat transfer in a heated pipe. After careful examination, the author found that trapezoidal

fins exhibited the highest total heat transfer rate, making them the optimal choice for this type of application (Shakya & Ahmad, 2021). The author studied steady and transient analysis of engine cylinder head with fins of Hero Honda 100 cc bike. In this paper author modeled the 100 cc Hero Honda Cruiser engine head using solidworks software and found the result after examining the internal temperature of the engine. Transient heating test in a real-world setting was performed with an ambient temperature of 40 °C (Kumar & Pandey, 2022). In previous studies fins are found to be very helpful in increasing the rate of heat transfer from an IC engine. Fins are having complex shapes (rectangular, circular, triangular, and trapezoidal) that are very time consuming while doing analysis experimentally, that's why CFD is used to analyze such complex shapes. The surface area of the fin plays a great role in heat transfer to the surrounding by mode of convection.

In this study rectangular, circular, triangular, and trapezoidal profiles are considered for analysis and calculating their effectiveness. Here two cases are taken:

Case-1 Keeping base area and length same for all the fin profiles.

Case-2 Keeping base area and surface area same for all the fin profiles.

Primarily there are three modes of heat transfer, conduction, convection, and radiation. But in the study, two modes of heat transfer conduction and convection are considered. From cylinder wall to the fins heat transfer through conduction and from fins to the surrounding heat transfer through forced convection. To examine the internal temperature of the IC engine, there are some tools used that are thermocouples, infrared thermography, exhaust gas temperature (egt) sensors, coolant temperature sensors, data logging and obd-11 scanners, diagnostics and warning lights.

2 Objective

To compare different fin profiles on the basis of their effectiveness.

3 Methodology

Different fin geometries are modeled in Solidworks 2019 and saved into IGS file for importing in Ansys Workbench R19.3. In Workbench, Fluid Fluent module is used and in that meshing is generated of the models. After that boundary conditions are applied in the setup and then temperature and heat transfer coefficient distributions are obtained. The Flow chart of the methodology is given below in Fig. 1.

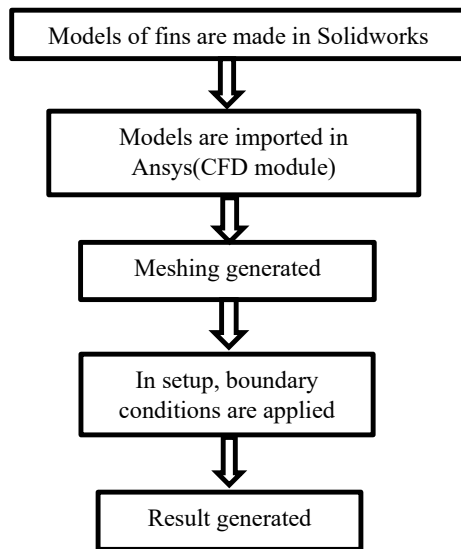


Fig. 1 Proposed workflow

Stage 1: Solidworks is a design and simulation software which created model of fin profile. Firstly, created a simple model of fin of IC engine on solidworks (Wu et al., 1303).

Stage 2: Imported After creating 3D model changed its extension file name to the IGS file and then import in Ansys (fluid flow fluent) and use the Ansys workbench R19.3.

Stage 3: Meshing is an essential step in transforming irregular shapes into recognizable volumes known as “elements.” To begin the simulation process in software such as Ansys Mechanical, you must first upload a geometry or CAD model. Nodes are defined as points that are joined by lines, creating a network or mesh. This network is also referred to as a grid, which provides a discrete representation of the model's geometry and state. In analysis software, the mesh is critical for obtaining solution convergence. There are various types of meshes, including triangular, quadrilateral, tetrahedral, pyramidal, and hexahedral, each with its unique characteristics (Mote et al., 2016). Table 1 shows the number of nodes and elements of rectangular fin, circular fin, triangular fin, and trapezoidal fin at a constant base area of 154 mm² and fin length of 40 mm. Table 2 shows the number of nodes and elements of rectangular fin, circular fin, triangular fin, and trapezoidal fin at constant base area 154 mm² and surface area 3161.817 mm². Figure 2 shows the meshing of 3D model of IC engine fins.

Table 1 Nodes and elements of meshing for case-1

Fin	Rectangular	Circular	Triangular	Trapezoidal
Nodes	2272	6904	2176	2190
Elements	10,176	34,769	9784	9852

4 Boundary Condition

Boundary conditions are set of values of some parameters which are giving analysis for example fluid material properties, solid material properties, fluid temperature, heat flux, solid temperature, choosing any turbulence model (for ex.- K-epsilon, Laminar, etc.) and K-epsilon model is used to analyze the fins for case-1 and case-2 in this study.

Aluminium 6063 is taken as fin material and assumes constant speed of 40 km/h = 11.11 m/s. Thus, air will also move with the same velocity in reverse direction (Mote et al., 2016).

Material properties:

Thermal Conductivity = 202.4 W/m-K.
Density = 2700 kg/m³.

Ambient air properties:

Ambient air temperature = 300 K.
Ambient air Velocity = 40 km/h = 11.11 m/s.

Cylinder insights:

Cylinder Wall Thickness = 20 mm.
Cylinder Temperature = 873 K (Shivam et al., 2019).

Effectiveness:

Effectiveness of the fin is the ratio of heat transfer rate with fin and without fin. Improving the effectiveness of fins involves maximizing their heat transfer capabilities to enhance the overall performance of a system. There are some keys involved to improving the effectiveness of fins, improving fin spacing and thickness, utilizing fins with high thermal conductance, considering multi-layer fins, regular maintenance, etc.

Calculated effectiveness of fins by using below formula:

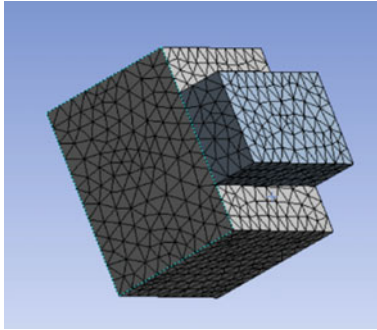
$$\epsilon_{\text{Fin}} = \frac{Q_{\text{fin}}}{Q_{\text{without fin}}} \quad (1)$$

For rectangular and circular profile

$$\epsilon_{\text{Fin}} \sqrt{\frac{KP}{hA_{cs}}} \left[\frac{\tanh(ml) + \frac{h}{mk}}{1 + \frac{h}{mk} \tanh(ml)} \right] \quad (2)$$

Table 2 Nodes and elements of meshing for case-2

Fin	Rectangular	Circular	Triangular	Trapezoidal
Nodes	2262	9156	2234	2247
Elements	10,069	46,386	9981	10,068

**Fig. 2** Meshing of 3D model of IC engine fins

For triangular and trapezoidal profile

$$\epsilon_{\text{Fin}} = \frac{2w}{mA_{cs}} \frac{I_1(2ml)}{I_0(2ml)} \quad (3)$$

(Mirapalli & Kishore, 2015) $m^2 = \frac{2h}{kT}$ (for triangular profile).

$$m^2 = \frac{2h}{k(T-t)} \quad (\text{for trapezoidal profile}).$$

Where:

ϵ_{fin} —Effectiveness of the fin.

Q_{fin} —Heat transfer rate with fin.

$Q_{\text{without fin}}$ —Heat transfer rate without fin.

K —Thermal conductivity.

P —Perimeter of the cross section of the fin.

A_{cs} —Cross sectional area of the fin.

h —Heat transfer coefficient.

l —Length of the fin.

I_1 —Bessel function for $n(\text{order}) = 1$.

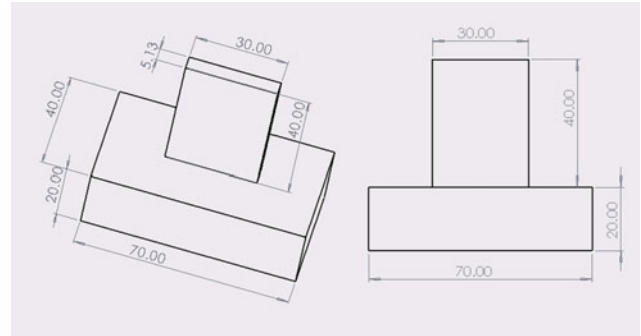
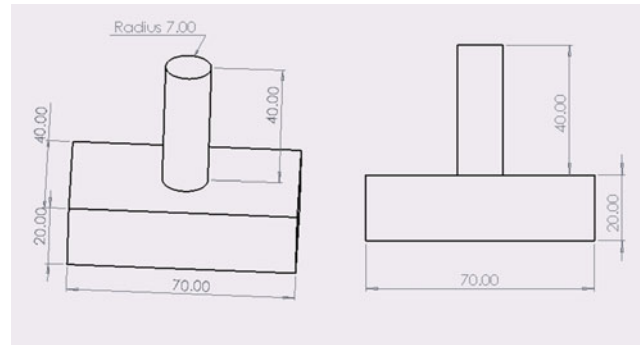
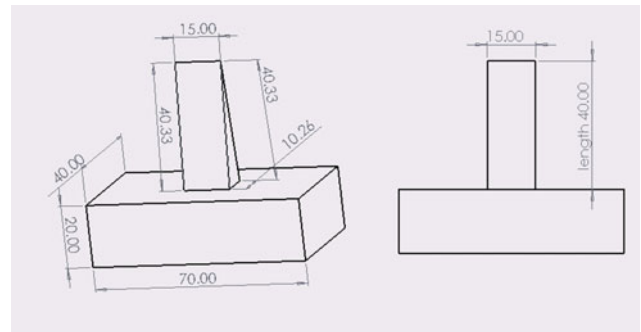
I_0 —Bessel function for $n(\text{order}) = 0$.

5 Modeling of Different Fins

The modeling of different fins refers to the process of creating 3D representations or digital models that accurately depict the geometry and characteristics of various types of fins. Different types of fins (rectangular, circular, triangular, and trapezoidal fin) are modeled in solidworks.

Case-1

Dimension of circular fin profile and rectangular fin profile taken from the literature. Dimension of circular fin is 40 mm

**Fig. 3** Dimension of rectangular fin for case-1**Fig. 4** Dimension of circular fin for case-1**Fig. 5** Dimension of triangular fin for case-1

length (L) and 14 mm diameter (D), width (w) of rectangular fin profile is 30 mm (Das et al., 2021). Dimension of the rectangular fin, circular fin, triangular fin, and trapezoidal fin are shown in Figs. 3, 4, 5, 6. Base area of circular fin is calculated using literature dimensions and after calculation base area of circular fin is found to be 154 mm^2 . For comparative analysis of different fin geometries, base area of all

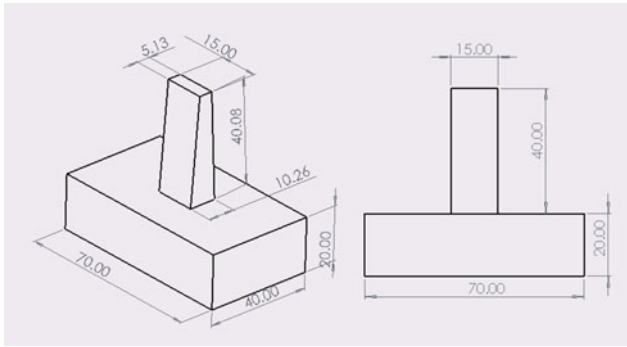


Fig. 6 Dimension of trapezoidal fin for case-1

Table 3 Dimensions of fin for case-1

Rectangular fin	Circular fin	Triangular fin	trapezoidal fin
L = 40 mm	L = 40 mm	L = 40 mm	L = 40 mm
b = 5.1313 mm, w = 30 mm	D = 14 mm	T = 10.26 mm, w = 15 mm	T = 10.26 mm, b = 5.1313 w = 15 mm
Base area = 154mm ²	Base area = 154mm ²	Base area = 154mm ²	Base area = 154mm ²

profiles should be same. So by keeping base area same for all fin shapes, other dimensions like thickness (T), width (w), etc., are calculated using below formula for all fin shapes.

Base area of rectangular fin = $b \times w$ (b and w are mentioned in Table 3 and shown in Fig. 9).

Base area of circular fin = $\frac{\pi D^2}{4}$ (D mentioned in Table 3 and shown in Fig. 10).

Base area of triangular fin = $T \times w$ (T and w are mentioned in Table 3 and shown in Fig. 11).

Base area of trapezoidal fin = $T \times w$ (T and w are mentioned in Table 3 and shown in Fig. 12).

Case-2

Dimension of the rectangular fin, circular fin, triangular fin, and trapezoidal fin are shown in Figs. 7, 8, 9, 10. In case 2 base area and surface area should be same for all the shapes. Since, base area is same and surface area has also to be same for all shapes, hence length (L) going to change for all shapes. Firstly, any one fin's surface area should be calculated so rectangular fin's surface area is calculated with 45 mm length (L) because if 40 mm length is taken then it will be same as case 1 and it can create problem in comparison, so closer value (45 mm) to the 40 mm is taken.

Surface area of rectangular fin = $2L(b + w) + bw$

By using above formula, surface area is calculated and mentioned in Table 4. So, by keeping surface area and base area is same, length (L) is calculated for all the fin profiles using below formulas:

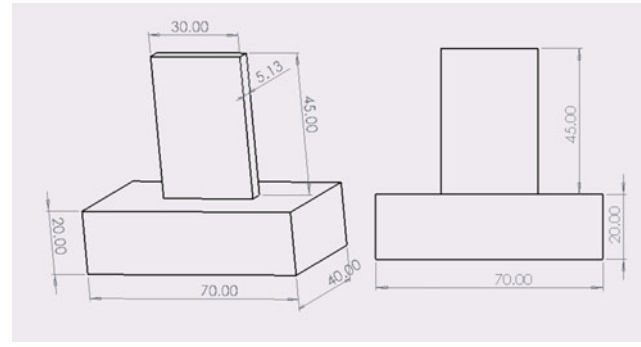


Fig. 7 Dimension of rectangular fin

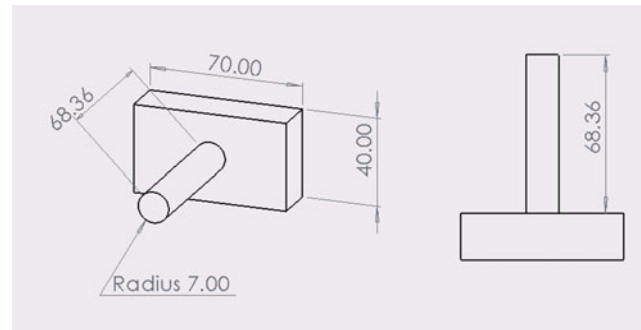


Fig. 8 Dimension of circular fin

Surface area of circular fin = $\pi DL + \frac{\pi D^2}{4}$ (D and L are mentioned in Table 4 and shown in Fig. 14).

Surface area of triangular fin = $L \times T + 2[w \times \sqrt{(L^2 + \frac{T^2}{4})}]$ (L, T, and w are mentioned in Table 4 and shown in Fig. 15).

Surface area of trapezoidal = $L(T + b) + 2[w \times \sqrt{(L^2 + \frac{T^2}{4})}]$ (L, T, b, and w are mentioned in Table 4 and shown in Fig. 16).

6 Results and Discussion

Analyzed different types of fin profiles and obtained temperature distribution and heat transfer coefficient distribution. Table 5 shows effectiveness of fin and average heat transfer coefficient for both cases.

6.1 Temperature Distribution Profile for Case-1

Temperature distribution of the fin shapes (Rectangular, Circular, Triangular, Trapezoidal) is shown in Figs. 11, 12, 13 and 14. Temperature is decreasing when length is increasing and minimum temperature is observed on the tip of every fin and maximum temperature is observed on base of the fin. The

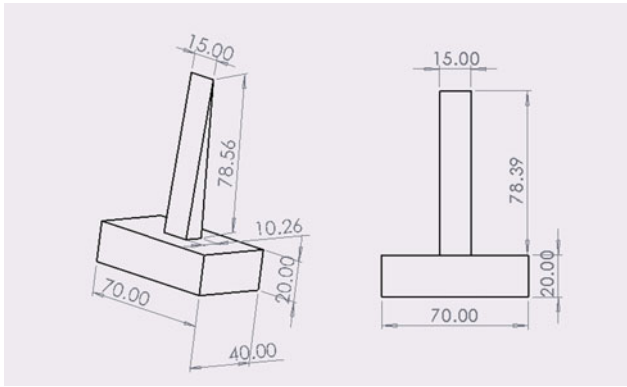


Fig. 9 Dimension of triangular fin

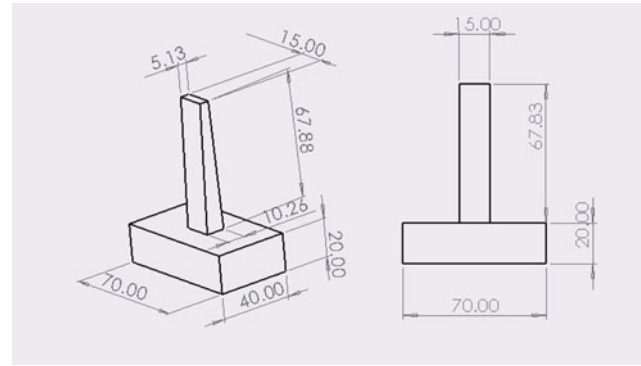


Fig. 10 Dimension of trapezoidal fin

Table 4 Dimensions of fin for case-2

Rectangular fin	Circular fin	Triangular fin	Trapezoidal fin
L = 45 mm	L = 68.36 mm	L = 78.39 mm	L = 67.83 mm
b = 5.1313 mm, w = 30 mm	D = 14 mm	T = 10.26 mm, w = 15 mm	T = 10.267 mm b = 5.1313 w = 15 mm
Base area = 154mm ²	Base area = 154mm ²	Base area = 154mm ²	Base area = 154mm ²
Surface area = 3161.817mm ²	Surface area = 3161.817mm ²	Surface area = 3161.817mm ²	Surface area = 3161.817mm ²

Table 5 Effectiveness and average heat transfer coefficient of fins in both cases

Fins	Case 1		Case 2	
Fin	Effectiveness	Average heat transfer coefficient (W/m ² k)	Effectiveness	Average heat transfer coefficient (W/m ² k)
Rectangular	34.42	80.83	38.698	61.665
Circular	8.17	877.8	8.92	727.045
Triangular	8.293	76.065	16.514	79.85
Trapezoidal	8.827	73.30	22.27	80.27

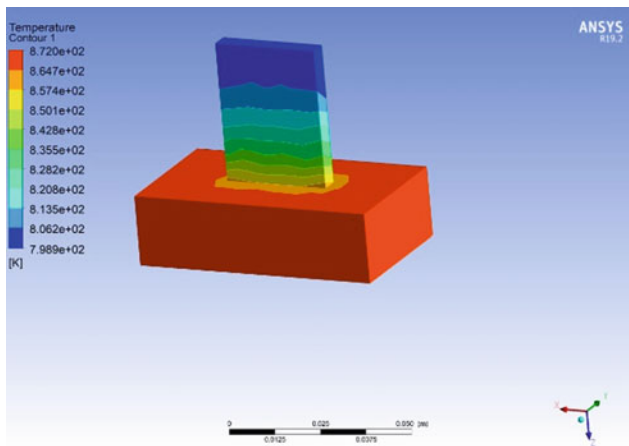


Fig. 11 Temperature distribution of rectangular fin

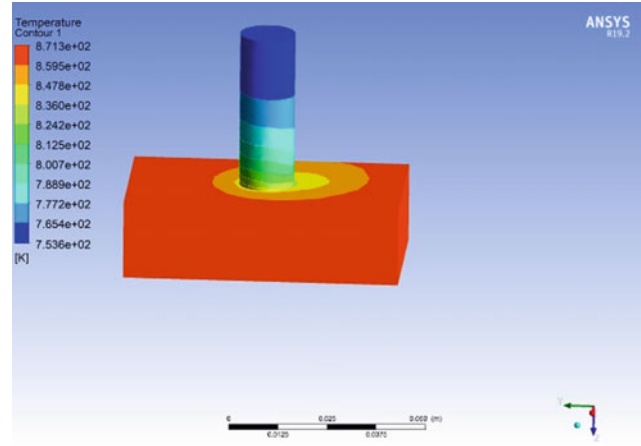


Fig. 12 Temperature distribution of circular fin

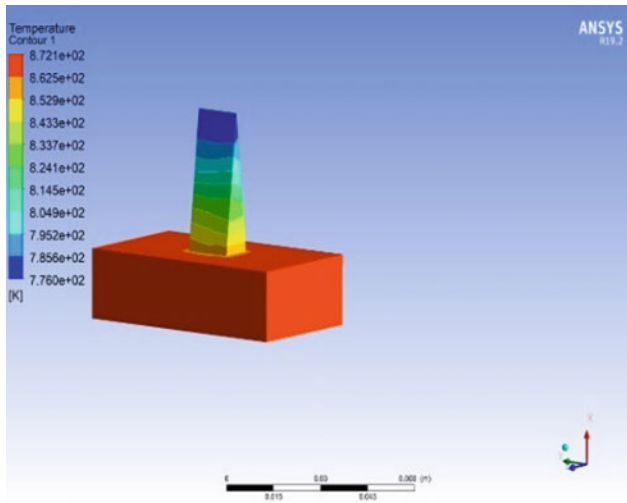


Fig. 13 Temperature distribution of triangular fin

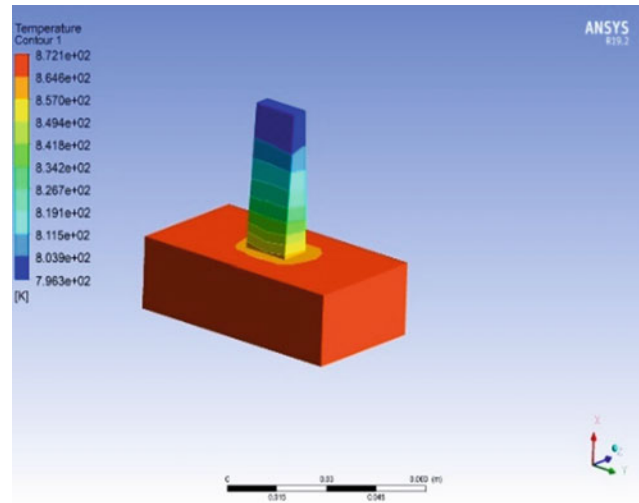


Fig. 14 Temperature distribution of trapezoidal fin

temperatures at the tip of different fin shapes (rectangular, circular, triangular, and trapezoidal) are 798.9, 753.6, 776, and 796.3 K respectively as shown in Figs. 11, 12, 13 and 14. Hence maximum temperature drop is for circular fin (Mathiazhagan & Jayabharathy, 2012). According to the Fourier law of conduction heat transfer rate is directly proportional to the temperature drop, i.e., heat transfer through conduction in material is maximum for circular fin.

6.2 Heat Transfer Coefficient Profile for Case-1

Heat transfer coefficient profile of the fin shapes (rectangular, circular, triangular, trapezoidal) is shown in Figs. 15, 16, 17 and 18. Heat transfer coefficient represents the rate of heat transfer per unit area per unit temperature difference in the mode of convection. The heat transfer coefficient describes how effectively heat can move through a medium or across a boundary between two different media. Maximum heat transfer coefficient for rectangular, circular, triangular, and trapezoidal are 144.2, 1596, 138.3, and 104.1 respectively as shown in Figs. 15, 16, 17 and 18 (Tao et al., 2007). Since, heat transfer coefficient (h) varies over the entire length and in calculation of the effectiveness constant value of h is needed. Hence average heat transfer coefficient (h_{avg}) is calculated because the meaning of average is to convert any variable data into uniform data. Average heat transfer coefficient (h_{avg}) for rectangular, circular, triangular, and trapezoidal is 80.83, 877.8, 76.065, and 73.30. Finning is only justified where 'h' is small, if value of h is very large, fins may reduce the heat transfer. In the circular fin temperature distribution shown in Fig. 18, it is observed that value of h is very high that is why it may reduce the effectiveness of fin.

6.3 Temperature Distribution for Case-2

Temperature distribution of the fin shapes (rectangular, circular, triangular, and trapezoidal) is shown in Figs. 19, 20, 21 and 22. In case-2, the temperatures at the tip of different fins shapes (rectangular, circular, triangular, and trapezoidal) are 780.8, 678.9, 654.3, and 710.1 K respectively as shown in Figs. 19, 20, 21 and 22. Hence maximum temperature drop is for triangular fin, i.e., heat transfer through conduction in material is maximum for triangular fin.

Generally in previous studies rectangular fins are found to be best for heat transfer. In heat transfer, the terms "short fin" and "long fin" refer to the relative length of the fins used to enhance heat transfer in various applications. Short fins have a length that is relatively small compared to their width, while long fins have a greater length in proportion to their width. Here are some ways to increase heat transfer in a system with fins: increase fin surface area, enhances fin geometry, optimize material conductivity, increase fluid flow, use heat sinks, apply thermal coatings, minimize thermal resistance, and optimize fin arrangement.

6.4 Heat Transfer Coefficient Profile for Case-2

Heat transfer coefficient profile of the fin shapes (rectangular, circular, triangular, trapezoidal) is shown in Figs. 23, 24, 25 and 26. Maximum heat transfer coefficient for rectangular, circular, triangular, and trapezoidal are 106.2, 141.3, 118.3, 119.2 respectively as shown in Figs. 23, 24, 25 and 26. Average heat transfer coefficient (h_{avg}) for rectangular, circular, triangular, and trapezoidal are 61.665, 727.045, 79.85, and 80.27.

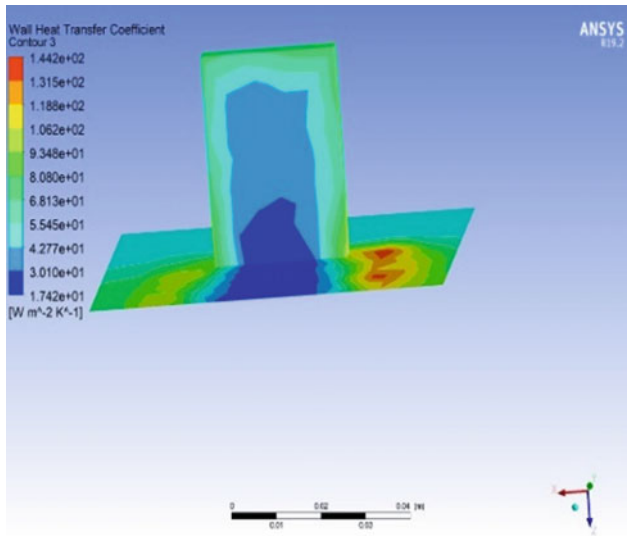


Fig. 15 Heat transfer coefficient of rectangular fin

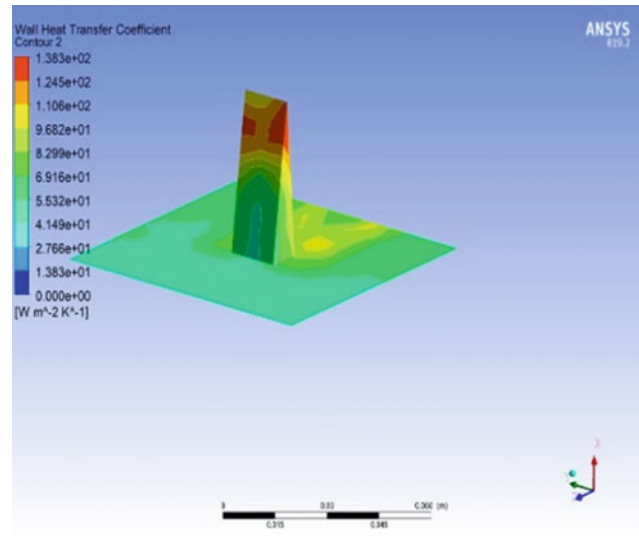


Fig. 17 Heat transfer coefficient of triangular fin

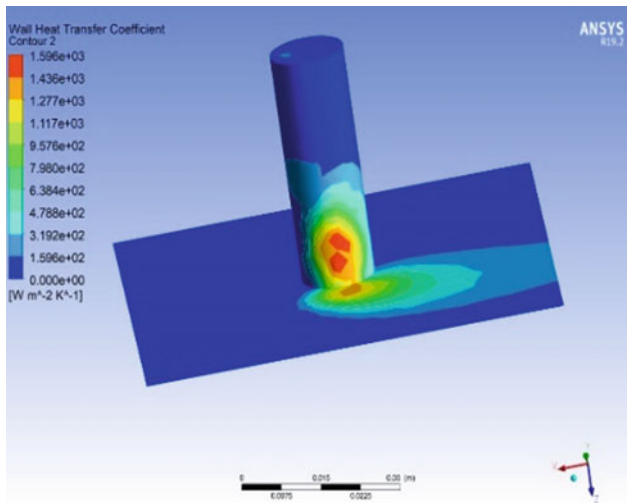


Fig. 16 Heat transfer coefficient of circular fin

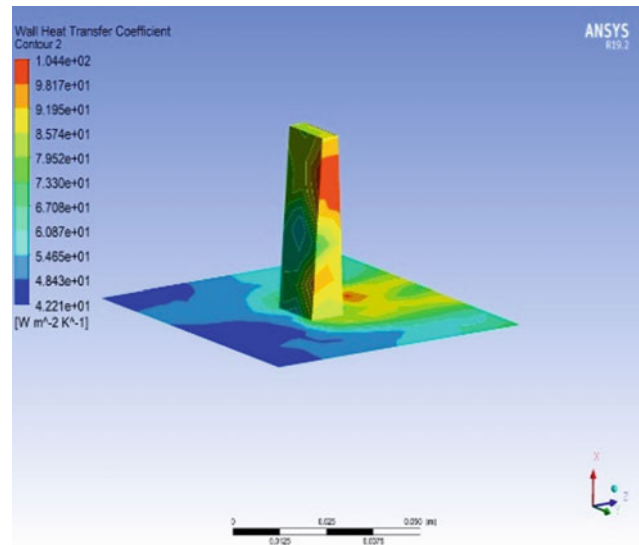


Fig. 18 Heat transfer coefficient of trapezoidal fin

7 Conclusion

In this article the CFD analysis provides a better understanding of fins shapes and their temperature distribution and heat transfer coefficient distribution. Heat transfer through conduction in material is maximum for circular fin and triangular fin in case-1 and case-2. Effectiveness of rectangular fin, circular fin, triangular fin, and trapezoidal fin in both cases are calculated. Among all fin profiles, in case-1 and case-2 effectiveness of rectangular fin is maximum. Among

all fin profiles, in case-1 and case-2 effectiveness of circular fin is minimum. Hence rectangular fin is best among all taken profiles for both the cases. Rectangular fins provide a larger surface area for heat transfer compared to other fin shapes with similar base dimensions. This increased surface area enhances the efficiency of heat dissipation. Rectangular fins can be easily attached to the base component using various methods, such as welding, brazing, or adhesive bonding, ensuring secure integration within the system.

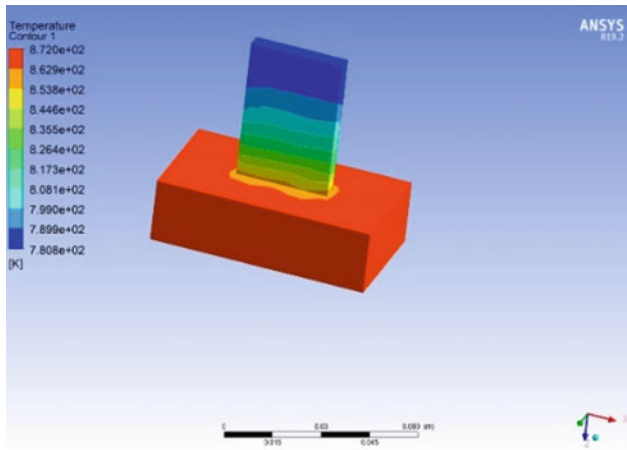


Fig. 19 Temperature distribution of rectangular fin for case-2

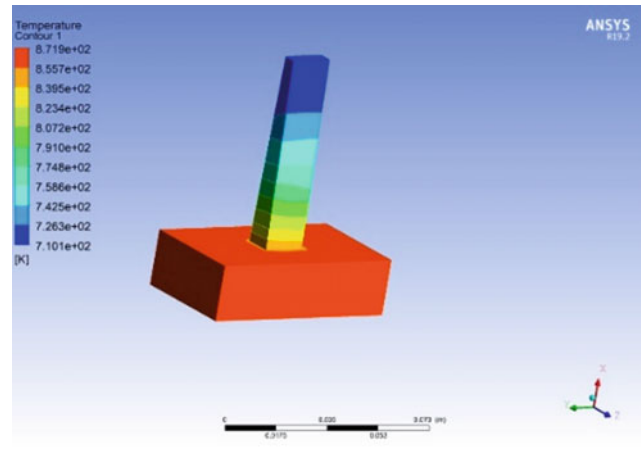


Fig. 22 Temperature distribution trapezoidal fin for case-2

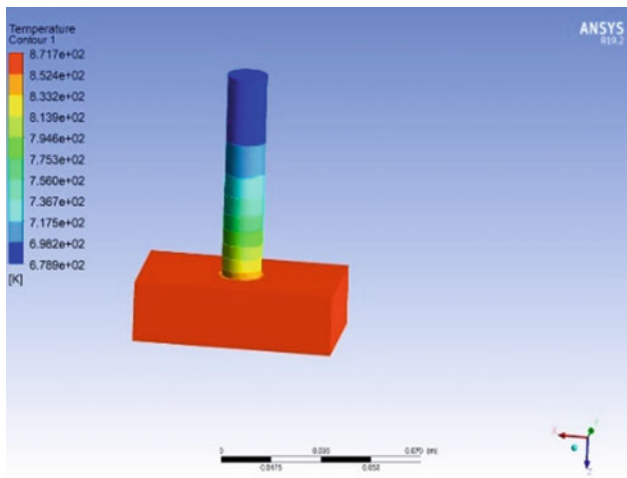


Fig. 20 Temperature distribution of for circular fin for case-2

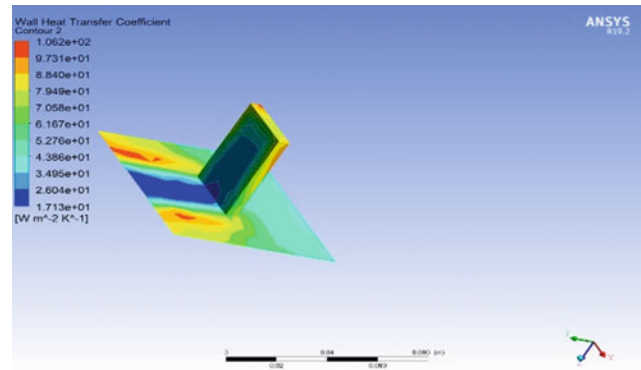


Fig. 23 Heat transfer coefficient of rectangular circular fin for case-2

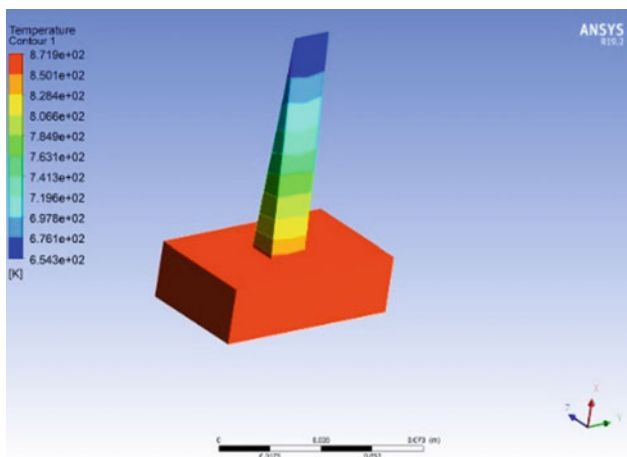


Fig. 21 Temperature distribution of of triangular fin for case-2

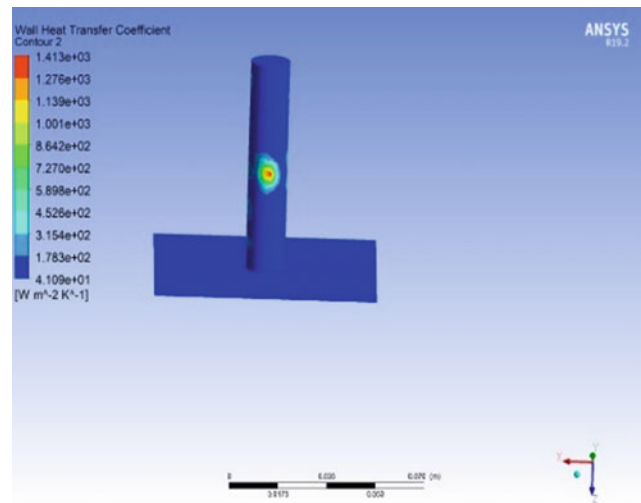


Fig. 24 Heat transfer coefficient of fin for case-2

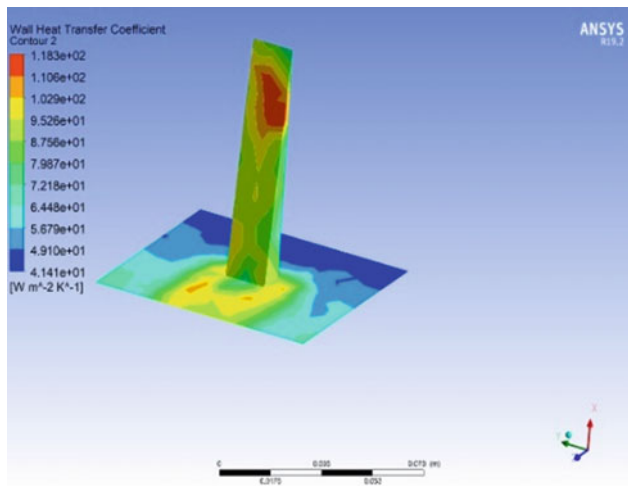


Fig. 25 Heat transfer coefficient of triangular fin for case-2

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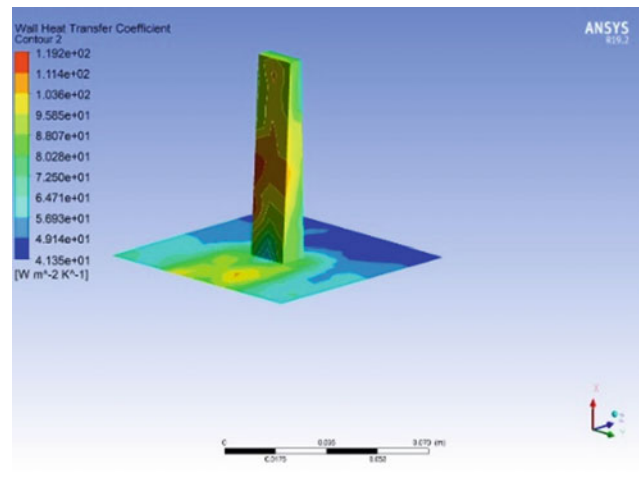


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Influence of Mechanical Properties on Natural Frequency and Mode Shapes of Multi-storey Storage Rack Used in Cargo Vehicles

Iresh Bhavi, Suresh Doddi, Mahantesh S. Matur, S. S. Chappara, V. V. Nagathan, and Pradeep V. Malaji

Abstract

The present paper reports the comparison of experimental and Finite Element Analysis (FEA) technique for the determination of natural frequency and mode shapes of vibration of a multi-storey storage rack made of different structural materials. Storage racks of three-storey height fabricated with five different materials viz., Aluminum, Mild Steel, Stainless Steel, Grey Cast Iron and Polyethylene were tested experimentally to determine the fundamental natural frequency. CAD model of the rack is created by using CATIA-V5 software and Modal analysis is carried out in finite element analysis software ANSYS. FEA results agree closely with experimental results. Polyethylene material yielded lowest fundamental natural frequency of 2.875Hz whereas structural steel yielded highest fundamental natural frequency of 11.81Hz. In case of steels fundamental natural frequency depends upon the Young's modulus of the material. For materials having higher elasticity the value of fundamental natural frequency is higher.

Keywords

Experimental • Natural frequency • Modal analysis • Finite element analysis • Cargo rack • Noise • Vibration

1 Introduction

Storage racks used in heavy cargo vehicles are subjected to high noise and vibration during vehicle operation. The major sources of excitation are engine vibration, uneven road surfaces, and excitation due to operation of suspension system. Components experience high induced stresses due to higher amplitude of vibration. Hence knowledge of natural frequency plays a very important rule in avoiding high amplitude vibrations caused due to resonance so objective here is to investigate the suitability of different structural materials on modal parameters and analyze the effect of mechanical properties on fundamental natural frequency and mode shapes of vibration. The literature survey for the present work comprising of vibration analysis of different multi-storey structures is listed below.

Bhavi et al. (2022) investigated the NVH characteristics of bracket used to mount audio system in vehicles both by experimental and Finite Element Analysis. The experimental setup consisting of a dynamic shaker, on which the bracket was mounted and the sound and vibration data were acquired by using a four channel data acquisition system. Wang et al. (2021) carried out vibration test and optimization of axle box bracket structure by experimental methods and provided simplified design methods for the frame and flow racks. López-Almansa et al. (2022) studied seismic analysis of adjustable pallet rack systems and concluded that tests on full racks can be static, pseudo-dynamic or dynamic. Bhavi et al. (2021a; b) studied the NVH (Noise, Vibration and Harshness) characteristics of an automobile piston and differential gear box both by experimental and FEA. They investigated that vibration signatures of any machine or component depend on its complete assembly and interaction with other bodies coming in contact. Zhang and Tong (2021) studied the seismic response spectra of two-story frames with racks on the elastic floor and provided simplified design methods for the frame and flow racks. Shi et al. (2015) carried out Finite element and experimental analysis of

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pinion bracket-assembly of three gorges project ship lift and established correlation between experimental and FEA results. Zhang et al. (2020) studied the vibration response of Crawler rice combine harvester threshing rack excited by different frequencies of multiple working parts and provided a theoretical reference for the structural design and optimization of combine harvester threshing rack. Kumar et al. (2014) carried out the modal analysis of transmission gearbox by using FEA. The natural frequencies and mode shapes of vibration are determined for the casing of a heavy vehicle transmission gearbox. Four materials were considered for gear box viz., grey cast iron, structural steel, aluminum and magnesium alloy (Wang et al., 2021). Flaieh et al. (2020) compared theoretical and FEA results of modal analysis of Fixed-free beam made up of three different materials of hollow and solid circular cross section. He studied the effects of diameter and length of beam on the fundamental natural frequency. Blatnická et al. (2019) described the design and strength analysis of storage rack with pullout arms used to store metal rods in a manufacturing unit. FEA is used to carry out stress analysis in the designed rack to meet the safety requirements. Al-Sarraf and Ali (2009) described a numerical solution to find the natural frequency for vibration of transverse type and one simply supported beam with symmetric overhang. Two limiting cases were proposed with no overhang and no span. Numerical results agreed with analytical results. Avcar (2014) considered Clamped–Clamped (C–C), Clamped–Simply Supported (C–SS) Simply Supported–Simply Supported (SS–SS) and Clamped–Free (C–F) boundary conditions for study of free vibrations in aluminum beams of square cross sections. The effects of the geometric characteristics and boundary conditions are obtained by using Euler–Bernoulli beam theory and Newton–Raphson Method. The results obtained were validated by using the FEA software ANSYS. Diwan et al. (2019) compared experimental method, Classical Rayleigh method, modified Rayleigh method and finite element analysis using ANSYS software to determine maximum deflection under static loading and natural frequency of stepped cantilever beam made up of aluminum. Effects of change in diameter of the beam on natural frequency were studied. From the literature survey we can conclude that less work is recorded in the experimental determination of fundamental natural frequency of structures and a very scarce work is recorded in the experimental investigation and FEA of multi-storey storage racks used in cargo vehicles.

2 Experimental Work

In modal analysis one of the most used excitation sources is, an Electro dynamic vibration exciter, i.e., Shaker. It is an electromechanical device that provides a vibrating motion

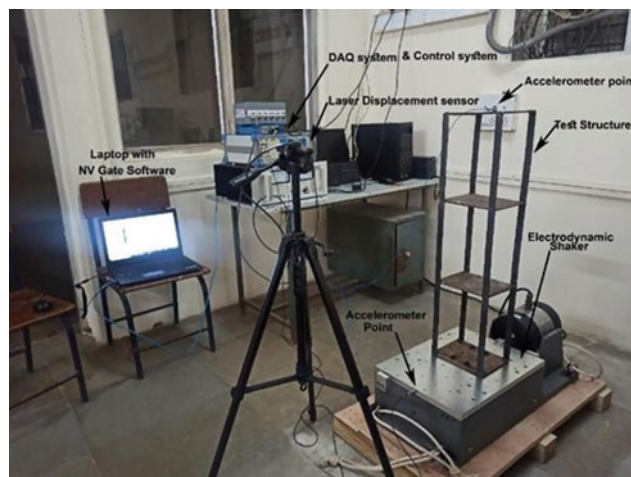


Fig. 1 Experimental Setup

with respect to the input signal. A uniaxial accelerometer is used to measure the vibrations as shown in Fig. 1. A laser displacement sensor is used to measure displacements by using a corresponding software and FFT software the fundamental natural frequencies are obtained.

As the frequency of excitation matches with the natural frequency of the structure the resonance occurs resulting in very large amplitudes of vibration. When the test structure passes through its resonant frequency there is a sudden decrease in the force delivered by the shaker causing the force drop-off phenomenon. From this, the natural frequency of the structure can be easily identified. Figure 1 shows the experimental setup with all necessary sensors viz. displacement sensor, accelerometer used for measurement and determination of fundamental natural frequency of the test rack.

An electrodynamic shaker with digital vibration controller that can apply Sine, RSTD, and Random and shock force of up to 100 kgf is used for the excitation as shown in Fig. 1. Two uniaxial accelerometers are mounted on the test structure at specific points to measure the vibrations. A non-contact type laser displacement sensor is used to measure displacement in first mode of vibration. Table 1 lists the various materials used to fabricate the storage rack and their mechanical properties.

3 Results and Discussion

3.1 Experimental Results

With the help of a four-channel data acquisition system the data from the sensors are continuously acquired and from the DAQ software variation of acceleration in time domain is obtained. And with the help of FFT (Fast Fourier

Table 1 Materials used for storage rack

S No	Material	Youngs modulus (GPa)	Density (kg/m ³)	Poissons ratio	Bulk Modulus (GPa)	Shear modulus (GPa)
1	Polyethylene	1.1	950	0.42	2.291	3.873
2	Aluminum	71	2770	0.33	69.608	26.692
3	Grey cast iron	110	7200	0.28	83.33	42.97
4	Stainless steel	193	7750	0.31	169.3	73.664
5	Structural steel	200	7850	0.3	166.67	76.92

Transforms) software variation of acceleration in frequency domain is obtained. As an example the plots for aluminum material are shown in Figs. 2 and 3. Experimental results for various rack materials are shown in Table 2.

Figure 2 shows plot of fundamental natural frequencies of various storage rack materials obtained from experimental results.

Figure 3 shows the relation between elasticity of the material and fundamental natural frequencies for various storage rack materials obtained from experimental results. From the figure we can observe that fundamental natural frequency of any structure depends primarily on the modulus of elasticity of the material. And fundamental natural frequency increases with increase in elasticity of the material except for gray cast iron. This behavior is due to highly brittle nature of gray cast iron.

Figure 4 shows plot of six modes of natural frequency for various materials from experimental results.

Figure 5 shows the variation of Acceleration with frequency for the storage rack made of aluminum.

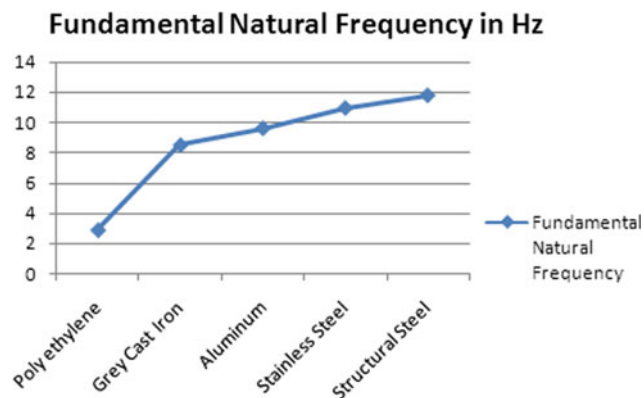
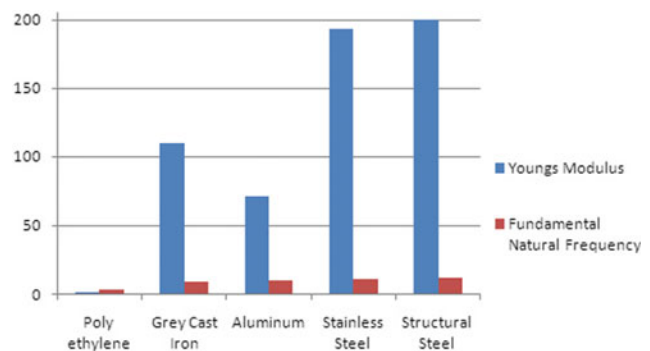
**Fig. 2** Experimental fundamental natural frequencies for various materials**Fig. 3** Relation between elasticity of the material and fundamental natural frequencies

Figure 6 shows the variation of Acceleration with time for the storage rack made of aluminum.

3.2 Finite Element Analysis Results

Table 3 shows the natural frequency of storage rack made of various materials for up to six mode shapes. Fundamental natural frequency is high for structural steel with a value of 11.212 Hz whereas it is lowest for polyethylene material with a value of 2.3735 Hz.

Figure 7 shows plot of fundamental natural frequencies of various storage rack materials obtained from FEA results.

Figure 8 shows plot of six modes of natural frequency for various materials from FEA results.

Figures 9, 10, 11 and 12 shows the fundamental natural frequency and mode shape of vibration of storage rack made of different materials viz. Structural steel, stainless steel, Grey CI, Aluminum and Polyethylene using Finite Element Analysis.

Table 2 Experimental results for various rack materials

S No	Natural frequencies in Hz				
	Polyethylene	Grey cast iron	Aluminum	Stainless steel	Structural steel
1	2.875	8.51	9.625	10.97	11.81
2	7.19	26.24	19.25	31.25	23.625
3	7.63	31.72	28.875	36.7	35.43
4	7.96	32.76	38.5	39.65	47.25
5	10.22	36.96	48.125	49.76	59.06
6	25.78	95.28	57.75	105.85	70.875

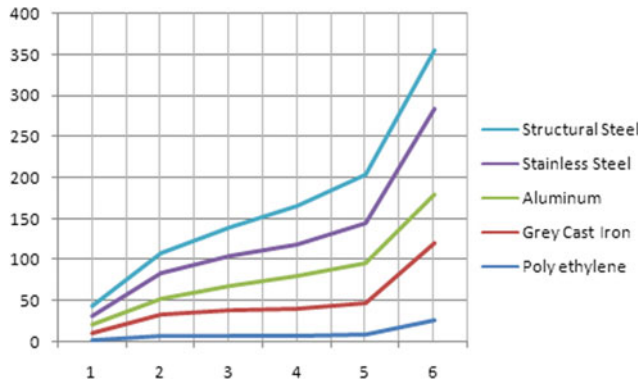
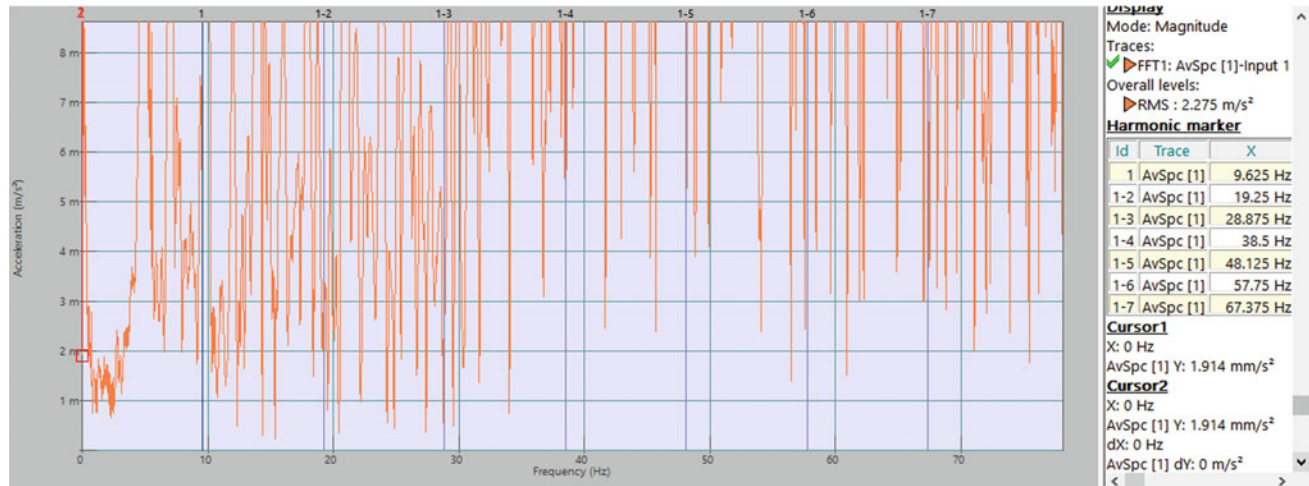
**Fig. 4** Plot of natural frequency in Hz for various materials from experimental results

Figure 9 shows the mode shape of vibration of storage rack made of structural steel at its fundamental natural frequency of 11.212 Hz as shown in figure.

Figure 10 shows the mode shape of vibration of storage rack made of stainless steel at its fundamental natural frequency of 10.779 Hz as shown in figure.

Figure 11 shows the mode shape of vibration of storage rack made of Gray Cast Iron at its natural frequency of 37.142 Hz as shown in figure.

Figure 12 shows the mode shape of vibration of storage rack made of Aluminum at its fundamental natural frequency of 10.082 Hz as shown in figure below.

**Fig. 5** Variation of acceleration with frequency of the storage rack made of aluminum

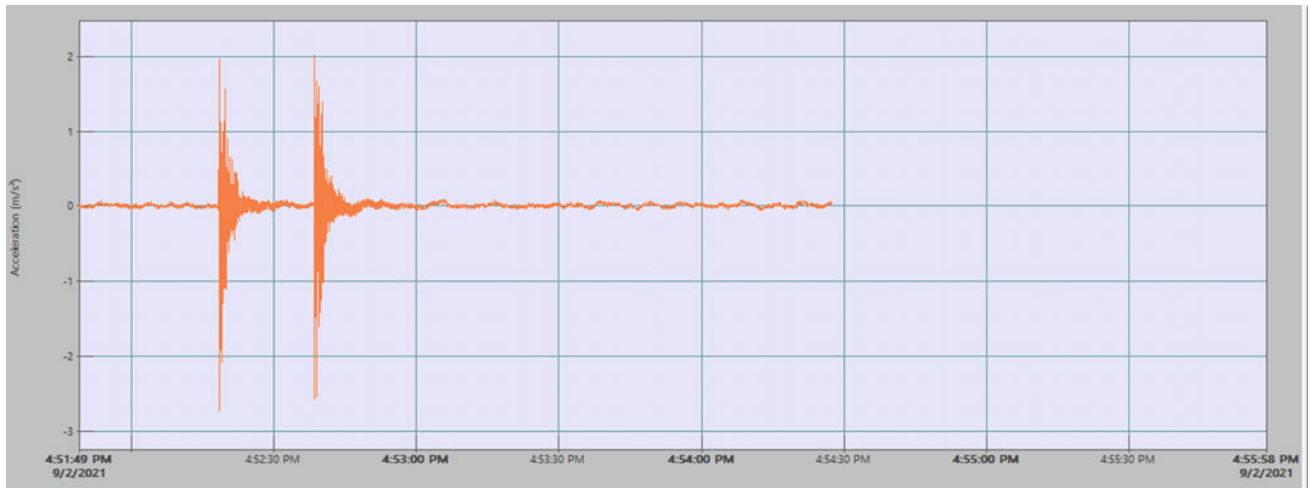


Fig. 6 Variation of acceleration with time for the storage rack made of aluminum

Table 3 FEA results for various rack materials

S No	Natural frequencies in Hz				
	Polyethylene	Grey cast iron	Stainless steel	Aluminum	Structural steel
1	2.3735	8.4131	10.779	10.965	11.212
2	6.7959	24.114	30.892	31.422	31.959
3	7.5267	27.372	34.907	35.394	36.175
4	7.8736	28.786	36.661	37.142	38.183
5	10.082	35.816	45.876	46.658	47.228
6	24.576	89.298	113.93	115.54	117.14

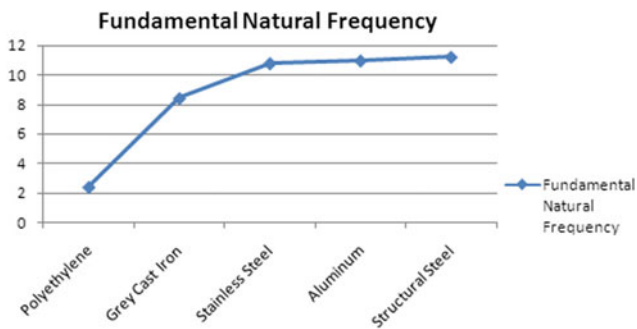


Fig. 7 Fundamental natural frequencies for various materials from FEA results

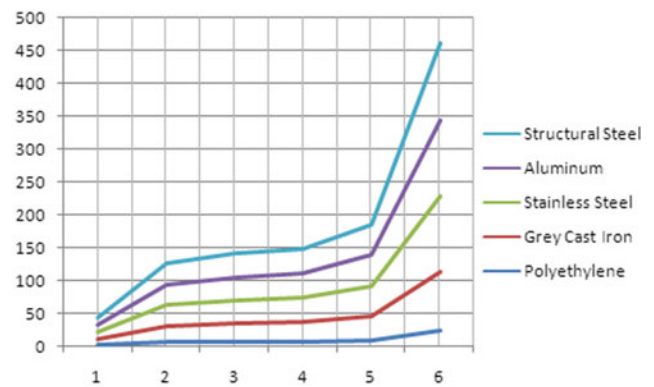


Fig. 8 Plot of natural frequency in Hz for various materials from FEA results

4 Comparison Between Experimental and FEA Results

Table 4. lists the fundamental natural frequencies obtained from Experimental and Finite element analysis for various materials.

Figure 13 shows the comparison of fundamental natural frequencies obtained from Experimental and Finite element analysis for various materials

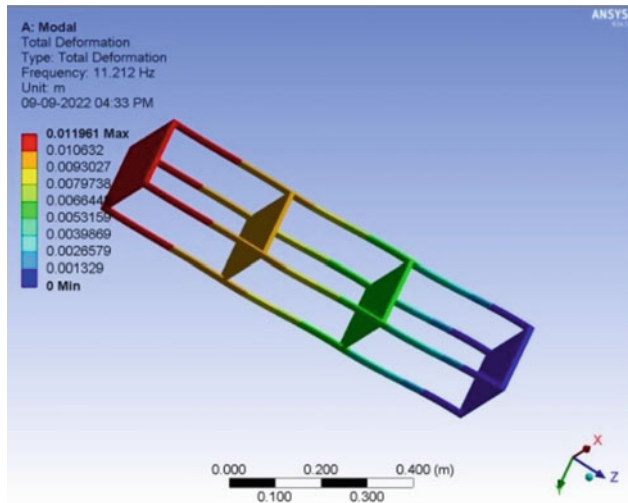


Fig. 9 Mode shape at fundamental natural frequency for structural steel rack

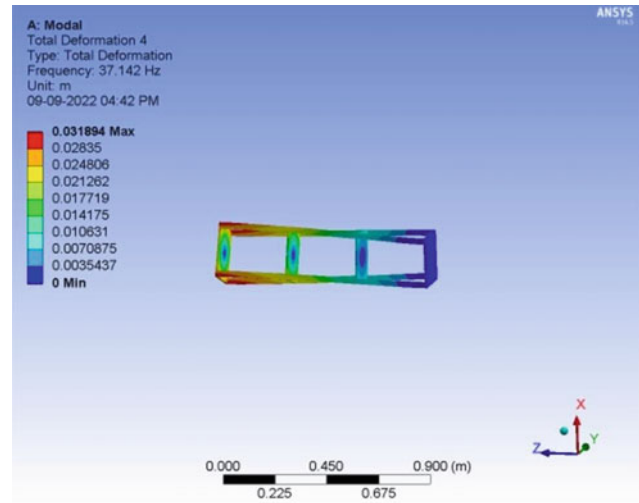


Fig. 11 Mode shape at fundamental natural frequency for grey CI rack

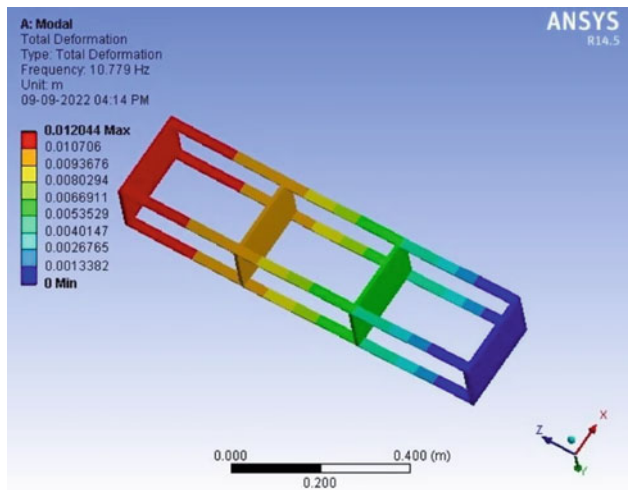


Fig. 10 Mode shape at fundamental natural frequency for stainless steel rack

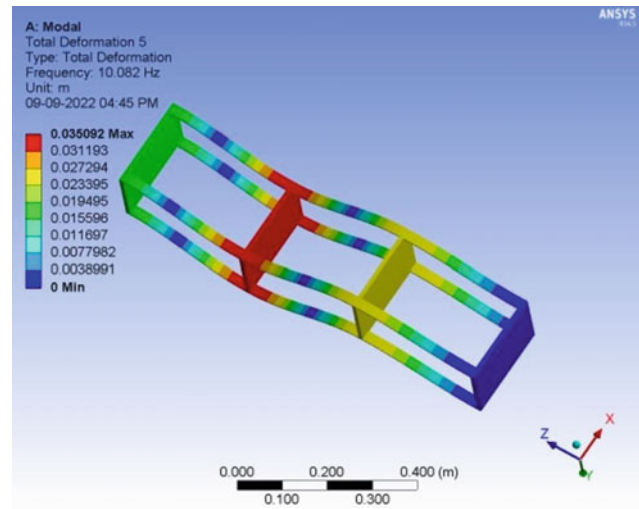


Fig. 12 Mode shape at fundamental natural frequency for aluminum rack

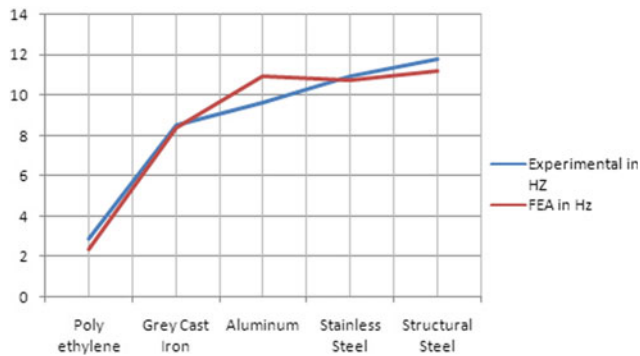
5 Conclusion

Fundamental natural frequency for storage rack made of different engineering materials were obtained experimentally and by using finite element analysis a correlation is established between the experimental and FEA results. The fundamental natural frequency for structural steel is higher

whereas it is lower for polyethylene material. The natural frequency of a mechanical oscillating system depends on elastic properties, dimensions, and mass of the system. The more flexible a part or the more mass of the part, the lower is its natural frequency and the more rigid a part, the higher is the natural frequency. The results obtained can be utilized in the design and development of storage racks in cargo vehicles.

Table 4 Comparison of experimental and FEA results for various rack materials

Rack materials	Fundamental natural frequencies in Hz				
	Polyethylene	Grey cast iron	Aluminum	Stainless steel	Structural steel
Experimental	2.875	8.51	9.625	10.97	11.81
FEA	2.3735	8.4131	10.965	10.779	11.212

**Fig. 13** Comparison of fundamental natural frequency obtained from experimental and FEA

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Effect of Exhaust Gas Recirculation on the Performance and Emissions of a Common Rail Diesel Engine Powered by B20 Mix Waste Cooking Oil Methyl Ester Using CFD

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Abstract

Internal combustion engines (IC engines) are broadly applied in goods and people transportation, as well as agricultural and industrial activities. The most widely recognized biodiesel mix is B20, 20% biodiesel is mixed with diesel. Many diesel vehicles can operate on B20 and relatively low blends without requiring any engine change. A number of computational fluid dynamics (CFD) assessments have also been performed since they have shown to be a beneficial tool in aiding with experimental work. A CFD Analysis of a Toroidal re-entrant combustion chamber (TRCC), 17.5 CR, Injection timing 10° BTDC and Injection pressure 900 bar with 0.2 mm dia 8 holes injector 4 stroke CRDI engine with WMCO biodiesel–diesel blends result is well accord with the experimental result. Further CFD analysis is carried out for different EGR rate for NOx reduction. The indicated thermal efficiency and indicated power are obtained constant for different EGRs. As percentage of EGRs increase, the percentage of NOx emission is reduced by 36, 40, and 80% for 10, 20, and 30% EGR rates, respectively, compared to 0% EGR. As percentage of EGR increases, Mean CO mass fraction is increased by 20, 42, and 62 percentage for 10, 20, and 30% EGR's compared to 0% EGR. As percentage of EGR increases, Mean Soot mass fraction is reduced by 6.25, 12.5, and 21.87 percentage for 10, 20, and 30% EGRs compared to 0% EGR. Ignition delay period increases with increase in percentage of EGR.

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Keywords

Exhaust gas recirculation • Waste • Computational fluid dynamics • Nitrogen dioxide • Deep frying cooking oil

Nomenclature

WMCO	waste mixed cooking oil
$\dot{m}_i$	Flow rate of mass (kg/s)
$\dot{m}_a$	Intake air flow rate (kg/s)
$\dot{m}_e$	flow rate of EGR (kg/s)
ρ	mean density
$\tilde{Y}_x$	Species Mass fraction average x
$\underline{u}_i$	Average weighted velocity
μ and μ_t	laminar and turbulent Dynamic viscosity
S_c and S_{ct}	Schmidt Numbers at Laminar and turbulent conditions
$\dot{w}_x$	Average combustion source term
μ_t and μ	viscosities at turbulent and laminar
$\tilde{Y}_{Fu}^b$	Fuel in burned gases
$\tilde{Y}_{Fu}^u$	Fuel in fresh gases
$\tilde{E}_{Fu}^{F \rightarrow M}$, $\tilde{E}_{Fu}^{A \rightarrow M}$, $\tilde{E}_{O_2}$	Mixing model
$\rho_{S_{Fu}}^{\sim}$	Gaseous fuel mass production rate
$\tilde{Y}_{O_2}^A$	Total mass of the oxygen
$\tilde{Y}_{Fu}^F$	Unmixed mass fraction
M^M	Mixed are molar gas mass
M_{Fu}	molar fuel mass
$M_{air + EGR}$	inmixed air molar mass of + EGR
ρ	Average Density
ρ_u^u	Density of the unburned gases
$\tilde{Y}_{O_2}^{\infty}$	unmixed Oxygen mass fraction in air
$\tilde{Y}_{NO}$	NOx Mean mass fraction
x_i	Cartesian coordinates
C_d	Co-efficient of Diffusion
$\tilde{NO}$	Nitric Oxide mean term

M_{NO}	Molecular Mass
$\frac{NO_{thermal}}{dt}$	Thermal mechanisms
$\frac{NO_{prompt}}{dt}$	Prompt Mechanisms
$\tilde{\phi}_{Soot}$	Mass fraction of Soot
x_j, x_i	Cartesian coordinates
μ	dynamic viscosity

1 Introduction

Internal combustion engines (IC engines) are broadly applied in goods and people transportation, as well as agricultural and industrial activities. For heavy-duty applications, diesel engines are preferred because they can deliver more power while burning less fuel. Increased energy demand has prompted nations to diversify their energy portfolios in order to reduce their reliance on petroleum fuels and strengthen their energy independence. Biofuels derived from sustainable sources with acceptable chemical properties have made a diesel engine the preferred option within internal combustion engines as a common method (Goh, et al., 2020a; Khandal et al., 2017; Qasim et al., 2018).

According to reported data, almost 3/5th of food is wasted in consumption, with a major portion of this being unavoidable or inedible. (Caldeira et al., 2017; Foo et al., 2021) Among the food wastes, cooking oil is a significant source of lipids. Waste cooking oil (WCO) is mostly produced in the home, hotel, and road side vendors. Because of unconscious practices, a lack of rules, or a lack of law enforcement, most WCOs are disposed of through drains and siphons, or as solid residues in landfills. As a result, the final outcome is a slew of cascading issues. WCO has emerged as one of the front-runner possibilities, with substantial research directed toward recycling and reusing the WCO can be a by-product for biofuels extraction using transesterification and etherification process (Orjuela & Clark, 2020; Qasim et al., 2018).

Biodiesel is recognized as fuel and fuel additive by the Environmental Protection Agency (EPA). The EPA registration is feedstock and process agnostic, encompassing all biodiesel that fulfills the ASTM D6751 biodiesel definition. These standards safeguard forests and native grasslands while ensuring that renewable energy outperforms fossil fuels in terms of environmental benefits (Kiran et al., 2021; Orjuela & Clark, 2020).

Experts believe that the use of biodiesel directly and its blends has certain detrimental effects on engines, such as diminished fuel consumption, efficiency and performance, among other things, owing to variances in fuel characteristics, operation settings, and the current engine geometry

(Cheng et al., 2013; Kiran et al., 2021; Petranović et al., 2015). Hence, to increase the performance of CI engines running on biodiesel, either improve the fuel qualities or adjust the engine's design parameters. Changing the combustion chamber shape and injection timing to increase engine performance are also viable alternatives. The movement of air–fuel mixture with various piston bowl geometry inside the combustion chamber (CC) has a notable impact on fuel combustion rate, hence affecting the engine's performance and efficiency. Toroidal Re-entrant combustion chamber (TRCC) and Toroidal combustion chamber (TCC) powered by biodiesel perform better in terms of performance. Increased effort is done owing to improve TRCC and TCC combustion chamber to boost brake thermal efficiency while reducing fuel consumption, compared to other geometries (Kiran et al., 2021; Liu et al., 1993; Petranović et al., 2015). The heat release rate is higher in the case of modified combustion chamber geometry than in the case of standard combustion chamber for biodiesel due to improved combustion. The biodiesel heating value is lower than that of diesel fuel, due to higher viscosity and surface tension, which results in inferior spray atomization properties. Furthermore, the heat release rate can be enhanced with increasing injection, resulting in proper combustion. Increases in injection pressure led to good atomization and air–fuel mixture (Fayad et al., 2021).

The most widely recognized biodiesel mix is B20, i.e., 20% biodiesel is mixed with diesel. Many diesel vehicles can operate on B20 and relatively low blends without requiring any engine changes. Use of biodiesel with the diesel will increase the lubricate due to increase in the cetane number. A higher Cetane number means that the engine will start more quickly and readily. Diesel engines rely on the lubricity of the fuel to keep moving components from wearing out prematurely. Lubrication improves lubricity by reducing the interfacial tension between moving parts, leading to reduced wear. Biodiesel has several benefits, namely that it may boost the lubricity of fuel at low blend level (Khandal et al., 2017; Kiran et al., 2021; Qasim et al., 2018).

Blending Exhaust Gas Recirculation (EGR) with biodiesel offers a promising avenue to enhance engine performance. EGR reduces nitrogen oxide emissions by recirculating exhaust gases, lowering combustion temperatures. Blending biodiesel, a renewable fuel, with diesel improves lubricity, enhancing engine durability and reducing wear. Biodiesel's higher cetane number promotes efficient combustion, potentially enhancing power output. Additionally, biodiesel's oxygen content can facilitate more complete combustion, enhancing fuel efficiency. However, careful calibration of EGR rates and biodiesel blends is crucial to prevent combustion instability and deposits.

Integrating EGR with biodiesel necessitates comprehensive engine mapping, optimizing injection timing, and air–fuel ratios to fully exploit the combined benefits for improved performance, emissions, and sustainability.

A number of computational fluid dynamics (CFD) assessments have also been performed since they have shown to be a beneficial tool in aiding with experimental work. For clean diesel engines, several CFD approach is inculcated to find out the characteristics performance, and emission of biodiesel using common rail direct injection (CRDI) engines (Fayad et al., 2021; Petronović et al., 2015).

1.1 Specification of Engine and Fuel Properties

In the current work, the CRDI engine utilized by Kiran et al. (2021) is considered for CFD approach. Table 2 contains information on the diesel engine and the injection parameters. A B20 blend of biodiesel extracted from mix waste cooking oil (MWCO) collected from local vendor, hotel, and restaurants with neat diesel is considered in the present study. Table 1 lists the parameters of plain diesel and B20 mix biodiesel. Simulations are also run for 10, 20, and 30% EGR rates for injection timings at 100 BTDC. In steady-state operation, the EGR rate is computed as the ratio of EGR rate of Mass flow to rate of intake mass.

$$\dot{m}_i = \dot{m}_a + \dot{m}_e \quad (1)$$

$$\text{EGR rate in steady state} = \dot{m}_e / \dot{m}_i \quad (2)$$

2 Numerical Procedures

2.1 Computational Model

As shown in Fig. 1, the AVL FIRE's Engine Simulation Environment (ESE) is utilized for modeling TRCC diesel engine and for computational. Since an injector has eight

nozzles, a 450 symmetric segment is chosen for computational modeling. A high injection pressure cycle is explored in the current study to minimize calculation time. The simulation is focused on in-cylinder flow and combustion process, the computational mesh excludes exhaust and intake ports. The calculations begin with the Intake Valve Closure (IVC) and terminate with the Exhaust Valve Opening (EVO). All computations employ the identical beginning and boundary conditions. Crank angle (CA) of 0.2° is used for the computation time step. The final mesh comprises of a hexahedral dominating mesh. Figures 2 and 3 show the results of a grid independence test used to determine the optimal grid size. The computation is done for various grid sizes, to study grid independence for peak pressure, peak temperature, and computing time. From Figs. 2 and 3, the total number of grids at 3.9×10^5 discovered that the parameters under consideration are invariant. Tables 3, and 4 show the simulation boundary conditions and models used for stimulation.

2.2 Mathematical Model Equations

For chemical species fuel, the transport equations are modeled as:

$$\frac{\partial(\rho \tilde{Y}_x)}{\partial t} + \frac{\partial(\rho \tilde{u}_i \tilde{Y}_x)}{\partial x_i} = \frac{\partial}{\partial x_i} \left(\left(\frac{\mu}{S_c} + \frac{\mu_t}{S_{ct}} \right) \frac{\partial \tilde{Y}_x}{\partial x_i} \right) + \dot{w}_x \quad (3)$$

$$\text{Mass fraction average of species } x : \tilde{Y}_x = \frac{m_x}{m} \quad (4)$$

The transport equations for fuel are.

$$\frac{\partial(\rho \tilde{Y}_{Fu}^\mu)}{\partial t} + \frac{\partial(\rho \tilde{u}_i \tilde{Y}_{Fu}^\mu)}{\partial x_i} = \frac{\partial}{\partial x_i} \left(\left(\frac{\mu}{S_c} + \frac{\mu_t}{S_{ct}} \right) \frac{\partial \tilde{Y}_{Fu}^\mu}{\partial x_i} \right) + \rho \tilde{S}_{Fu}^\mu + \dot{w}_{Fu}^\mu + \dot{w}_{Fu}^{\mu \rightarrow b} \quad (5)$$

Table 1 Biodiesel properties compared with diesel (Kiran et al., 2021)

Parameters/Properties	Units	Diesel	B20	B100	ASTM standard
Flash point	°C	55	73	91	D93
Kinematic viscosity	mm ² /s	2.5	2.3	2.1	D445
Density	kg/m ³	830	839	844	D4052
Calorific value	kJ/kg	43,481	42,845	39,372	D5865
Pouring point	°C	−11.4	−12	−5	D5949
Cetane number		50	51	52	D613
Cloud point	°C	−9.3	−7	−1	D5773

Table 2 Specification of duel fuel diesel test ring (Kiran et al., 2021)

Model and make	Kirloskar TV1
Engine type	4 stroke Direct injection
Stroke, bore	110 mm, 87.5 mm
Compression ratio	17.5: 1
Displacements volume	600 CC
Combustion chamber	TRCC
Arrangement of valves	Overhead
Cooling medium	Water cooled
Rated Power	@1500 rpm, 5.2 kW
Dynamometer	0–180 m Length
Inlet valve closed (IVC)	−147° ATDC
Inlet valve open (IVO)	−32° ATDC
Exhaust valve closed (IVC)	29° ATDC
Exhaust valve open (EVO)	134° ATDC
Range of fuel measurement	0–50 ml
Type of injector	Common Rail type
Injection pressure	Variable (upto 1000 bar)
Injector nozzles	8
Injector nozzle diameter	0.2 mm
Starting of injection	−10 °BTDC
Duration of injection	21.5 °C

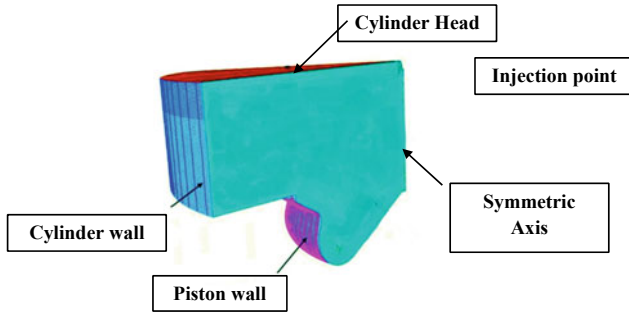


Fig. 1 Computational modeling of TRCC with Boundary condition

$$\frac{\partial(\rho \tilde{Y}_{Fu}^b)}{\partial t} + \frac{\partial(\rho \tilde{u}_i \tilde{Y}_{Fu}^b)}{\partial x_i} = \frac{\partial}{\partial x_i} \left(\left(\frac{\mu}{s_c} + \frac{\mu_t}{s_{ct}} \right) \frac{\partial \tilde{Y}_{Fu}^b}{\partial x_i} \right) + \rho \tilde{s}_{Fu}^b + \dot{w}_{Fu}^b + \dot{w}_{Fu}^{u \rightarrow b} \quad (6)$$

For fictitious unmixed species are:

$$\frac{\partial(\rho \tilde{Y}_{Fu}^F)}{\partial t} + \frac{\partial(\rho \tilde{u}_i \tilde{Y}_{Fu}^F)}{\partial x_i} = \frac{\partial}{\partial x_i} \left(\left(\frac{\mu}{s_c} + \frac{\mu}{s_{ct}} \right) \frac{\partial \tilde{Y}_{Fu}^F}{\partial x_i} \right) + \rho \tilde{s}_{Fu}^F + \rho \tilde{E}_{Fu}^{F \rightarrow M} \quad (7)$$

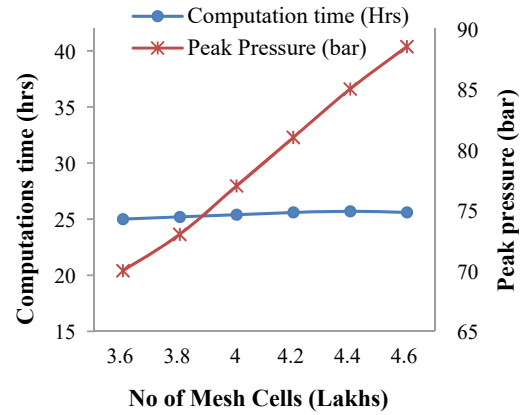


Fig. 2 Show the grid independence study carried out for peak pressure

$$\frac{\partial(\rho \tilde{Y}_{O_2}^A)}{\partial t} + \frac{\partial(\rho \tilde{u}_i \tilde{Y}_{O_2}^A)}{\partial x_i} = \frac{\partial}{\partial x_i} \left(\left(\frac{\mu}{s_c} + \frac{\mu}{s_{ct}} \right) \frac{\partial \tilde{Y}_{O_2}^A}{\partial x_i} \right) + \rho \tilde{E}_{O_2}^{A \rightarrow M} \quad (8)$$

the k-epsilon model (κ - ϵ model)

$$E_{Fu}^{F \rightarrow M} = -\frac{1}{\tau_m} \tilde{Y}_{Fu}^F \left(1 - \tilde{Y}_{Fu}^F \frac{\rho M^M}{\rho u|_u M_{Fu}} \right) \quad (9)$$

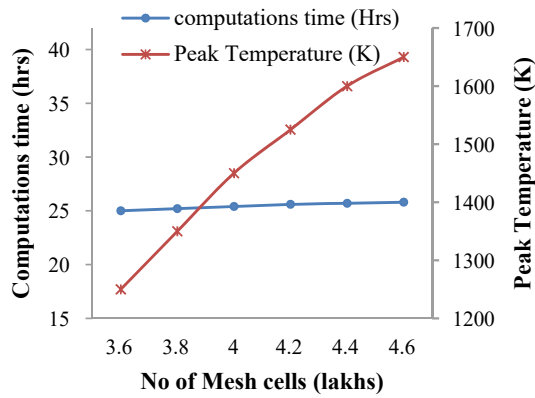


Fig. 3 Shows the study of grid independence at peak temperature

With mixing rate of the oxygen

$$E_{O_2}^{-A \rightarrow M} = -\frac{1}{\tau_m} \tilde{Y}_{O_2}^A \left(1 - \frac{\tilde{Y}_{O_2}^A}{\tilde{Y}_{O_2}^\infty} \frac{\rho M^M}{\rho^u |u| M_{air+EGR}} \right) \quad (10)$$

The mixing time scale τ_m is given by $\tau_m^{-1} = \beta_m \frac{\varepsilon}{k}$, where $\beta_m = 1$.

The mass of oxygen in unmixed air, $\tilde{Y}_{O_2}^\infty = \frac{\tilde{Y}_{TO_2}}{1 - Y_{TFu}}$ in unmixed air.

2.3 The NOx Model

Nitrogen oxide is a key component of internal combustion (IC) engine emissions.

The nitrogen monoxide transport equations modeled.

$$\frac{\partial(\rho \tilde{Y}_{NO})}{\partial t} + \frac{\partial(\underline{u}_i \rho \tilde{Y}_{NO})}{\partial x_i} = \frac{\partial}{\partial x_i} \left(\rho C_d \frac{\partial \tilde{Y}_{NO}}{\partial x_i} \right) + N\tilde{O} \quad (11)$$

The term $N\tilde{O}$ represents NOx pollutant formation in the equation

$$N\tilde{O} = M_{NO} \left(\frac{NO_{Thermal}}{dt} + \frac{NO_{prompt}}{dt} \right) \quad (12)$$

Mass fraction formation is modeled by using Transport equation given by

$$\frac{\partial}{\partial t} \left(\rho \tilde{\phi}_{Soot} \right) + \frac{\partial}{\partial x_j} \left(\rho \underline{u}_j \phi_{soot} \right) = \frac{\partial}{\partial x_j} \left(\frac{\mu_e}{\sigma_s} \frac{\partial \phi_{soot}}{\partial x_i} \right) + S_{\phi_{Soot}} \quad (13)$$

Formation rate of Soot is given by.

$$S_{\phi_{Soot}} = S_n + S_g + S_{O_2} \quad (14)$$

Table 3 Stimulation boundary conditions

Parameters	Boundary conditions	Initial value
Piston wall temperature	Moving mesh	550 K
Axis symmetric	Periodic inlet/outlet	Periodic
Cylinder head temperature	Wall	550 K
Cylinder volume	Wall	Thermal/adiabatic boundary
Cylinder wall temperature	Wall	425 K

Table 4 Shows the models used in stimulation

Turbulence model	$\kappa - \zeta - f$ model
Turbulent dispersion model	Enable
Breakup model	Wave
Model for ignition	3 zone coherent flame model (ECFM-3Z)
Combustion model	Coherent flame model (CFM)
Model of wall impingement	Wall jet 1
Treatment for Wall	Hybrid
Wall Model for heat exchange	Standard
Model for Evaporation	Dukowicz and multi-component
Solver for Chemistry	CHEMKIN-II
Nox mechanism	Extended Zeldovich
Model for Soot formation and oxidation	Kinetic
Equivalence Ratio	0.47

3 Result and Discussion

In present work, the engine simulation was combined with the exact reaction mechanisms of AVL-FIRE with CHEMKIN II. For the circumstances mentioned in Table 2, the simulation is validated using the literature (Kiran et al., 2021). Figure 2 depicts the results for rate of heat release and peak in-cylinder pressure versus crank angle. The simulation results (Fig. 4) accord well with the reported experimental data of Biodiesel B20 blend and 10°C injection timing for a rated speed of 1500 rpm.

3.1 Effect of Inner Cylinder Temperature and Peak Pressure for Different % EGR

Figure 5 depicts the cylinder pressure development during combustion on a 20% Biodiesel/local available diesel blend with varied EGR range (0, 10, 20, and 30%) at 10°C injection time and rated 1500 rpm. EGR had a dilution impact on thermal, delay period, and chemical effect on fuel charge, resulting in a 5.5% drop in peak pressure. The oxygen percentage will decrease in the combustion chamber with EGR decreases, resulting in a temperature drop owing to dilution. Also EGR contains water vapor, which helps to lower temperature during combustion. Furthermore, the specific heat capacity of the fuel mixture increases as the CO₂ proportion increases, lowering the adiabatic flame temperature. In pre-flame combustion, inner cylinder temperatures for B20 diesel blends are lower than for diesel, but higher in post-flame combustion. Figure 8 shows the graph plot of average inner cylinder temperature versus injection crank angles. The temperature contours for different % EGR for B20 WMCO Biodiesel–Diesel Blend are shown in figure. The contour plots conclude a process of combustion developed with different percentage of EGR (Figs. 6 and 7).

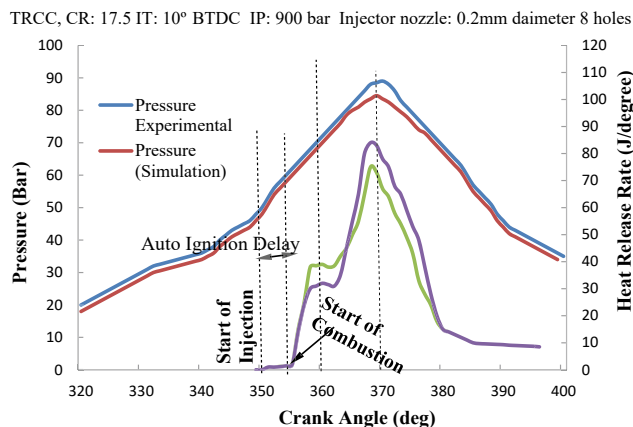


Fig. 4 The variation of inner cylinder pressure and Heat release rate versus crack angle

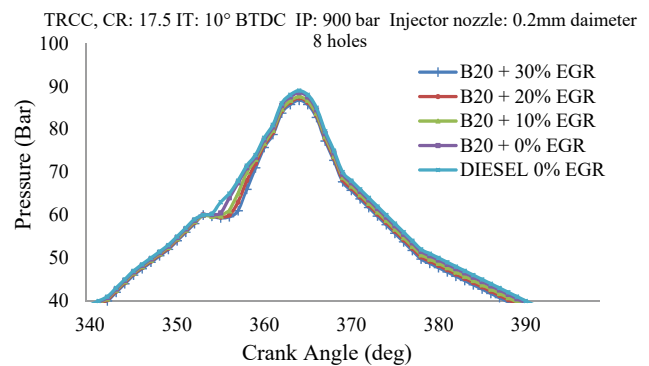


Fig. 5 Shows the variation of inner cylinder pressure versus different EGR %

3.2 The Effect of Inner Cylinder Temperature for Different % EGR

To reduce temperature rise during combustion, optimize air–fuel ratio, enhance fuel atomization, and employ pre-combustion cooling techniques. Incorporate advanced engine designs, use additives to inhibit high-temperature reactions, and apply exhaust gas recirculation to dilute combustion gases. These strategies promote efficient energy conversion while minimizing temperature-related emissions and potential engine damage.

3.3 EGR% Effect on Auto Ignition Delay

The difference between the timing of the injection of fuel and start of the heat release rate curve is computed as autoignition delay. The ignition delay period increases with proportion of WMCO biodiesel blends have the lower cetane number. With the increasing %EGR rate lower the oxygen concentration in the combustion chamber, hence increasing the ignition delay period.

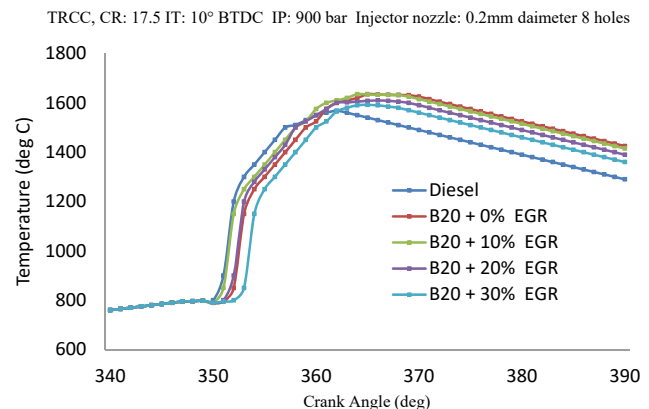
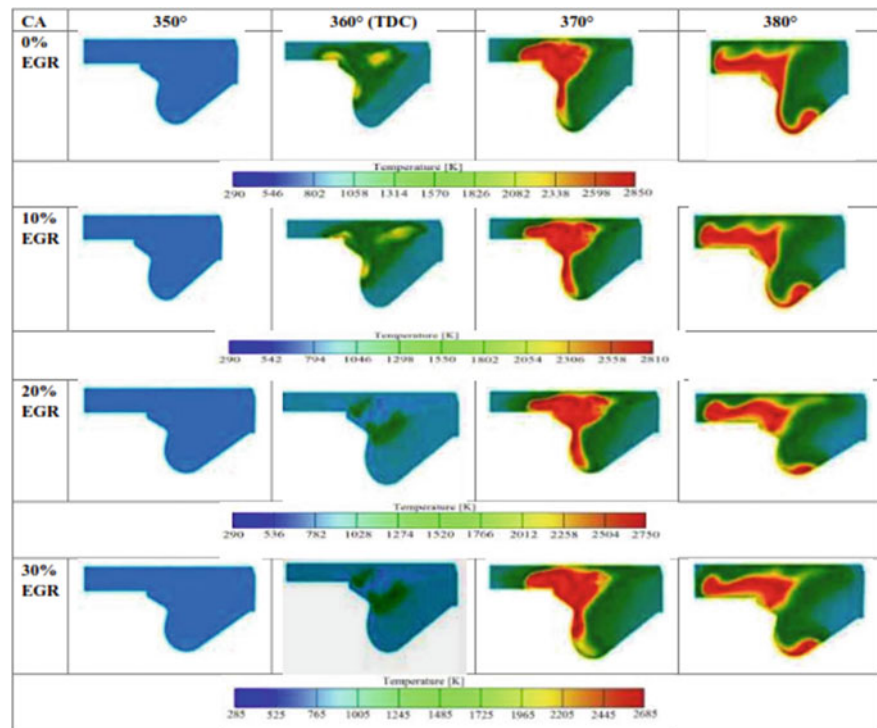


Fig. 6 Shows the variation of inner cylinder Temperature versus different EGR %

Fig. 7 Shows the temperature contour of B20 blend biodiesel at IT 10°CA versus various EGR %



3.4 Effect of Various EGR% on NO_x Mass Fraction

Figure 8 represents the NO_x developed during the B20 blend combustion with different EGR percentage at 10° BTDC injection timing. Lowering cylinder temperature reduces peak combustion temperature, limiting formation of nitrogen oxides (NO_x) during combustion process. Cooler conditions inhibit reactions that create NO_x, resulting in decreased emissions from the engine. The mean NO_x production reduces as the total inner cylinder temperature lowers dramatically with an increasing EGR rate. The EGR specific heat is higher than air intake, hence increase in heat capacity of the intake air in turn decreases the temperature rise during combustion. NO_x production is reduced by 36, 40, and 80% for EGR rate of 10%, 20%, and 30% respectively and compared with diesel.

3.5 Effects of Various EGR % on CO Mass Fraction

It is important to note that at 10° CA injection timings, CO creation is less for the B20 biodiesel mix with various EGR %, than for non-EGR available diesel operation. CO production is an intermediate phase in the burning of fossil fuels. The oxygen atom inside the combustion chamber oxidizes the

CO with OH radicals and liberate CO₂. With increase in the percentage of EGR during combustion, reduces the oxygen availability, thus inefficient fuel–air mixing, oxidation of CO stops. A greater percentage of EGR dilutes the mixture and produces more CO as shown in Fig. 9.

3.6 Effect of EGR Percentage on Soot Formation

It is important to evaluate the soot because the size of soot particles affects the environment and health. The smaller the size of the soot, tendency to suspend in the air for longer time, which lead to hazards to living being (Fayad et al., 2021). The main reason for lowering the formation of soot is to enhance the oxidation rate and combustion temperature. At higher injection pressure, good atomization and higher mixing rate will develop, hence leading to good combustion rate. Comparing the Diesel and B20 blends operating at higher injection pressure, soot is liberated more in B20 blend biodiesel due to soot deposition at inside combustion chamber occurring due to higher atomization and lower balance point temperature at some part of combustion chamber. With addition of 10, 20, and 30% of EGR to charge reduces the soot formation by 6.67, 13.33, and 18.67% respectively as per Fig. 10. The addition of the EGR, suppresses the soot formation due to warm-up of charge and tends to reduce the deposition.

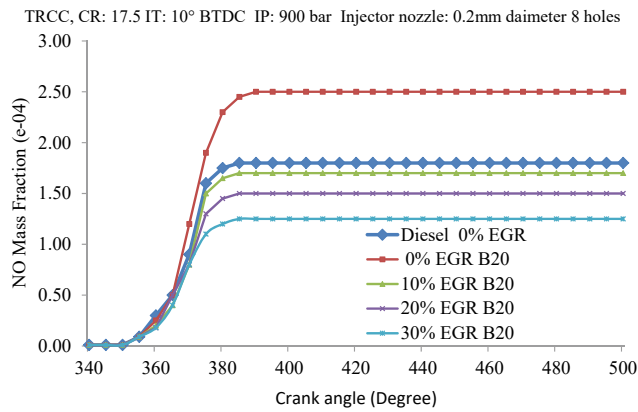


Fig. 8 Shows the variation of NO mass fraction versus different EGR %
Fig. 8 Shows the variation of NO mass fraction versus different EGR %

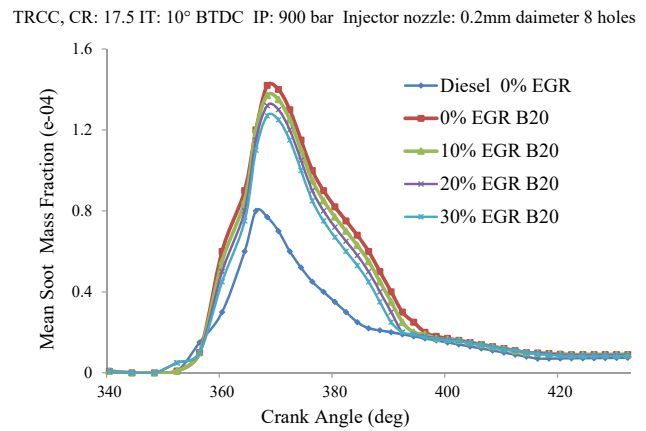


Fig. 10 Shows the variation of Soot formation versus different EGR %

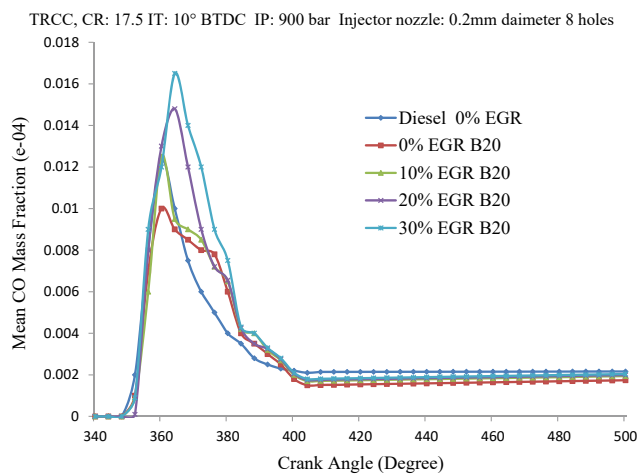


Fig. 9 Shows the variation of CO mass fraction versus different EGR %

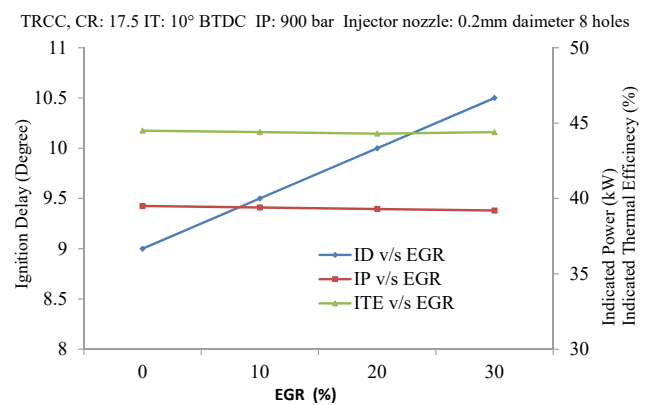


Fig. 11 Shows the variation of Ignition delay versus different EGR %

3.7 Effects of Different Percentage EGR Rate on Performance of Diesel Engine

The related thermal efficiencies and ability dependent on EGR rates are shown in Fig. 11. By repeating the simulations with different levels of EGR (varying the EGR percentage), can observe how ITE changes with the level of EGR. This provides insights into the impact of EGR on engine efficiency. For various EGR rate it is observed that the indicated thermal efficiency (ITE) and indicated power is continued constant. The influence of EGRs on the ignition delay is shown in Fig. 11. The Cetane value plays an important role in performance, the rise in ratio of EGR with biodiesel raises ignition delay due to low oxygen concentration.

4 Conclusion

A CFD Analysis of a Toroidal re-entrant combustion chamber (TRCC), compression ratio (CR) 17.5, fuel Injection timing 10° BTDC and fuel Injection pressure at 900 bar with 8 holes 0.2 mm diameter nozzle injector, 4 stroke CRDI engine running using B20 WMCO biodiesel—diesel blends result is well accord with the experimental result. Further CFD analysis is carried out for different EGR rate for NO_x reduction. The following are the conclusions obtained from simulation results.

- The indicated thermal efficiency and indicated power is obtained constant for different EGRs.
- As percentage of EGRs increase, the percentage of NO_x emission is reduced by 36, 40, and 80% for 10, 20, and 30% EGR rate respectively and compared with 20% WMCO biodiesel blend and neat Diesel.

- As percentage of EGR increases, Mean CO mass fraction is increased by 20, 42, and 62 percentage for 10, 20, and 30% EGR and compared with 0% EGR B20 biodiesel blend and Diesel.
- As percentage of EGR increases, Mean Soot mass fraction is reduced by 6.67, 13.33 and 18.67% for 10, 20, and 30% EGR and compared with 0% EGR B20 biodiesel blend and increases with Diesel.
- With increases in percentage of EGR, ignition delay and combustion duration also increase by 5.55, 11.1, and 16.67% respectively.

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An Efficient Finite Element Approach Using A, B, and D Matrices for Buckling Analysis of Functionally Graded Material (FGM) Plates

Mohnish Kumar Sahu, Alfia Bano, and Gangadhar Ramtekkar

Abstract

This study introduces an effective approach for estimating the critical buckling load of functionally graded materials (FGMs) using a finite element analysis. The approach employs A, B and D matrices to simplify the modeling process and overcome the challenges associated with layer-wise modeling in the finite element software ABAQUS. By adopting this new efficient approach, the need for intricate layer-wise modeling is eliminated. Instead, only the aggregate property of the functionally graded materials is required as an input, utilizing the general shell stiffness matrix. MATLAB code has been developed for the calculation of the coefficient of the matrices. Uniaxial buckling investigation of the FGM plate has been performed for SSSS boundary conditions. The present results are validated through comparative studies, which involve analyzing and comparing them with other established results. This helps to ensure the accuracy and reliability of the findings.

Keywords

Buckling • Matrices • Finite element analysis • Functionally graded material (FGM) • Plate • Aspect ratio • Power law

1 Introduction

Functionally graded material (FGM) is a special category of engineered composite that exhibits unique properties due to its microstructural design. FGMs are designed with a spatial variation property of the material in required directions, resulting in a material that is tailored to meet specific performance requirements. These materials are composed of two or more different materials, such as ceramics and metals, that are bonded together and gradually transition from one material to another. The development of new materials that combine high heat resistance with high mechanical qualities has been a crucial area of research for many industries. The concept of functionally graded materials (FGMs) is not new and has been established in nature for a long time. Bio tissues of plants, such as bamboo and coconut leaves, have a gradual variation in material properties that allows them to withstand environmental stressors such as wind and water. Similarly, shells and bones also exhibit a gradient in properties that helps to distribute stresses more evenly and resist fracture (Pandey et al., 2021).

In the 1980s, researchers in Japan successfully developed a new type of composite material that met these requirements. Laminated composites are popular in many industries for their flexibility in design and ability to achieve the required stiffness and strength. However, bonding two distinct materials together can cause delamination and cracking at interfaces, leading to a reduction in mechanical properties. Functionally graded materials (FGMs) have overcome this problem (Garg et al., 2021). The metal component of the FGM imparts mechanical strength along with toughness and due to the limited thermal conductivity of ceramic components, it is resistant to high temperatures (Ruys & Sutton, 2021). The use of FGMs is expected to continue to grow as new applications are discovered and advances in manufacturing technologies allow to produce more complex structures (Udupa et al., 2014).

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The laws of mixture created by Voigt and Mori–Tanaka is the significant and frequently used mathematical model to characterize varying material qualities in the literature. Additionally, the Exponential, Sigmoidal and Power laws are frequently used to explain mechanical properties distribution (Jha et al., 2013; Nikbakht et al., 2019).

Over the past few years, FGMs have found widespread use in the construction of plate structures across various engineering disciplines, including aerospace, mechanical and civil engineering. For predicting FGMs plate's behavior and gain insights into static and dynamic analysis and effective design, various theories have been proposed in the literature. These theories are based on a variety of models, with Kirchhoff's being the first presented plate theory. The equations for the condition of equilibrium and stability are derived using classical Kirchhoff's plate theory (Javaheri & Eslami, 2002). The finite element procedure is utilized to model and analyze the buckling behavior of functionally graded plate and the displacement field is derived using Kirchhoff's classical plate theory (Ramu & Mohanty, 2014). Other models assume constant transverse displacement field which are based on the first-order shear deformation theory (FSDT) thereby predicting transverse shear stress to be constant along the thickness (Zhao et al., 2009), whereas high order shear deformation theory (HSDT) assumes parabolic transverse displacement. HSDT and FSDT are the two major plate theories used for the study of FGM plates, including CLPT, FSDT and HSDT and unified formulation is done for these plate theories. For the finite element investigation of the FGM plate, a 4-noded element has been employed to predict the buckling response (Tati, 2021).

In addition to being acknowledged as essential and immensely helpful methods in design to fulfill the needs of structures, numerical techniques analyses are also used to reduce exploratory iterations, which is a significant problem in recent times. To achieve the spatial variation of the property for the FGM, the modelling is performed considering the number of laminas in thickness direction perfectly bonded with each other and each layer considering homogeneous and isotropic (Gitea et al., 2012; Sitli et al., 2021). Present approach is advantageous as it enables the input of

aggregate composite material behavior with minimal parameters. This results in simplified input data that can be used to model laminates with an unlimited number of laminas, using only four matrices (Barbero, 2013) but it is given for only composite laminates.

In this study, a new approach has been used for functionally graded material with little change in the method to compute the matrix coefficient. MATLAB program has been developed for the calculation of the coefficient of matrices and then Numerical analysis was then computed using ABAQUS industrial software. Then, parametric analyses for various material models, aspect ratios, and length-to-thickness ratios are carried out. The present results are validated through comparative studies, which involve analyzing and comparing them with other established results. This helps to ensure the accuracy and reliability of the findings.

2 FGM Properties Calculation

To determine the properties of the material from the two materials (i.e., metal and ceramic) it is made of in order to model FGM materials. There are other methods like the Mori–Tanaka scheme and the rule of linear mixture for calculating properties effectively, but the rule of linear mixture with power law is the most straightforward and widely used. Coordinates of functionally graded plate are shown in Fig. 1.

The linear rule of mixture

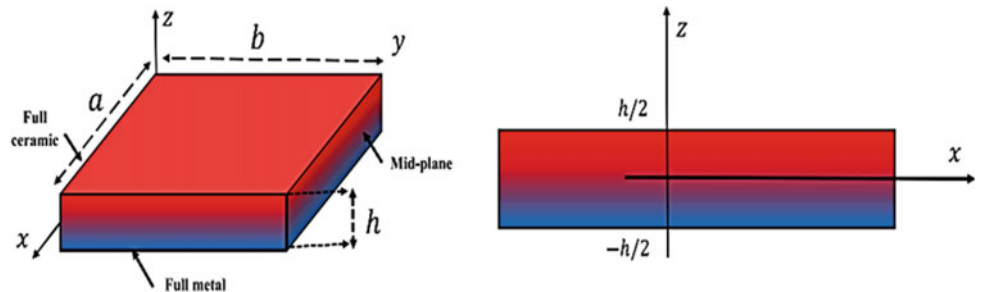
$$P = V_{\text{material 1}} * P_{\text{material 1}} + V_{\text{material 2}} * P_{\text{material 2}} \quad (1)$$

where P is the property of material like Young's modulus and Poison's ratio and V is the fraction of volume in the new FGM material.

$$V_{\text{material 1}} + V_{\text{material 2}} = 1 \quad (2)$$

It is assumed that the properties change with respect to one direction only here in the 'z' direction for the determination of the properties of the FGM. Thus, the property is dependent on the thickness direction 'z'.

Fig. 1 Coordinates of functionally graded plate



$$P_{fgm} = P_{fgm}(z) \quad (3)$$

The FGM plates' Poisson's ratios are assumed constant, but in the case of Young's modulus, it varies gradually along the thickness direction according to the volume percentage.

$$V_{material\ 2}(z) = \left(\frac{1}{2} + \frac{z}{h}\right)^p \quad (4)$$

where 'p' represents the power law index, 'h' represents the plate's overall thickness. The 'p' shows the transition of the material from fully ceramic to fully metal phase which is the power law index. An illustration of the distribution of power-law along the thickness is shown in Fig. 2.

By rearranging the above equations, the Voight model's equation is

$$P(z) = (P_{material\ 1} - P_{material\ 2})\left(\frac{1}{2} + \frac{z}{h}\right)^p + P_{material\ 2} \quad (5)$$

$P(z)$ represents any material property of the material, which is material density (γ), modulus of rigidity (G), Poisson's ratio (μ) and Young's modulus (E). ' $P_{material\ 1}$ ' and ' $P_{material\ 2}$ ' are the material properties at the top-most ($z = +h/2$) and bottom-most ($z = -h/2$) surfaces. 'h' is the total thickness of the FGM plate. 'p' is the power-law index of the FGM plate.

The higher the power law index (p), the steeper be change from ceramic fraction to metallic fraction. Power law index '1' means a change from ceramic fraction to metallic fraction will be linear and power law index '0' means the is made up

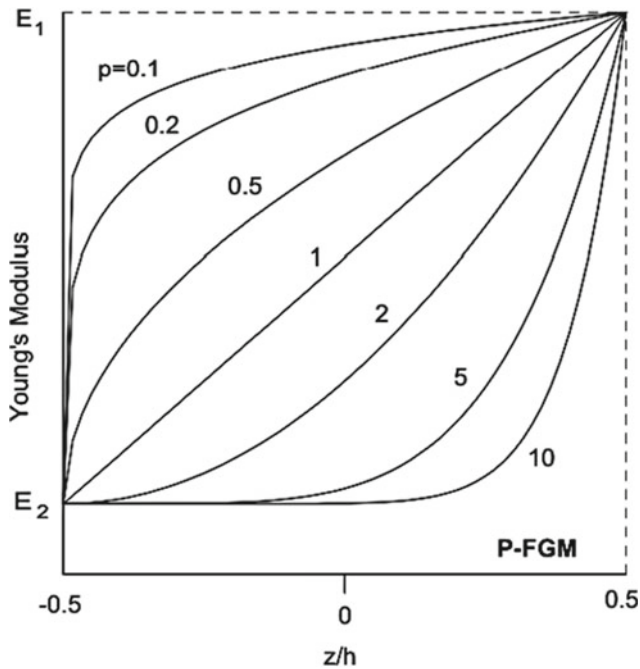


Fig. 2 Illustration of the distribution of power-law along the thickness

of pure ceramic. For the present case, considering a change in modulus of elasticity along the 'z' direction and keeping the Poisson's ratio constant as there is no significant difference in result during variation of Poisson's ratio (Magnucki et al., 2019).

Considering aluminum/alumina (Al/Al_2O_3) functionally graded material for this case. Effective Young's modulus is calculated by the Voight model using the equation given below.

$$E(z) = E_m + (E_c - E_m)\left(\frac{1}{2} + \frac{z}{h}\right)^p \quad (6)$$

$E(z)$ represents Young's modulus of FGM along the 'z' coordinate, E_m represents metal's Young's modulus and E_c represents ceramic's Young's modulus. Material properties of FGM are shown in Table 1.

3 Methodology

3.1 A, B, D Matrices Formulations

In this section, numerical modelling of the FGM plate is discussed using the A, B, D matrices approach. This new efficient approach developed is totally different from layer-wise modelling, in this with the help of A, B, D, matrices the general stiffness of the plate is given as an input and that stiffness is called general shell stiffness. The model prepared using this is 2D-shell model in 3D space so for the meshing purpose shell elements have been used. Hence, the computational effort is reduced with good convergence. Also, a user does not need to perform layer-wise modelling to incorporate the spatial variation of the FGM plate as the stiffness of the whole plate is input at once.

First-order shear deformation theory (FSDT) has been used for the finite element process, as ABAQUS is based on first-order shear deformation theory.

Using FSDT displacement fields are given as

$$\begin{aligned} u(x, y, z) &= u_0(x, y) + z\phi_x(x, y) \\ v(x, y, z) &= v_0(x, y) + z\phi_y(x, y) \\ w(x, y, z) &= w_0(x, y) \end{aligned} \quad (7)$$

where u_0 , v_0 and w_0 represent the mid-plane displacements along the x, y and z direction and ϕ_x and ϕ_y represent the transverse normal rotations along the y and x axes, respectively.

In relation of strain-displacement,

$$\begin{Bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \gamma_{xy} \end{Bmatrix} = \varepsilon_0 + z\kappa, \begin{Bmatrix} \gamma_{yz} \\ \gamma_{xz} \end{Bmatrix} = \gamma_0 \quad (8)$$

Table 1 Material properties of FGM

Materials	E_m (Metal)	E_c (Ceramic)	Poisson's ratio (μ)
Al/Al ₂ O ₃	70 GPa	380 GPa	0.3

where ε_{xx} represents strain in the x-axis, ε_{yy} represents strain in the y-axis and γ_{xz}, γ_{yz} represents the shear strain along the xz and yz planes, respectively.

Using constitutive relation isotropic FGM,

$$\begin{Bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \tau_{xy} \\ \tau_{yz} \\ \tau_{xz} \end{Bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & 0 & 0 & 0 \\ Q_{12} & Q_{11} & 0 & 0 & 0 \\ 0 & 0 & Q_{66} & 0 & 0 \\ 0 & 0 & 0 & Q_{44} & 0 \\ 0 & 0 & 0 & 0 & Q_{55} \end{bmatrix} \begin{Bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \gamma_{xy} \\ \gamma_{yz} \\ \gamma_{xz} \end{Bmatrix} \quad (9)$$

Here, Q_{ij} represents stiffness coefficients, which can be given as

$$Q_{11} = \frac{E(z)}{1 - \nu^2}, Q_{12} = \mu Q_{11}, Q_{22} = Q_{11}$$

$$Q_{44} = Q_{55} = Q_{66} = \frac{E(z)}{2(1 + \mu)}$$

where $E(z)$ can be given as

$$E(z) = E_m + (E_c - E_m)\left(\frac{1}{2} + \frac{z}{h}\right)^p \quad (10)$$

The total in-plane force resultants (N), total moment resultants (M) and transverse force resultants (Q^s) are given by

$$N = \begin{Bmatrix} N_{xx} \\ N_{yy} \\ N_{xy} \end{Bmatrix} = \int_{-h/2}^{h/2} \begin{Bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{xy} \end{Bmatrix} dz$$

$$M = \begin{Bmatrix} M_{xx} \\ M_{yy} \\ M_{xy} \end{Bmatrix} = \int_{-h/2}^{h/2} \begin{Bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{xy} \end{Bmatrix} z dz$$

$$Q^s = \begin{Bmatrix} Q_y \\ Q_x \end{Bmatrix} = \int_{-h/2}^{h/2} \begin{Bmatrix} \gamma_{yz} \\ \gamma_{xz} \end{Bmatrix} dz \quad (11)$$

In matrix form, the relation between the stress resultants and strains can be written as

$$\begin{Bmatrix} N_x \\ N_y \\ N_{xy} \\ M_x \\ M_y \\ M_{xy} \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} \\ A_{12} & A_{22} & A_{26} & B_{12} & B_{22} & B_{26} \\ A_{16} & A_{26} & A_{66} & B_{16} & B_{26} & B_{66} \\ B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} \\ B_{12} & B_{22} & B_{26} & D_{12} & D_{22} & D_{26} \\ B_{16} & B_{26} & B_{66} & D_{16} & D_{26} & D_{66} \end{bmatrix} \begin{Bmatrix} \epsilon_x^0 \\ \epsilon_y^0 \\ \gamma_{xy}^0 \\ \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{Bmatrix} \quad (12)$$

$$\begin{Bmatrix} Q_y \\ Q_x \end{Bmatrix} = \begin{bmatrix} A_{44} & A_{45} \\ A_{45} & A_{55} \end{bmatrix} \begin{Bmatrix} \gamma_{yz} \\ \gamma_{xz} \end{Bmatrix} \quad (13)$$

Thus, it can be also written in another form

$$\begin{Bmatrix} N \\ M \end{Bmatrix} = \begin{bmatrix} AB \\ BD \end{bmatrix} \begin{Bmatrix} \epsilon_0 \\ \kappa \end{Bmatrix}$$

$$Q^s = A^s \gamma_0 \quad (14)$$

A, B, D, A^s matrices represent the stiffness matrix of in-plane load, stiffness matrix of combined bending-in plane action, stiffness matrix of bending action and stiffness matrix of transverse shear, respectively.

$$A = \begin{bmatrix} A_{11} & A_{12} & 0 \\ A_{12} & A_{22} & 0 \\ 0 & 0 & A_{66} \end{bmatrix}; B = \begin{bmatrix} B_{11} & B_{12} & 0 \\ B_{12} & B_{22} & 0 \\ 0 & 0 & B_{66} \end{bmatrix}; D = \begin{bmatrix} D_{11} & D_{12} & 0 \\ D_{12} & D_{22} & 0 \\ 0 & 0 & D_{66} \end{bmatrix};$$

$$A^s = \begin{bmatrix} A_{44} & 0 \\ 0 & A_{55} \end{bmatrix}$$

The coefficients of the above matrices can be calculated as

$$A_{11} = A_{22} = \int_{-h/2}^{+h/2} \frac{E(z)}{1 - \mu^2} dz, A_{12} = \int_{-h/2}^{+h/2} \frac{\mu E(z)}{(1 - \mu^2)} dz$$

$$A_{33} = \int_{-h/2}^{+h/2} \frac{E(z)}{(1 + \mu)2} dz$$

$$B_{11} = B_{22} = \int_{-h/2}^{h/2} z \frac{E(z)}{1 - \mu^2} dz, B_{12} = \int_{-h/2}^{h/2} \mu z \frac{E(z)}{1 - \mu^2} dz,$$

$$B_{33} = \int_{-h/2}^{h/2} z \frac{E(z)}{2(1 + \mu)} dz$$

$$D_{11} = D_{22} = \int_{-h/2}^{h/2} z^2 \frac{E(z)}{1 - \mu^2} dz, D_{12} = \int_{-h/2}^{h/2} \mu z^2 \frac{E(z)}{1 - \mu^2} dz,$$

$$D_{33} = \int_{-h/2}^{h/2} z^2 \frac{E(z)}{2(1 + \mu)} dz$$

$$A_{44} = A_{55} = K \frac{1 - \mu}{2} A_{11}, \text{ where } K = 5/6$$

MATLAB code has been developed for the calculation of the above coefficients of matrices. After calculating the above values are defined in the ABAQUS software in the general shell stiffness under the material property section. The finite element analysis has been carried out by ABAQUS software. Parametric studies are then performed for different material models and aspect ratios.

3.2 Meshing and Boundary Condition

For the discretization of the domain, 8-noded (6 degrees of freedom on each node) isoperimetric quadrilateral shell element has been used, S8R as mentioned in the ABAQUS element library. The boundary condition is considered as simply supported along all 4-edges. Figures 3, 4 and 5 are related to meshing and boundary conditions.

A mesh size of 10 mm is used for achieving convergence and all the results generated are for a mesh size of 10 mm irrespectively of any aspect ratio (a/b).

4 Results and Discussion

The smallest eigenvalue obtained is the critical load and the corresponding buckling mode shape is the 1st mode shape is the eigenvector.

The figures are the 1st mode shape of the FGM plate for the different aspect ratios.

From the above figures (Fig. 6), it can be clearly seen that the mode shape changes when the aspect ratio is changed, this affects the value of the critical buckling load. Mesh convergence curve of Al/Al₂O₃ is shown in Fig. 7. Results are tabulated in Tables 2, 3 and 4.

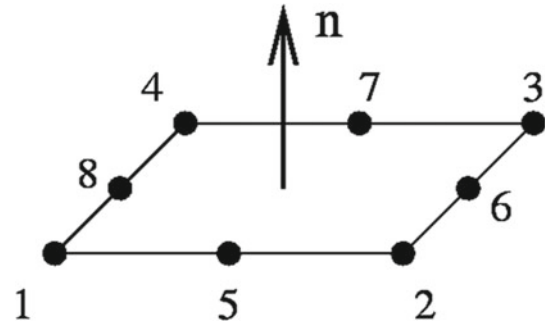


Fig. 4 S8R element

The obtained critical load can be converted into non-dimensionalized critical buckling load using the formula given below

$$\bar{N}_{cr}(\text{Non - dimensionlized critical buckling load}) = \frac{N_{cr}(\text{in N/mm}) \times a^2}{E_m \times h^3}$$

The error in the results obtained by the new approach is within the range when compared, so this methodology can be used for different FGMs.

More results are generated for plotting the graph between critical buckling load (P_{cr}) versus aspect ratio (a/b).

Figures 8 and 9 show that how critical buckling load varies with variation in aspect ratio. The buckling load first decreases then increases, and then again decreases then increases, this is due to the development of the extra modes in the plate. Also, the development of the mode shape is the same irrespectively of the power law used (when we compare graphs of Figs. 8 and 9, the shape of the graph is the same, only the critical buckling load varies). Critical buckling load versus aspect ratio for Al/Al₂O₃ for 'p' = 10 is shown in Fig. 10.

Fig. 3 Meshing of FGM plate

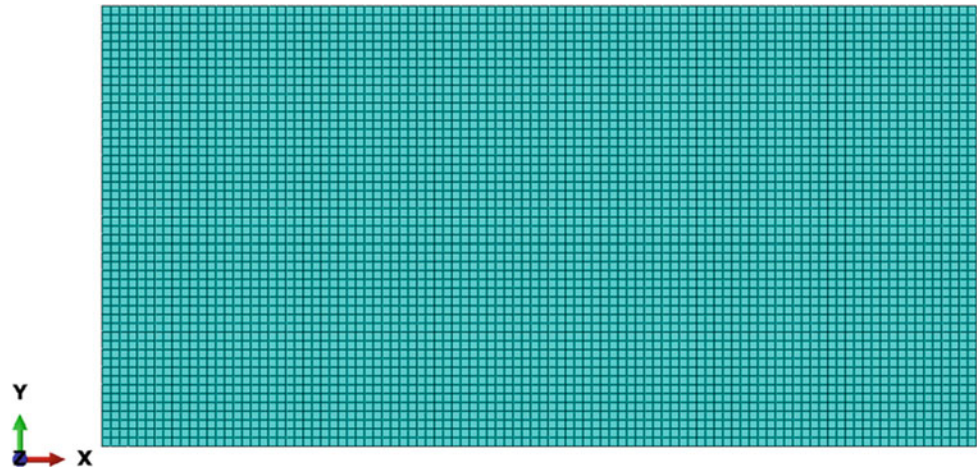


Fig. 5 Simply supported boundary condition

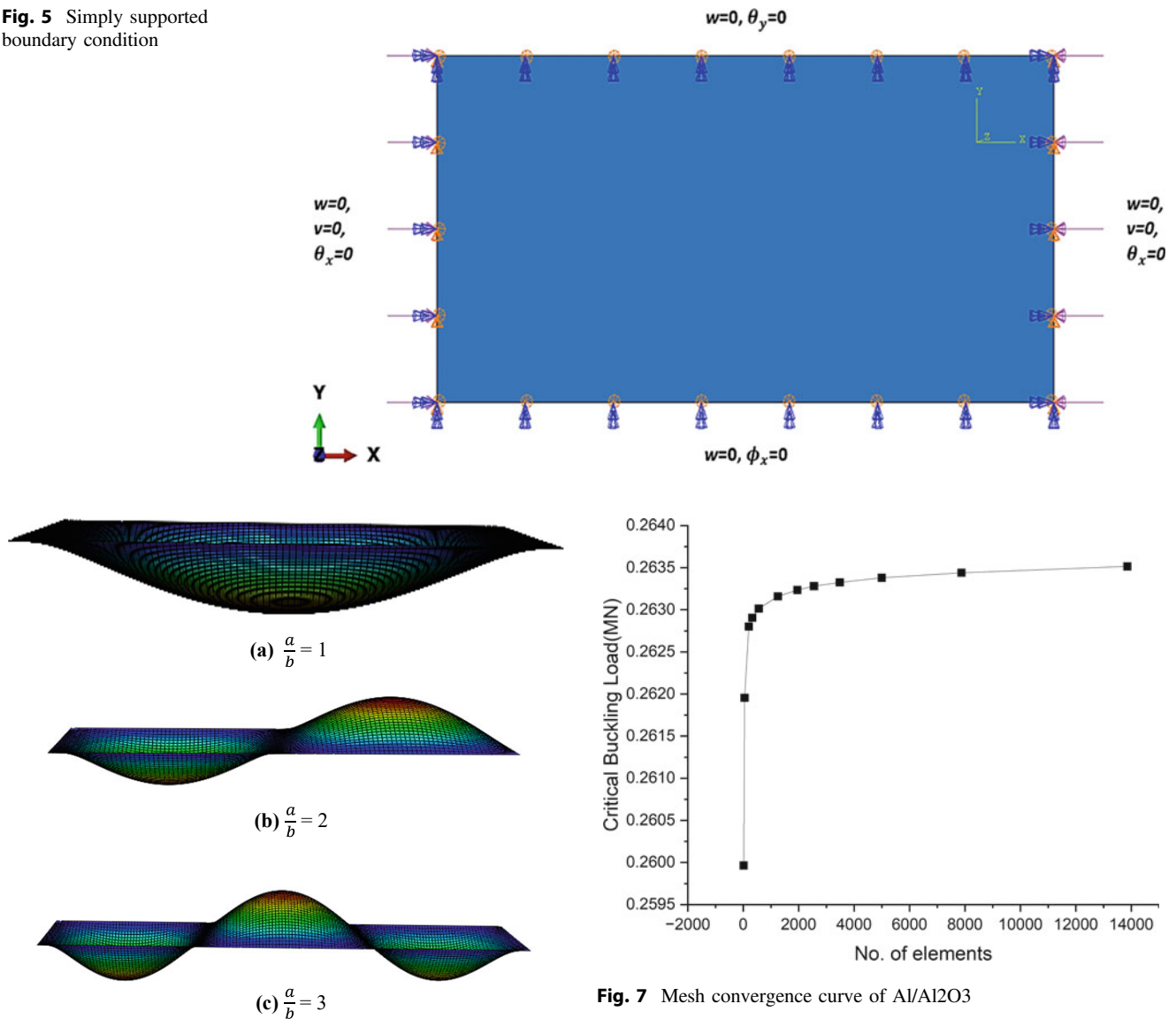


Fig. 6 Buckled mode shape of different aspect ratios

5 Conclusion

1. Functionally graded materials are the future composites and are of great use not only in engineering field but also in every field like aerospace, bio-medical application and communication.
2. The new approach using A, B, D matrices is easy to use and only the general shell stiffness matrix, i.e., the

Fig. 7 Mesh convergence curve of Al/Al2O3

stiffness matrix of the functionally graded material is to be calculated using the coefficient of matrices for the calculation of critical buckling load, which eliminate the problem of layer-wise modelling.

3. The critical buckling load decreases on increasing the power-law index as metallic fraction increases, thus highest buckling load achieved is for power law '1' in comparison with power law '5' and '10'.
4. FGM analysis in finite element analysis requires appropriate element selection, a good mesh-convergence study, to minimize time and computational efforts.

Table 2 Result for Al/Al₂O₃ FGM for $\frac{a}{b} = 0.5$

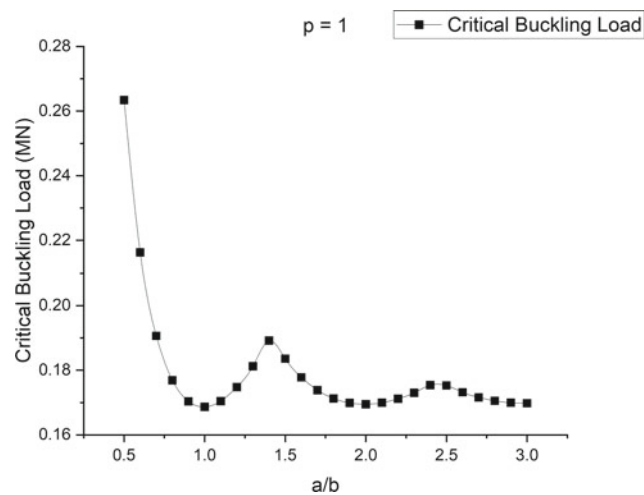
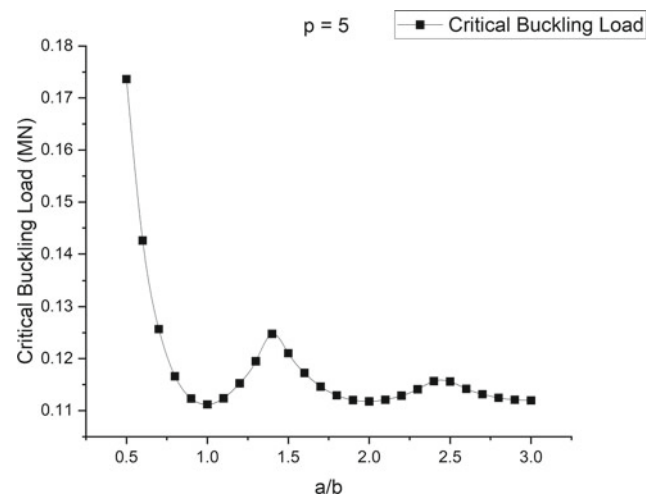
$\frac{a}{b} = 0.5$	$p = 1$	$p = 5$	$p = 10$
Non-dimensionalized $\bar{N}_{cr}$ (obtained)	3.762	2.48	2.257
Non-dimensionalized $\bar{N}_{cr}$ (Thai & Choi, 2012)	3.817	2.517	2.292
% error	1.430	1.478	1.539

Table 3 Result for Al/Al₂O₃ FGM for $\frac{a}{b} = 1$

$\frac{a}{b} = 1$	$p = 1$	$p = 5$	$p = 10$
Non-dimensionalized $\bar{N}_{cr}$ (obtained)	9.637	6.354	5.783
Non-dimensionalized $\bar{N}_{cr}$ (Thai & Choi, 2012)	9.7636	6.4373	5.8614
% error	1.297	1.294	1.337

Table 4 Result for Al/Al₂O₃ FGM for $\frac{a}{b} = 2$

$\frac{a}{b} = 2$	$p = 1$	$p = 5$	$p = 10$
Non-dimensionalized $\bar{N}_{cr}$ (obtained)	38.74	25.547	23.256
Non-dimensionalized $\bar{N}_{cr}$ (Thai & Choi, 2012)	38.834	25.536	23.227
% error	0.241	0.0419	0.121

**Fig. 8** Critical buckling load versus aspect ratio for Al/Al₂O₃ for 'p' = 1**Fig. 9** Critical buckling load versus aspect ratio for Al/Al₂O₃ for 'p' = 5

- The results generated are in good agreement with the literature available and this methodology can be used for the FGM analysis.
- However, analysis of FGM is not simple, as it needs development in a gradient material database that includes information about the material system, parameters, and

preparation of the material as well as performance evaluation.

- There is a requirement for more investigation and testing of the material model's physical characteristics which is costly and the fabrication process is difficult.

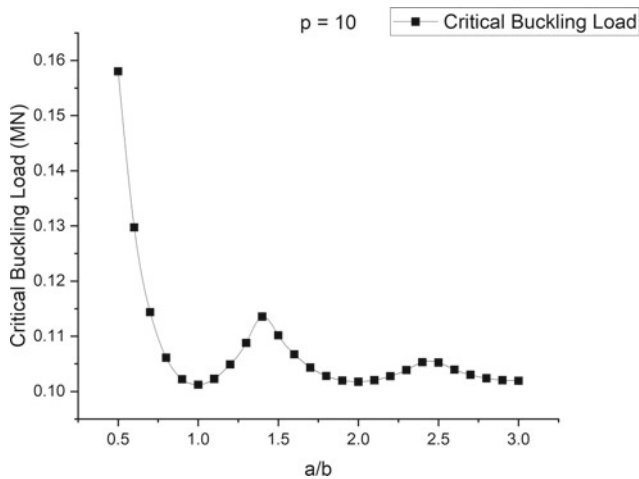


Fig. 10 Critical buckling load versus aspect ratio for Al/Al₂O₃ for 'p' = 10

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Characterisation of the Mechanical Properties and Chemical Durability of Eco-Paving Blocks with Silica Fume and Hypo Sludge

Brindha Sathiaselvan and Hannah Angelin Moses

Abstract

The use of concrete paver blocks has spread to traffic zones, where fractures on the paver blocks have formed due to vehicle movement. An effort is made by partially substituting silica fume and hypo sludge for cement. Silica fume is a mineral additive consisting of submicron particles. When the cement is compared with micro-silica fumes the grain size of amorphous silicon dioxide in cement is 100–150 times larger than that of micro-silica fume. Hypo sludge is also termed as paper mill sludge as it is the by-product of paper which is de-inked and re-pulped from the paper industry waste. The addition of hypo sludge and silica fume is made to alter the cement weight. This research emphasises the essential physical and chemical durability features of micro-silica and hypo sludge as well as its contribution to various proportions of concrete paving block quality improvement.

Keywords

Paver • Hypo sludge • Paving block • Silica fume • Durability

1 Introduction

Concrete block paving has become commonly employed due to its various functional purposes. The interest in using paving blocks tends to grow as they are sustainable and environmentally friendly construction. It is incredibly effective in supporting groundwater conservation and

environmental protection, can be done faster with minimum construction skills as it supports easier installation and enhanced maintenance, does indeed have a range of tints that boost the aesthetic value, and costs less than the other materials. Increased silica fume doses necessitate higher superplasticiser concentrations, resulting in a stickier combination. Moreover, excessive silica fume dosage can cause early autogenous shrinkage, which can lead to microcracking, reducing the long-term durability of structural components. Hypo sludge is the preparatory waste in paper manufacturing. Because of its low calcium content, it was chosen for our project to substitute cement in concrete. Concrete's durability is described as its capacity to withstand chemical assault, weathering action, permeability, or any other deterioration caused by environmental factors. Concrete durability is currently a key problem in many nations. It is acknowledged that the concrete strength alone is not the most significant factor, but that the ecological impact on the bare concrete surface is as vital. The w/c ratio has a considerable bearing on the quality of pavement. Because of the low water-cement ratio, only the surface of the cement grains is hydrated, leaving the centre of the cement grains un-hydrated. When micro fissures appeared, the un-hydrated cement crystals moistened by absorbing moisture from the crevices, sealing the gaps and restoring the integrity and durability properties. The experimental study is to enhance the cement content and utilise the waste industrial residues and the studied specimen should satisfy the IS code for pavement.

2 Literature Survey

Patel and Sohal (2022) have reviewed the durability and mechanical properties of concrete with partial replacement of cement with waste paper sludge (WPS) and found that WPS can be used as an alternative building material when added to the mix up to a certain limit. Wang et al. (2018)

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have reported that considering the importance of the mechanical strength and bonding strength of crack repair materials, it is recommended to use 3–5% replacement of cement by silica fume as the preferred quantity. Ahirwar and Chandak (2018) have studied the M40 concrete using cement with various replacements of hypo sludge. It is found that the compressive strength of the conventional concrete is more than the hypo sludge incorporated the strength reduction is due to the impurities present in hypo sludge like free lime, loss on ignition and other raw minerals. Further, it reported that the strength complies with the target strength up to a replacement of 10%. When hypo sludge greater than 10% is added, the strength of the concrete gets reduced to the target strength of the concrete. Pitroda et al. (2013) have studied the effective utilisation of hypo sludge to reduce disposal costs and storage problems; also produced greener concrete for low-cost rural roads. Further, it is reported that for a CBR value of 2% and wheel load of 30KN; the cost of rigid pavement decreases from Rs. 785.67 to Rs. 580.12. Sabir (1997) has conducted freeze–thaw tests, the study focuses on comparing the properties of concrete prisms with varying dosages of Condensed Silica Fume (CSF). He has conducted tests to determine the compressive and flexural strengths and the static modulus of elasticity. It is observed that the control concrete gave better durability factors (92%) than those obtained for the CSF concrete (85%).

3 Improving the Quality of Concrete Paving Blocks

Cohesiveness is essential to keep the mix together and to decrease the potential of coarse and fine particle segregation during handling. The form and texture of the aggregate particles influence overall cohesiveness; smooth and spherical aggregate particles have better cohesiveness than rough and angular aggregate particles. Concrete cohesiveness may be improved by adding certain chemicals or mineral admixtures to the mix. To enhance the concrete workability, 0.75% of the cement weight of CONPLAST SP430 is used as a chemical admixture. Silica fume is used as a partial replacement for cement and this silica fume itself is a mineral admixture and also supports the performance of fresh and hardened concrete enhancement.

4 Materials

4.1 Cement

The cement used in this study is Ordinary Portland Cement 43 grade conforming to IS: 12269-1987 (1987). The inclusion of tricalcium silicate (C3S) is an essential aspect of

concrete production, as it serves as a fundamental factor in the initial strength formation of the substance. This can be attributed to its capacity to enhance the initial compressive strength of the concrete, a pivotal parameter in ascertaining the ultimate robustness and efficacy of the end product. The inclusion of C3S in concrete is imperative to ensure that the material satisfies the requisite advantages demands for its intended application. Dicalcium silicate (C2S) is recognised for its substantial contribution towards enhancing the long-term endurance and strength of concrete, thereby elevating its overall performance over an extended duration. Tricalcium aluminate (C3A) is a compound that exerts a notable influence on the starting time for the setting of cement, thereby promoting optimal workability during the construction process. The compound known as tetracalcium aluminoferrite (C4AF) has been observed to have a noteworthy impact on the pigmentation of cement, as well as on certain traits such as resistance to sulphate. Gypsum, a mineral compound with the chemical formula $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$, is employed for regulating the cement's setting period for cement. Its primary purpose is to delay the initial setting process of cement, which results in the ideal versatility of concrete during its placement and finishing. The constitution of the cement used is shown in the Table 1 and the properties of OPC 43 grade of cement is shown in Tables 2 and 3.

4.2 Fine Aggregate

M-sand is used in this experimental investigation. It is produced by grinding coarse aggregates of size 20 and 10 mm in separate sand mills, or by employing -stage vertical shaft impact crusher. If necessary, this material is further treated by washing with water or dry sieving to enhance grading and minimise fine powder content. The fine aggregate utilised in this experiment complies with BIS: 383-1970 Zone-II (IS: 383-1970). According to IS-383, the bulk density and specific gravity of M-sand are equivalent to that of river sand, as chemical properties and strength are the same as that of sand. M-sand has a silt content of roughly 0.2% and a

Table 1 OPC 43 grade constituents

Constituents	Cement OPC43 Grade (%)
Lime (CaO)	52
Silica (SiO ₂)	22
Iron oxide (Fe ₂ O ₃)	2.3
Magnesium oxide (MgO)	5
Aluminium (Al ₂ O ₃)	1
Calcium sulphate (Ca ₂ SO ₄)	4
Sulphite (SO ₃)	2.4
Percentage loss on ignition	1.8

Table 2 Properties of OPC43 grade cement

Properties	Properties of OPC 43 grade cement	IS recommendations	IS codal provisions
Specific gravity	3.15	3.15 g/cc	IS- 2720 Part - 3
Standard consistency	32.50%	25–35%	IS:4031 Part IV 1988
Fineness: blaine method	289 m ² /kg	Not less than 225 m ² /kg	IS:269–2015
Soundness test: Le-chatelier expansion (mm)	1–2 mm	Not more than 10 mm	IS:269–2015
Initial setting time	40 min	Minimum 30 min	IS:8112–2013
Final setting time	197 min	Maximum 600 min	IS:8112–2013

Table 3 Typical percentage in OPC 43 cement

Chemical compound	Typical percentage in OPC 43 cement
Tricalcium silicate (C3S)	50–60%
Dicalcium silicate (C2S)	15–30%
Tricalcium aluminate (C3A)	5–10%
Tetracalcium aluminoferrite (C4AF)	5–10%
Gypsum (CaSO ₄ .2H ₂ O)	Added during the grinding process
Minor compounds and additives	Varies

water absorption rate of 1.6%, compared to 0.45 and 1.15% in river sand. The fineness modulus of M-sand is 2.57.

4.3 Coarse Aggregate

It is to be noted that according to IRC: SP: 63-2004 (2004), the amount of coarse aggregate in the mix is normally 40% and the proportion of fine aggregate is 60%. The coarse aggregate size should be between 6 and 12 mm. According to IRC: SP: 63-2004 (2004), the aggregate and cement ratio should be between 3:1 and 6:1. IS: 15658-2006 (2006), on the other hand, defines a maximum size of coarse aggregate of 12 mm for the manufacturing of paver blocks. The adopted coarse aggregate in this study is 60% of 6–10 mm size aggregate and 40% of 12 mm size aggregate. The fineness modulus of coarse aggregate is 6.8.

4.4 Water

Water used in the manufacturing of paving blocks must meet the specifications established in IS: 456–2000 (2000) and IS: 15658-2006 (2006). According to IRC: SP: 63-2004 (2004), the water content in the mix must be between 5 and 7% of the entire mix.

4.5 Pigment

For aesthetic purposes, paving blocks can be made in the desired colour by adding pigmentation. Metal oxides are common colouring agents. If colour saturation is desired, a pigment volume of 5–9% of the cement composition may be applied. According to IRC: SP: 63-2004 (2004) and IS: 15658-2006 (2006), Pigments ought to be finer in particle size than cement. In this research, no colouring agent is added.

4.6 Admixtures

0.5% of cement weight of CONPLAST SP430 is used as super-plasticising chemical admixture to enhance cohesion, and workability in the fresh concrete. This admixture supports to gain early-age strength to the concrete and reduces concrete permeability. Silica fume or micro-silica is a mineral admixture and is used as a partial cement replacement of cement for various proportions.

Hypo sludge is a waste substance obtained from the paper mills. It is used as a concrete admixture in the production of concrete paving blocks. Because of its silica and magnesium content, hypo sludge acts similarly to cement. This silica and magnesium increase the concrete's settling process. In this

Table 4 Constituents of hypo sludge and silica fume

Sl. No	Constituents	Hypo sludge (%)	Silica fume (%)
1	Lime (CaO)	46.2	0.2
2	Silica (SiO ₂)	9	97
3	Iron oxide (Fe ₂ O ₃)	0.65	1.25
4	Magnesium oxide (MgO)	3.3	0.5
5	Aluminium (Al ₂ O ₃)	3.6	0.2
6	Calcium sulphate (Ca ₂ SO ₄)	4.04	-
7	Sulphite (SO ₃)	0.17	0.15

**Fig. 1** Hypo sludge before pulverising**Fig. 2** Micro-silica fume

study, cement is partially replaced by hypo sludge. The constituents of hypo sludge and silica fume are shown in Table 4 (Figs. 1 and 2).

5 Curing

The concrete paving block is cured in the safe zone. The National Standard IS: 9013–1978 (1999) includes guidance on diverse techniques for the curing of concrete, encompassing water-based curing, moist the cure process and membrane the process of curing. The optimal technique for the curing of concrete paving blocks may be contingent upon variables such as the thickness of the blocks, prevailing weather conditions, and prerequisites characteristic of the site.

6 Mix Design

The measure of quality control adopted is a necessary prerequisite for selecting the appropriate mix proportion. The fundamental objective of mix design is to provide appropriate hardened quality as well as sufficient workability and cohesiveness of the plastic state in fresh concrete. The choice

of using lean concrete is good as many of the hefty, high-density gravel and sand ingredients found in conventional concrete are absent in lean concrete. Lean concrete is significantly less expensive and easier to create and use than conventional concrete since it is made from a combination of standard concrete components and other substitute materials.

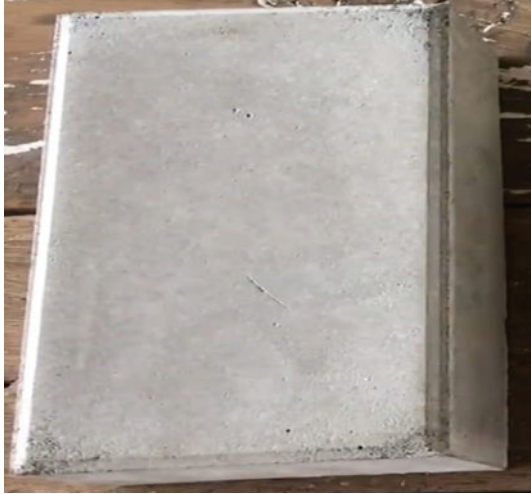
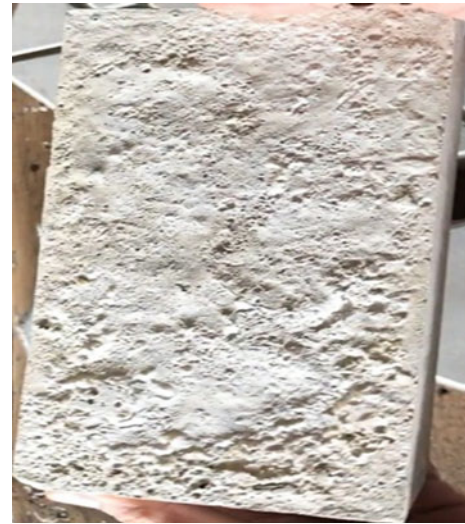
The trial mix yielded the mixture percentage for the controlled concrete of M40 grade, as specified by IS: 456–2000 (2000) and IS: 10262–2019 (2009). The cement is partially replaced with silica fume and hypo sludge with 0, 5, 7.5 and 10%, respectively. With a water-cement ratio of 0.36, 0.5% of CONPLAST SP430 is added by the cement weight and is used as a chemical admixture (Table 5).

7 Shape of the Specimen

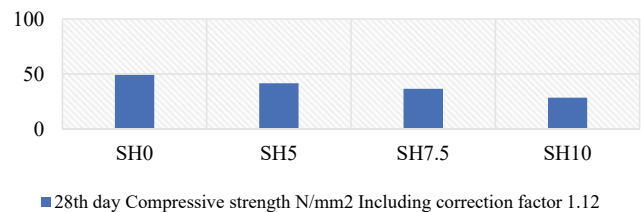
The shape of the specimen used in the entire experiment is 200 × 100 × 80mm. Table vibration compaction is done to compact the concrete in the specimen. The pavement is designed for medium traffic with the grade of paver blocks as M-40. With the minimum paver block thickness of 80 mm. The weight of a dry pavement concrete block is approximately 3.2 kg (Figs. 3 and 4).

Table 5 Silica fume and hypo sludge cement replacement percentage

Mix ID	Silica fume and hypo sludge cement replacement percentage
SH0	0%
SH5	5% + 5%
SH7.5	7.5% + 7.5%
SH10	10% + 10%

**Fig. 3** Front side of the concrete paving block**Fig. 4** Back side of the concrete paving block**Table 6** Compressive strength of concrete paving block in N/mm²

Mix ID	28th-day compressive strength, N/mm ²
SH0	49.16
SH5	41.59
SH7.5	36.45
SH10	28.42

**Fig. 5** 28th-day compressive strength of concrete paving block in N/mm²

8 Test Conducted

The compacting factor is tested as per IS: 1199-1959 (Reaffirmed 2013) (1959) and the obtained compacting factor is 0.88.

8.1 Compressive Strength

BS: 6717-1993 (1993) is followed in testing compressive strength for paver block. The minimum paving block is to obtain 40N/mm². The correction factor for thickness is incorporated 20 mm. For the 60 mm thickness of the plain paver block, the correction factor to include is 1.12. There by corrected paver block is found by adding compressive strength obtained in the experiment multiplied by the thickness correction factor of the paver block. IS: 15658-2006 (2006) recommended that the individual paver block strength should be a minimum of 85% of the specified strength (Table 6 and Fig. 5).

8.2 Durability Test

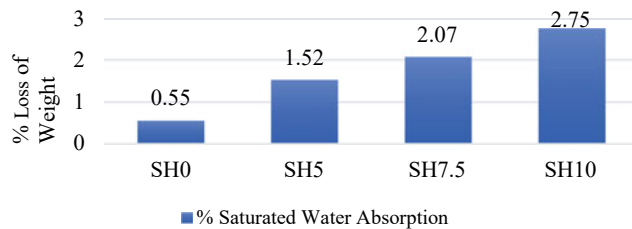
Saturated Water Absorption Test: ASTM D570 is used to evaluate the performance of paving material components in water (Table 7 and Fig. 6).

8.3 Chemical Attack

Chemical attack tests on the concrete paving block are essential to know the ultimate durability behaviour of the

Table 7 Saturated water absorption

Saturated water absorption	
Mix ID	% water absorption
SH0	0.55
SH5	1.52
SH7.5	2.07
SH10	2.75

**Fig. 6** % saturated water absorption

concrete paving block under various chemical exposures so as to utilise the material effectively in various aspects.

8.3.1 Sulphate-Resistant Test

The sulphate-resistant testing was performed in accordance with ASTM C1012/C1012M. The loss of weight due to the immersion of paver blocks in 5% sodium sulphate solution is noted periodically at 28, 56 and 90 days. Compression test is performed to check the loss of compression strength due to the ingress of sulphate solution (Tables 8, 9 and Fig. 7).

8.3.2 Chloride Attack

Chloride attack test is carried out as per the code ASTM C1152/C1152M. The loss of weight due to the immersion of paver block in 5% sodium chloride by weight of water is noted periodically at 28, 56 and 90 days. Compression test is performed to check the loss of compression strength due to the ingress of sodium chloride (Tables 10, 11 and Fig. 8).

8.3.3 Alkaline-Resistant Test

ASTM C614-20 is used to test the alkaline alkaline-resistant capacity of the paver block, sodium hydroxide solution is

used to conduct the test. The loss of weight due to the immersion of paver block in 5% sodium hydroxide by weight of water is noted periodically at 28, 56 and 90 days. Compression test is performed to check the loss of compression strength due to the ingress of sodium hydroxide (Tables 12, 13, Figs. 9 and 10).

9 Result and Discussion

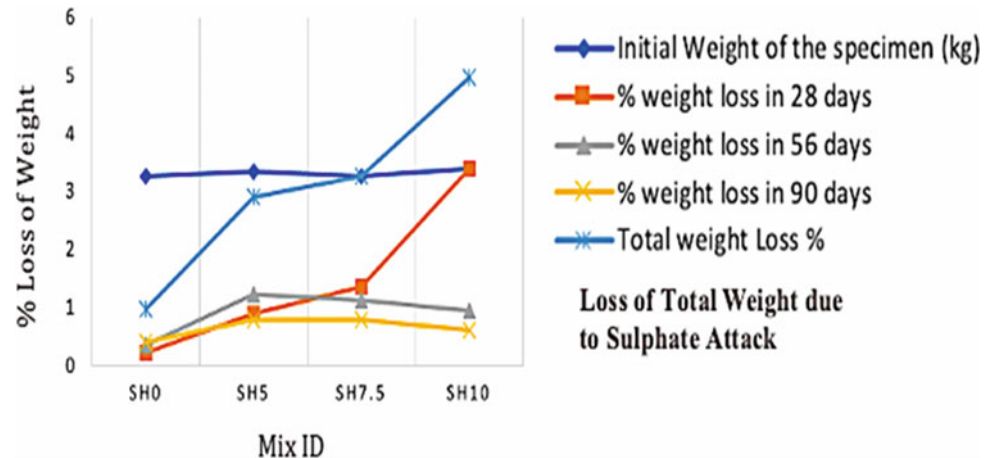
- To understand the durability and endurance of eco-paving concrete blocks, they are compared to control mix paving concrete blocks.
- The adopted size of the specimen in the experimental study is $200 \times 100 \times 80$ mm and M40 concrete mix.
- To make eco-paving concrete blocks hypo sludge and silica fume are added as a mineral admixture in percentage replacement of cement.
- Loss of weight due to chemical attack is identified during the period of the 28th day, 56th day and 90th day of immersion in the 5% sodium sulphate solution, 5% sodium chloride solution and sodium hydroxide solution as prescribed in the IS code.
- Percentage loss of compressive strength is compared with the control mix compressive strength.
- The experimental studies are aimed at implementing the concrete eco-paving blocks in the medium traffic zone.
- Individual paver block strength is needed to be at least 85% of the M40 specifications as mentioned in the IS 15658-2006.
- The weight of the eco concrete paving block is maintained at 3.2 kg approximately.
- Saturated water absorption is increased as high amounts of admixtures are added to the eco-concrete paving block.
- 5% replacement of cement with silica fume and hypo sludge maintained the compressive strength of 40N/mm^2 .
- The weight of the eco-concrete paving block is reduced up to 4.96% of the original weight of the paving block with the mix ID SH10. Mix ID SH5 provided adequate results in sulphate resistant.

Table 8 % loss of total weight due to sulphate-resistant test

Mix ID	Initial weight of the specimen (kg)	% weight loss in 28 days	% weight loss in 56 days	% weight loss in 90 days	Total weight loss %
SH0	3.256	0.23	0.34	0.4	0.97
SH5	3.327	0.9	1.23	0.78	2.91
SH7.5	3.264	1.35	1.12	0.8	3.27
SH10	3.396	3.4	0.94	0.62	4.96

Table 9 % loss of compressive strength due to sulphate attack

Loss of compressive strength due to sulphate attack		
Mix ID	90th-day compressive strength N/mm ²	% Loss of compressive strength
SH0	49.16	1.93
SH5	41.59	2.06
SH7.5	36.456	1.86
SH10	26.91	5.61

Fig. 7 % loss of total weight due to sulphate-resistant test**Table 10** % loss of total weight due to chloride attack

Mix ID	Initial weight of the specimen (kg)	% weight loss in 28 days	% weight loss in 56 days	% weight loss in 90 days	Total weight Loss %
SH0	3.328	1.23	0.39	0.17	1.79
SH5	3.183	1.34	0.48	0.25	2.07
SH7.5	3.352	2.14	0.59	0.29	3.02
SH10	2.983	2.45	0.48	0.23	3.16

Table 11 % loss of compressive strength due to chloride attack

Loss of compressive strength due to chloride attack		
Mix ID	90th-day compressive strength N/mm ²	% loss of compressive strength
SH0	48.38	1.61
SH5	40.77	2.01
SH7.5	35.12	3.8
SH10	27.33	3.99

10 Conclusion

Silica fume and hypo sludge have an impact as a filler in the eco concrete paving blocks. They fill the cavity in between the aggregates and cement. The maximum compressive strength by incorporating silica fume and hypo sludge is produced by SH5. As it gives the minimum compressive strength that is needed for the medium traffic. SH7.5 can be

recommended for light traffic zones. % loss in compressive strength and % loss of weight of the eco-paving block under various chemical attack has proved that SH5 lose a minimum of 2% of compressive strength and almost 2% weight of the specimen when compared with the other mixes. SH7.5 and SH10 have given nearly 3 to 4% loss of compressive strength and weight of the specimen. The saturated water absorption test has proved that the % of water absorbed is getting high when silica fumes and hypo sludge are

Fig. 8 % loss of total weight due to chloride attack

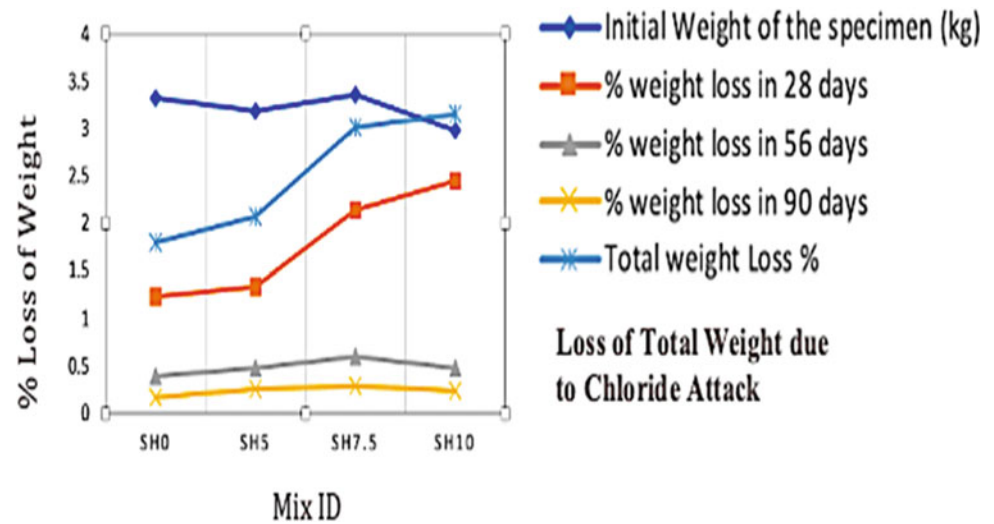


Table 12 % loss of total weight due to alkaline attack

Mix ID	Initial weight of the specimen (kg)	% weight loss in 28 days	% weight loss in 56 days	% weight loss in 90 days	Total weight loss %
SH0	3.261	0.5	0.61	0.16	1.27
SH5	3.312	1.32	0.38	0.25	1.95
SH7.5	2.962	2.11	0.49	0.29	2.89
SH10	3.169	2.25	0.49	0.23	2.97

Table 13 % loss of compressive strength due to alkaline attack

Loss of compressive strength due to alkaline attack		
Mix ID	90th-day compressive strength N/mm ²	% loss of compressive strength
SH0	47.91	2.61
SH5	40.65	2.31
SH7.5	35.17	3.66
SH10	26.98	5.34

Fig. 9 % loss of total weight due to alkaline attack

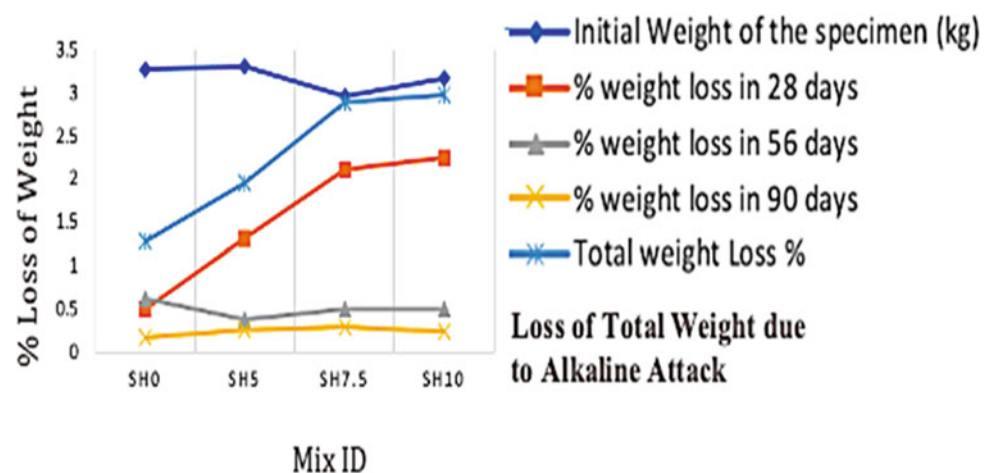
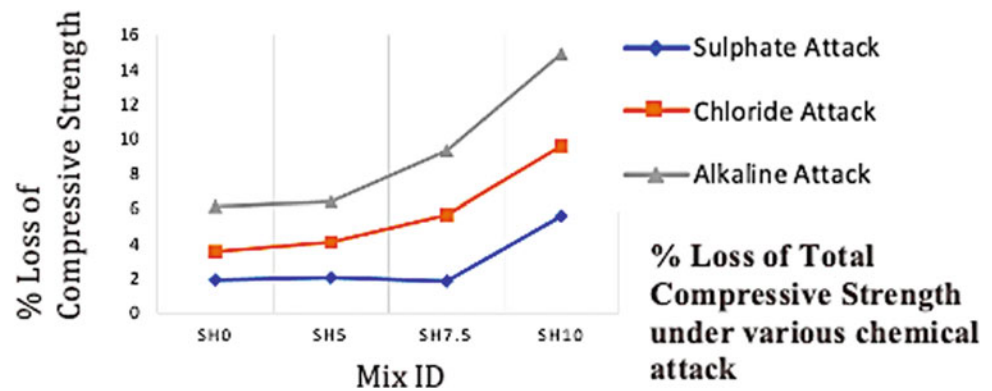


Fig. 10 % loss of compressive strength under various chemical attacks



increased. Concrete strength has been decreased, when hypo sludge and silica fume are introduced. Still, the inclusion of hypo sludge and silica fume has certain advantages. For instance, it provides an ecologically consistent method of disposing of hypo sludge and silica fume. Furthermore, it lowers the overall cost of the structural part. However, the coherence of the structural element will be greater due to the reduced strength of the hypo sludge and silica fume mixed concrete.

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Mechanical Properties of Concrete with Partial Replacement of Natural Sand by Fly Ash

H. Dinesh and P. S. Aravind Raj

Abstract

The durability of concrete significantly influences its overall performance and longevity within construction projects. A viable strategy to enhance concrete durability involves the partial substitution of natural sand with fly ash, a residue from coal-fired power plants. Fly ash's fine powder texture allows it to replace portions of both cement and natural sand in concrete mixtures. Several notable benefits arise from employing fly ash in this manner. It improves the workability of concrete, making it easier to blend, place, and finish during construction initially and additionally, this method increases the concrete's long-term strength and durability, which is crucial for sustained performance over the structure's lifetime. In addition, the incorporation of fly ash aligns with sustainability goals by reducing the reliance on virgin resources. By utilizing a waste product, construction lessens its environmental footprint and promotes efficient resource usage. Notably, using fly ash reduces the demand for natural sand, mitigating the environmental impact of sand mining. To evaluate the effectiveness of this approach, various tests can be conducted. These include analyzing the fresh properties of the concrete mixture and assessing its compressive strength. These tests provide insight into the practicality and structural integrity of the resulting concrete. The environmental benefits of this practice are noteworthy. By diminishing the need for extensive cement production, fly ash employment leads to reduced greenhouse gas emissions. Furthermore, it aids in conserving valuable natural resources, supporting a more sustainable building paradigm. In essence, incorporating fly ash into concrete represents a progressive stride toward sustainable

construction practices. The method's potential to enhance durability, reduce environmental impact, and conserve resources signifies its valuable contribution to the evolution of responsible building techniques.

Keywords

Concrete • Fly Ash • Greenhouse gas emissions • Coal-fired power plant

1 Introduction

Concrete is a ubiquitous building material used for a wide range of construction projects. It is made by combining several key ingredients, including Portland cement, fine and coarse aggregates, and water. The ingredients are carefully measured and mixed together to achieve the desired consistency and strength. Over time, the mixture hardens and cures, resulting in a durable, long-lasting material. Portland cement, a type of hydraulic cement, is the most commonly used variety in the production of concrete. The unique combination of materials and the curing process results in a material that is strong, versatile, and resistant to many environmental factors, making it an ideal choice for a wide range of construction applications. Cement is an important building material that acts as a binding agent that is used to set and harden with other building materials. Cement is rarely used on its own instead it binds with sand and gravel together. Cement is mixed with mortar or with sand and gravel with water to produce concrete mortar.

Cement is an inorganic material that is made up of lime or calcium silicate used to construct buildings, often limestone powder can influence their properties such as dilution, nucleation, filler and chemical effects (Jolanta Harasymiuk Andrzej Rudzinski, 2020). Hydraulic cement is the most commonly used cement which is formed based on the reaction of lime and silica that can able to set and harden in

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the presence of water. Romans used hydraulic cement for their construction projects, which are produced based on slaked lime and volcanic ash and still some of the buildings are standing. On the other hand, Non-hydraulic cement does not require wet conditions or water to set and harden concrete mortar instead it sets in dry conditions based on the reaction of CO₂ present in the air and it usually takes a long time to set, and harden which is made up of lime, gypsum plasters and oxychlorides.

Fly ash, having its unique characteristics of finer particle size, enhances the permeability resistance of the hardened concrete surface which would result in improvement. With the partial replacement of the cement or fine aggregate in the concrete by fly ash, the workability and durability can be improved significantly and without 3nsr concrete being preferred (Aravind Raj et al., 2020; Divahar et al., 2021).

In order to give the concrete mix bulk and strength, fine aggregates are employed. Additionally, they lessen shrinkage and cracking, enhance the mix's usability, and lower the price of the concrete. Natural or synthetic aggregates are also acceptable. Sand, gravel, and crushed stone are some examples of natural aggregates that are often taken from quarries or gravel pits. Fly ash, slag, and recycled concrete are some examples of the recyclable resources used to make manufactured aggregates (Ravina, 1997; Sangeetha et al., 2019).

In order to form the concrete mix, coarse aggregates are often blended with cement, water, and fine aggregates (like sand). The durability of the concrete, as well as its workability and fracture resistance, are influenced by the size and distribution of coarse particles.

Generally, Coarse aggregate is made from different materials such as gravel, slag, recycled concrete, crushed stone, etc. The properties of coarse aggregate can have a direct impact on the building (Aravind Raj et al., 2022). For example, packing using rounded coarse aggregate will be difficult when compared to other irregularly/angular shaped coarse aggregates but at the same time rounded aggregates can produce a comparatively smoother surface.

Water plays a crucial role in the construction industry. Water is considered a primary component in various processes of concrete production and application. In the concrete production process, water is mixed with cement, sand, and coarse aggregates to create the right concrete mixture. The quality and the amount of water used can directly impact the strength and durability of the constructed building. It is always important to ensure that the water used for construction purposes is safe and suitable. Utilizing contaminated water may lead to various challenges such as staining, corrosion, and weakness. Hence, it is always better to test the quality of water before using it for construction purposes.

In addition to the cement, water, and coarse aggregates, an additional substance called "Admixtures" will be added to the concrete. This substance is added to increase the strength of the concrete mixture by controlling the settling time and resisting harsh weather conditions. This substance is available in different categories, such as water-reducing agents, plasticizers, retarders, and air-entraining agents. For example, air-entraining agents are generally added to the prepared concrete mix to create small-sized air pockets in the mixture in order to improve the freeze–thaw resistance of the concrete. Further, water-reducing agents are added to the prepared concrete mix to reduce the consumption of water to reach the desired consistency without impacting the concrete strength.

Admixtures are indispensable additives that enhance concrete durability, especially in unique environments like corrosive settings or high temperatures. They enable tailored concrete properties to combat specific challenges, highlighting their adaptability in modern construction. In corrosive or chemically aggressive conditions, chemical admixtures play a crucial role. They fortify concrete against corrosive agents, such as acids or salts, prolonging its structural integrity amidst adverse circumstances. Beyond durability, admixtures contribute to various concrete aspects. They enhance workability, strength, and setting times, adapting mixes to project needs. However, precise application is vital. Proper dosages and combinations are imperative to reap benefits without compromising concrete characteristics. Imbalanced usage may diminish strength or delay setting. Integrating admixtures strategically furnishes diverse advantages, bolstering durability in challenging settings. Their capacity to address specific needs while augmenting performance underscores their significance.

In this paper, we presented the durability of concrete with partial replacement of natural sand by fly ash can be evaluated through a range of tests, including tests to measure its strength and resistance to various forms of deterioration. The results of these tests can provide important information on the suitability of the concrete for specific applications, and can help to ensure that the final product is durable, sustainable, and of high quality.

2 Literature Survey

The conventional research techniques used in the study included grain size analysis and loss on ignition (LOI) determination. Grain size analysis was used to determine the particle size distribution of the ODFA, which is important for its ability to bind with cement and other components in the mix. LOI determination was used to determine the

amount of carbon and other volatile substances in the ODFA, which can affect its performance in the concrete mix.

The modern research techniques used in the study included thermal analysis, scanning microscopy, and electronic spectroscopy. Thermal analysis was used to determine the thermal behavior of the ODFA, which can affect its performance in high-temperature environments. Scanning microscopy was used to study the surface and internal structure of the ODFA, which can provide important information on its suitability for use in concrete. Electronic spectroscopy was used to determine the chemical composition of the ODFA, which can help to predict its behavior in the concrete mix.

The results of the study showed that ODFA can be used as a partial replacement of sand in cement composites, providing that certain conditions are met. Specifically, the study found that ODFA with a suitable particle size distribution and low levels of volatile substances can be used as a partial replacement for sand, leading to improvements in the strength, workability, and durability of the concrete.

Harasymiuik and Rudzinski (2020), conducted an experiment focusing on exploring the viability of incorporating old dumped fly ash (ODFA) as a partial substitute for sand in cement composites. The research aimed to assess the potential of ODFA through the utilization of both traditional and contemporary research methodologies (Harasymiuik & Rudzinski, 2020).

Singh et al. (2018) conducted a study investigating the substitution of fine aggregates with coal bottom ash in normal and self-compacting concrete. Their aim was to assess the effects on concrete properties. They prepared concrete mixtures with varying proportions of bottom ash and evaluated characteristics including compressive strength, workability, air content, and self-compacting behavior. The findings highlighted significant impacts: higher bottom ash ratios led to increased compressive strength, moderate ratios improved workability, and higher proportions reduced air content, crucial for high-strength concrete. Moreover, self-compacting concrete with bottom ash exhibited enhanced workability and favorable flow qualities, making it a viable choice for construction requiring self-compacting features. This study contributes insights into optimizing concrete formulations for diverse construction contexts.

Samba Siva Rao and Aditya Nandini (2016) explored the viability of substituting 40% of natural sand in concrete with quarry rock dust, while concurrently replacing cement with fly ash. They formulated concrete mix designs encompassing three grades, spanning both conventional and non-conventional compositions, and subsequently assessed the resultant concrete properties. The evaluation entailed analyses of physical, mechanical, and durability traits, alongside sieve analysis and water absorption measurements. This evaluation was performed on concrete incorporating fly

ash and quarry rock dust, and the outcomes were juxtaposed against those of concrete featuring natural sand (Singh et al., 2018). The results of the study showed that quarry rock dust can be used as a substitute for natural sand in concrete, with fly ash as a partial replacement for cement. The concrete made with quarry rock dust and fly ash had comparable or improved physical, mechanical, and durability properties compared to natural sand concrete. The sieve analysis and water absorption results were also found to be within the acceptable range for concrete (Samba Siva Rao & Aditya Nandini, 2016).

Thomas and Nair (2015) examined the implications of substituting sand with fly ash in concrete blocks. Their investigation encompassed an assessment of strength, economic factors, and environmental considerations for concrete blocks with fly ash replacing sand at various levels, ranging from 0 to 100%. The findings revealed that up to a 20% replacement of sand with fly ash, there was an increase in compressive strength and density of the concrete blocks. However, beyond this threshold, block strength diminished as fly ash content increased. The study further highlighted the economic and environmental benefits of using fly ash as a sand substitute in concrete blocks. This approach reduced sand consumption while offering a more sustainable solution, aligning with environmental considerations (Thomas & Nair, 2015).

Aruna Kanthi and Kavitha (2014) researched the effects of substituting portions of sand with fly ash in concrete. Employing a singular mix proportion, they explored various percentages of sand replacement and conducted comprehensive analyses of the resulting concrete blends. Remarkably, the study revealed that the workability of these concrete mixtures remained consistently within a certain range, irrespective of the extent of sand replacement. Assessing strength characteristics, including compressive strength, split tensile strength, and modulus of elasticity, across curing periods of 7, 14, and 28 days, the researchers noted noteworthy trends. The findings indicated that the partial replacement of sand with fly ash yielded positive outcomes for concrete strength attributes. Notably, compressive strength and modulus of elasticity exhibited improvements. However, the study observed a marginal reduction in split tensile strength with higher levels of fly ash replacement. This investigation underscores the dynamic interplay between sand and fly ash substitution, revealing nuanced impacts on concrete properties. While maintaining workability and enhancing key strength attributes, the study contributes valuable insights into optimizing concrete formulations to meet specific engineering requirements (Aruna Kanthi & Kavitha, 2014).

Rajamane and Ambily (2013) conducted a study exploring the viability of integrating fly ash into concrete. They devised a method centered around fly ash's "cementing

efficiency” (k) to modify concrete formulations. The research scrutinized the feasibility of fly ash incorporation across varying proportions and its consequent influence on concrete properties. Notably, concrete density was observed to decrease with fly ash utilization. The researchers introduced and elucidated novel metrics, including the strength-weight ratio, strength-cost ratio, and strength-energy ratio, serving as tools to assess the feasibility of fly ash integration. An array of parameters—such as workability, density, compressive strength, and microstructural attributes were scrutinized, revealing that these factors remained feasible up to a 60% replacement of cement with fly ash (Rajamane & Ambily, 2013).

Parvathi and Prakash (2013) conducted an experimental exploration aiming to assess the strength characteristics of concrete when natural sand was replaced by fly ash at various percentages and subsequently exposed to elevated temperatures. The study specifically investigated the influence of fly ash on concrete strength within temperature ranges spanning from 200 to 800 °C. This research involved the substitution of fine aggregate in the concrete mix with fly ash, covering a spectrum of replacement levels ranging from 0 to 80%. Subsequently, the resulting concrete specimens were subjected to elevated temperatures to simulate high-temperature conditions. The analysis centered around key strength parameters, encompassing compressive strength, flexural strength, split tensile strength, and shear strength. By scrutinizing the interplay between fly ash replacement and elevated temperatures, this study contributes to a deeper understanding of how these factors collectively influence concrete strength properties. The investigation offers valuable insights into the performance of concrete under extreme thermal conditions, which is essential for designing structures that can withstand challenging environments (Parvathi & Prakash, 2013).

Sukhvarsh Jerath and Hanson (2007) investigated the influence of substituting Portland cement with fly ash and adopting a dense aggregate gradation on the durability of concrete mixtures. Their study involved the preparation of four concrete mixtures adhering to prevailing specifications, alongside four additional mixtures utilizing dense aggregate grading. These mixtures were designed to maintain a 6% air content and a 25–38 mm slump, ensuring optimal properties for freshly mixed concrete. The research focused on gauging concrete durability through a series of examinations. Rapid chloride ion penetration tests, permeability assessments, and microscopically analyzed were conducted to ascertain the presence of air voids. The results derived from these tests were then meticulously evaluated to ascertain the impact of both fly ash replacement and the incorporation of dense aggregate gradation on concrete durability. By exploring the interplay between these factors and concrete durability, the study contributes to a more comprehensive understanding of

how specific adjustments in material composition can influence the long-term performance and resilience of concrete structures. This research is crucial for informed decision-making in constructing durable and reliable infrastructure (Sukhvarsh Jerath & Hanson, 2007).

Siddique (2003) carried out an experimental analysis to ascertain the effects of substituting Class F fly ash for fine aggregate in concrete mixes. Five different replacement percentages of fly ash by weight (10, 20, 30, 40, and 50%) were used in the research. At different curing times (7, 14, 28, 56, 91, and 356), the concrete mixes’ mechanical parameters, such as compressive strength, flexural strength, split tensile strength, and modulus of elasticity, were assessed. The study’s findings were contrasted with those of concrete mixes without any fly ash replacement, and it was shown that for all fly ash replacement percentages, the mechanical qualities of the concrete mixture got better with time (Siddique, 2003).

Ravina (1997) looked at how the characteristics of newly poured concrete were affected by replacing the sand with fly ash. The author examined a number of factors, including workability, the amount of water needed to achieve the desired slump, the effectiveness of chemical admixtures, bleeding, and setting of the fly ash mix. The findings indicated that most fly ash blends worked better than the reference mix. However, the water content of the concrete mix was impacted by the sand gradation. Comparing the chemical admixture’s effectiveness to non-fly ash concretes, it was marginally less effective. When chemical admixtures were added, bleeding was found to be identical to the reference mix but was significantly lessened. When compared to the reference, it was discovered that the fly ash mix took longer to set.

Thus it is observed from the literature review, that the performance study of concrete with fly ash as the replacement for natural sand is very scarce. This paper studies the fresh concrete mechanical properties where the natural sand is partially replaced with fly ash.

3 Methodology and Materials

3.1 Materials

The materials employed in this study encompass a range of essential components in concrete formulation. Cement, serving as the binding agent, interacts with fine aggregate to achieve the desired surface finish in the concrete mix. Coarse aggregate contributes both structural strength and form to the mixture. Water, a vital element, facilitates the chemical reactions required for concrete formation. Additionally, a mineral admixture, fly ash, is introduced to augment the overall properties of the concrete blend.

Fly ash assumes the role of a supplementary cementing material, enhancing both durability and strength in the concrete. Derived from coal combustion in power plants, fly ash is a mineral admixture consisting of fine, solid particles captured from flue gases through air pollution control devices. The characteristics of fly ash are influenced by factors including coal source, power plant type, and air pollution control techniques. These particles are often present in small, spherical, or angular shapes.

Two primary types of fly ash exist: Class F and Class C. Class F fly ash exhibits higher proportions of silica, alumina, and iron oxide. It commonly functions as a pozzolanic material within concrete, contributing to its cohesive properties. On the other hand, Class C fly ash, characterized by lower concentrations of these constituents, is employed for construction applications like filling and backfilling. Fly ash plays a significant role in the construction industry as a supplementary cementing material. Its inclusion in concrete formulations enhances properties like strength, durability, and workability.

The material can also replace cement, leading to reduced greenhouse gas emissions and minimized environmental impact. Beyond construction, fly ash serves environmental purposes, such as stabilizing heavy metal-contaminated soils and remediating groundwater contamination. In summary, fly ash's multifaceted contributions span from improving concrete to addressing environmental challenges.

Table 1 shows the sample oxide analyses of fly ash for various compounds with Class F and Class C fly ash.

4 Experimental Investigation

4.1 Test on Materials

4.1.1 Standard Consistency

The standard consistency of cement paste is a measure of its fluidity and is determined through the Vicat consistency test. The test involves filling a Vicat mould with a mixture of cement and water and then measuring the depth to which a Vicat plunger can penetrate the mixture. According to IS 4031, the standard consistency is achieved when the plunger



Fig. 1 Standard consistency-Vicat apparatus

penetrates to a depth of 5–7 mm from the bottom of the mould. Figure 1 shows the standard consistency—Vicat apparatus.

The Vicat consistency test serves the purpose of gauging the water quantity necessary to create a cement paste with a standardized consistency. This determination holds significance as the water content profoundly impacts the cement mixture's setting time, strength, and overall quality in the final product. Establishing this standard consistency equips engineers and technicians to ensure that the cement paste employed in construction endeavors aligns with requisite quality benchmarks.

The Vicat consistency test comprises determining the cement paste's ideal consistency and then calculating the precise water volume required to achieve it. This information is essential for ensuring that the final cement product meets the required quality criteria for use in building projects. The apparatus utilized for this test is depicted in Fig. 1. The outcomes of the standard consistency test are encapsulated in Table 2, providing essential insights into the water-cement ratio necessary to achieve the desired consistency.

Table 1 Sample oxide analyses of fly ash

Compounds	Fly ash class F	Fly ash class C
SiO ₂	55	40
Al ₂ O ₃	26	17
Fe ₂ O ₃	7	6
CaO (Lime)	9	24
MgO	2	5
SO ₃	1	3

Ultimately, this procedure empowers practitioners to optimize the cement mixture for performance, longevity, and adherence to construction standards.

4.1.2 Initial and Final Setting Time

The initial and final setting time of cement is a critical measure of its performance and suitability for use in construction projects. The purpose of the initial and final setting time test is to determine the time required for the cement to transition from a fluid state to a solid state. This information is important because it helps to ensure that the cement will have sufficient time to set before it begins to harden, and also that it will not harden too quickly, which can negatively impact the final product.

The initial and final setting time test, conducted according to IS 4031 Part 5, involves measuring the duration needed for a cement–water mixture to attain a specific level of rigidity. Utilizing a Vicat apparatus, which features a plunger, the test commences by gently pressing the plunger into the cement mixture. The time taken for the plunger to reach a predetermined depth within the mixture is recorded. This procedure is reiterated multiple times across several hours. The initial setting time denotes the interval from the test's commencement until the initial resistance to plunger penetration is encountered. Conversely, the final setting time signifies the period from the test's initiation until the point where the plunger can no longer penetrate the mixture.

The outcomes of this test yield crucial insights into the cement's setting characteristics. This data plays a pivotal role in ensuring that the cement adheres to prescribed quality benchmarks, thus verifying its suitability for integration into construction projects. Figure 2 showcases the setting time-vicat apparatus.

The initial and final setting time test is a critical quality control measure, integral to assessing cement performance and its appropriateness for construction purposes. This examination determines the time required for cement to transition from a liquid to a solid state, enhancing confidence in its quality. Tables 3 and 4 present the results of the initial and final setting time tests on the cement paste, as prepared for the study.

4.2 Fresh Concrete Properties

Fresh concrete is the initial state of concrete right after it is mixed, comprising a combination of cement, water, fine and

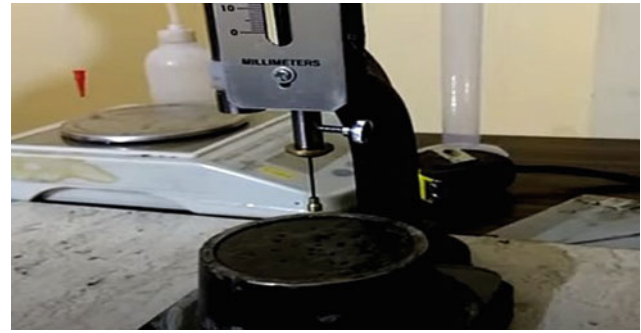


Fig. 2 Setting time-Vicat apparatus

coarse aggregates, and various optional additives. The properties of fresh concrete are crucial as they determine its workability, pumpability, and overall consistency, all of which significantly influence the construction process and the final quality of the structure.

Workability refers to the ease with which concrete can be mixed, placed, and finished without segregation or excessive bleeding of water. Concrete with good workability is easier to handle, ensuring that it can be properly placed in formwork, around reinforcement, or into intricate shapes. Adequate workability allows construction crews to efficiently achieve the desired concrete shape and finish, reducing the likelihood of defects. Pumpability is particularly important when concrete needs to be transported over long distances or to elevated locations using concrete pumps. If the concrete is not pumpable, it can lead to clogs in the pump system and disrupt the construction process. Consistency pertains to the uniformity of the concrete mixture, ensuring that the properties remain uniform throughout the placement and curing processes.

These properties directly influence the quality and performance of the final concrete structure. For instance, improper workability can lead to inadequate compaction, resulting in voids and reduced durability. Inadequate pumpability can cause delays in construction schedules and potential issues with concrete placement. Moreover, inconsistency in the mixture can lead to variations in strength and durability across different sections of the structure. Engineers and technicians monitor and control these fresh concrete properties to ensure that the resulting mixture meets the necessary quality standards for specific construction projects. By adjusting the water-cement ratio, the type and proportion of aggregates, and the use of chemical additives,

Table 2 Standard consistency test result

Test no	Weight of cement (gm)	% of water in cement	Weight of water (ml)	Needle penetration (mm)	Duration of time (min)
1	300	30.5	91.5	5	3

Table 3 Initial setting time test result

Test no	Weight of cement (gm)	% of water in cement	Weight of water (ml)	Needle penetration (mm)	Duration of time (min)
1	300	25.92	77.77	6	138

Table 4 Final Setting time test result

Test no	Weight of cement (gm)	% of water in cement	Weight of water (ml)	Needle penetration (mm)	Duration of time (min)
1	300	25.92	77.77	–	238

they can optimize the fresh concrete properties to suit the project's requirements.

In conclusion, the properties of fresh concrete significantly impact the construction process and the final product's quality. A well-balanced combination of workability, pumpability, and consistency ensures efficient construction practices and a durable, structurally sound concrete structure. Thus, understanding and managing these properties are crucial steps in achieving successful concrete projects..

4.2.1 Workability Test

The slump test stands as a prevalent technique for assessing the workability of fresh concrete. This procedure entails employing a slump cone, a tamping rod, and a scoop to gauge the degree of concrete's deformability. To ensure precise outcomes and uphold uniformity in concrete quality control, it's imperative to execute the slump test in accordance with established standards and guidelines (SP24, 1983). The slump value, which indicates the extent to which the concrete slumps or settles, offers insights into the mixture's workability and suitability for specific construction tasks. The test involves filling the slump cone with fresh concrete in layers, each layer compacted using the tamping rod. Subsequently, the cone is lifted, allowing the concrete to naturally slump. The difference between the initial height of the cone and the final height of the concrete slump indicates the slump value. This value aids in assessing the concrete's consistency, with higher values suggesting higher workability.

To maintain consistency and accuracy, the slump test must adhere to stipulated protocols. This practice is pivotal in guaranteeing reliable results and facilitating informed decisions in concrete quality assessment. The outcomes, presented in Table 5, exhibit the slump values across various concrete mix compositions. Graphical comparisons of these values are depicted in Fig. 3, providing a visual

representation of the variations in workability across different mixtures. Such data equips engineers and technicians with vital insights, assisting them in tailoring concrete formulations to meet specific project needs and ensuring optimal construction outcomes.

4.3 Compressive Strength

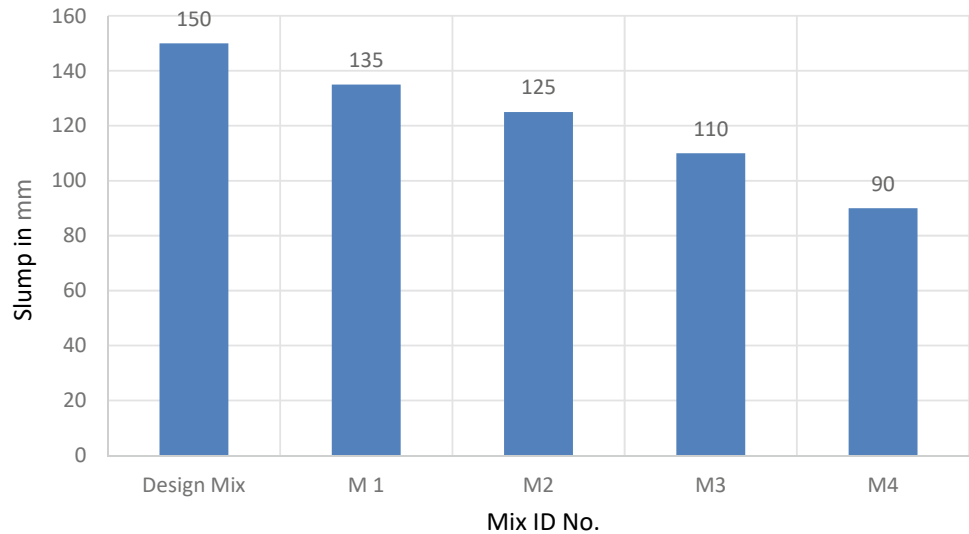
In order to comprehensively understand the hardened properties of concrete mixes that incorporated varying percentages of fly ash as a replacement for river sand (ranging from 5 to 20%), a pivotal testing method known as the standard cube compression test was employed. This test serves as a fundamental approach to assessing the compressive strength of concrete, a key parameter that reflects the structural performance and durability of the material. The experimental setup involved the preparation of ten distinct sets of concrete specimens. These sets comprised different fly ash replacement ratios: 0, 5, 10, 15, and 20%. These specimens were then subjected to two distinct curing periods—7 days and 28 days. These curing durations simulate real-world conditions and allow for the analysis of the concrete's strength development over time.

Table 6 provides a comprehensive representation of the results derived from the cube compression tests carried out on the various specimens. This tabulated data offers an overview of the compressive strengths exhibited by the concrete mixtures at different fly ash replacement percentages and curing intervals. Such data is instrumental in recognizing trends and patterns in terms of strength enhancement due to the incorporation of fly ash.

Significantly, the replacement of 15% of river sand with fly ash emerged as an optimal point in terms of compressive strength. This indicates that a balanced proportion of fly ash substitution positively influenced the hardened properties of

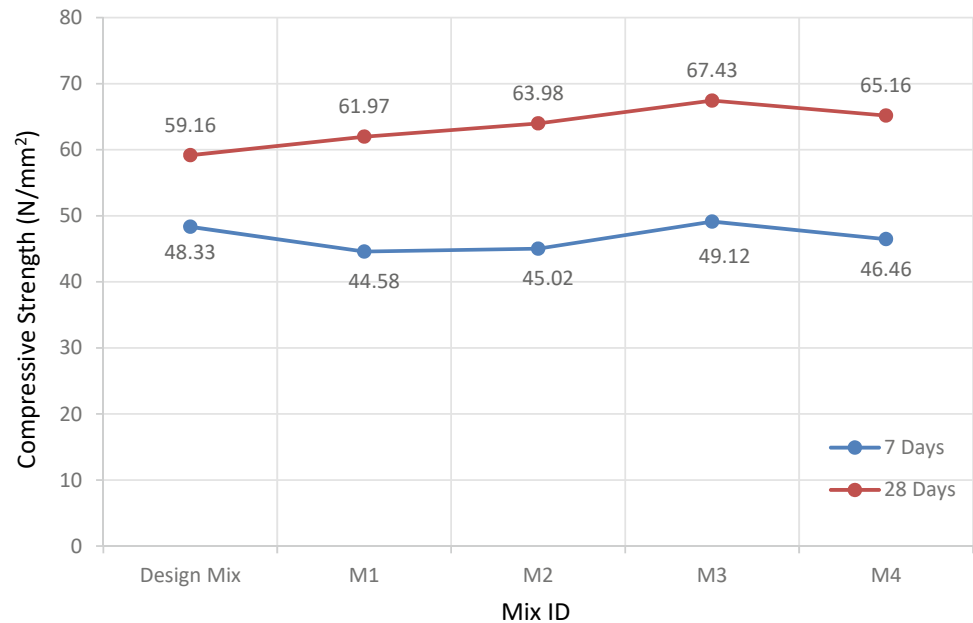
Table 5 Slump test results

–	Design mix	M1 (5%)	M2 (10%)	M3 (15%)	M4 (20%)
Slump Value	150 mm	135 mm	125 mm	110 mm	90 mm

Fig. 3 Slump test result comparison**Table 6** Compressive test results

Mix ID and proportions	Age in days	Weight of cube (gms.)	Load (KN)	Compressive strength (N/mm ²)	Avg. compressive strength (N/mm ²)
Design Mix	7	8675	1064.7	47.32	48.33
		8652	1102.5	49.00	
		8656	1095	48.67	
	28	8696	1305.5	58.02	59.26
		8692	1328.8	59.00	
		8689	1365.9	60.71	
M1 (5%)	7	8692	1000.5	44.47	44.58
		8612	987.7	43.90	
		8626	1021.1	45.38	
	28	8630	1385.5	61.58	61.97
		8615	1402.1	62.32	
		8606	1395.7	62.03	
M2 (10%)	7	8708	1025.5	45.58	45.02
		8714	1006.9	44.75	
		8755	1006.7	44.74	
	28	8766	1408.9	62.62	63.98
		8798	1465.2	65.12	
		8780	1444.5	64.20	
M3 (15%)	7	8825	1102.6	49.00	49.12
		8835	1098.1	48.55	
		8826	1114.8	49.10	
	28	8815	1533.8	68.17	67.43
		8847	1501.1	66.72	
		8801	1516.8	67.41	
M4 (20%)	7	8898	1064.8	47.32	46.46
		8869	1048.9	46.62	
		8866	1022.1	45.43	
	28	8864	1466.5	65.18	65.16
		8858	1459.8	64.88	
		8898	1471.9	65.42	

Fig. 4 Compressive test result comparison



the concrete, leading to improved strength performance. To provide a visual aid for interpreting the relationship between the extent of fly ash replacement and compressive strength, Fig. 4 depicts a graphical plot. This plot showcases the variations in compressive strength as the fly ash substitution percentage varies. The graph provides an intuitive illustration of how the compressive strength is affected by the alteration in the fly ash content.

The utilization of cube compression tests, coupled with meticulous data analysis and graphical representations, offers a comprehensive insight into the effects of fly ash incorporation on the hardened properties of concrete. These insights play a pivotal role in informed decision-making within the construction industry, guiding engineers and researchers toward optimizing concrete formulations to achieve desired structural attributes while considering sustainability and performance aspects.

5 Conclusion

Utilizing fly ash as a stand-in for fine aggregate in concrete confers several advantageous outcomes. The primary objective behind substituting fine aggregate with fly ash centers on elevating concrete density and proficiently occupying voids within the concrete matrix. The conducted study elucidated that the slump value of the concrete blend experienced a reduction with an increase in fly ash content. In order to preserve favorable workability, chemical additives like plasticizers or superplasticizers may be harnessed.

The project's outcomes revealed a distinct pattern: an escalation in fly ash replacement corresponded with a decline in the slump value of the concrete mixture. This observed decrease in slump value signifies a decrease in workability, underscoring the importance of strategies to sustain optimal workability. To address this, chemical additives such as plasticizers or superplasticizers can be judiciously employed.

Exploring the compressive strength attributes, the research delineated that the concrete's compressive strength displayed an upward trend until a 15% threshold of fly ash replacement was reached. Post this point, a downturn in strength was observed. This trend underscores the intricate interplay between fly ash content and compressive strength. The initial weaker strength is attributed to the pozzolanic characteristics of fly ash. Over a 28-day curing period, the pozzolanic reaction of fly ash contributed to a surge in compressive strength, underlining the time-dependent behavior of this material.

In summary, the study underscores the latent benefits of incorporating fly ash as an alternative to fine aggregate in concrete formulations. These benefits lie in the enhancement of density and the filling of voids, both of which are engendered by the presence of fly ash. However, the research also spotlights the need for further exploration and optimization of mix design. By delving deeper into the intricate interactions between fly ash and concrete, researchers and engineers can unlock its full potential, ensuring its integration aligns with specific performance goals and sustainability endeavors.

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Feasibility Study of Materials on Developing Green Materials to Achieve Sustainability in Building Construction

Sudarshan D. Kore, N. Balaji, J. S. Sudarsan, and Sanjay Bhoyar

Abstract

The industrial operations and infrastructure-related activities are causing global environmental challenges. Therefore, there is growing interest in developing renewable technologies and using sustainable materials. Sustainable, easily attainable, durable, easily maintained, and adaptable building materials are the wave of the future. The idea of using a wide variety of eco-friendly materials in building construction stems from the fact that these products have desirable qualities such as low carbon footprints, quick installation times, and resistance to earthquakes and fire. In order to meet this demand, scientists studied the effects of combining different types of plastic, marble dust, fly ash, glass fiber-reinforced gypsum, light-transmitting concrete, and bamboo. In the preliminary analysis, a questionnaire was distributed to various stakeholders to gather their thoughts on environmentally friendly materials. Following the first survey, the data is analyzed utilizing Statistical Package for the Social Sciences (SPSS) software to rank the detected risks related to building activities. There was a massive survey with questionnaires and plenty of numbers crunched. Materials like GFRG panels, plastic waste, AAC blocks, fly ash, etc., have seen increased adoption due to positive responses. The analysis's primary finding is that sustainable use of green materials in building construction is feasible thanks to the widespread availability of low-cost, high-performance green materials on the market.

Keywords

Sustainability • Green materials • Construction activities • Cost-effective

1 Introduction

When designing a green building, it's important to start with eco-friendly materials that really outperform the more conventional options. Green building or ecological building has become a focus in today's construction world (Poon et al., 2000). At present, the usage of green buildings depends on certain factors such as energy saving, material saving, and environment fortification. The building business needs everyone's attention on current development trends if it is to reach new heights in the framework of the new era.

We need to look at the newest green building techniques because there is a dearth of traditional materials. High-rise buildings are often constructed out of concrete. Carbon dioxide emissions from concrete production are estimated to be between 7 and 8% (Aggarwal et al., 2012; Javadian et al., 2014). Concrete's grey hue, heavy density, and composition of cement, sand, and aggregates prevent the material from letting any light through. "Light Transmitting Concrete" (or "LiTraCon") is a relatively new material. Fiber placement on structures determines the resulting illumination pattern on the surface. Because of the enormous quantities of non-biodegradable plastic waste produced, a new type of concrete has emerged: plastic concrete.

Due to its resilience, bamboo became a popular construction material in the 1980s. In areas where bamboo grows abundantly, it can be used as a building material. This has been a go-to building material since prehistoric times. Construction with rammed earth is on the rise because of the material's durability, accessibility, and minimal carbon emissions. In a similar vein, eco-friendly resources including stone dust, solar panels, autoclaved aerated concrete, fly ash,

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crushed granulated blast furnace, and marble powder are incorporated into the building process.

One of the mega industries in the world is the construction industry, which also contributes to the nation as well. All over the world in the construction sector, majorly conventional materials are used which also leads to pollution (Verma et al., 2016). The scarcity and drawbacks of traditional materials are driving our interest in these environmentally beneficial alternatives. Selecting and employing environmentally friendly materials with more desirable characteristics than conventional materials is a crucial first step in the design of a sustainable structure. Today's construction industry is increasingly concerned with green building practices. Currently, energy efficiency, material efficiency, and environmental preservation are the determinants of sustainable building usage. The building business needs everyone's attention on current development trends if it is to reach new heights in the framework of the new era. We need to look at the newest green building techniques because there is a dearth of traditional materials.

The key objective of this study is to analyze the use of Eco-Friendly materials for environmentally sustainable construction and the analysis of various benefits of those materials that can help us in achieving sustainability. We hope to contribute through research on the materials and all the benefits pertaining to it such as cost benefits, quality, and in some cases time-savings.

2 Past Research Work

Plastic concrete, marble dust, glass fiber gypsum panels, autoclaved aerated concrete (AAC) blocks, bamboo, solar panels, light transmitting concrete, fly ash, and so on are all examples of eco-friendly building materials. Researchers before us have studied the feasibility of employing such materials in environmentally beneficial and long-lasting building projects, and their findings are detailed here.

2.1 Light-Transmitting Concrete

Light-transmitting concrete also known as LiTraCon or translucent concrete or transparent concrete has gained a lot of recognition in the field of sustainable sources of materials, it was first introduced by Hungarian architect Aron Losoncz (Khalil, 2019; VanGeem, 2006). He developed the first LiTraCon block in the year 2003. Light can pass through the light-transmitting concrete through the slits that are provided by the use of optical fibers (Chiew et al., 2021).

To obtain the structure formed that possesses properties of transmission of light through it, the optical fibers have to be placed uniformly in horizontal alignment inside the

casting formwork, and then the concrete is cast and the process then forms units of Light transmitting concrete like panels or blocks. The types of optical fibers that could be used for this process include plastic optical fiber, Polymethylmethacrylate as polymer fibers, and glass optical fibers (Pytlík & Saxena, 1992).

Indian Green Building Council (IGBC) has stated that the percentage of daylight that must be transmitted should be at least 50% in green buildings. To achieve this condition Light Transmitting concrete is being widely used in green buildings and thus they achieve sustainability (Sukumar et al., 2017). There are several other materials were used to produce the LTC. Each material had some impact on the properties of concrete. According to Desta and Jun (2018) using waste glass in LTC will not react under Alkali-Silica Reaction test (ASR) test. The research also concluded that if the transmission of light is around 11% then the demand for energy could be reduced up to 20.6%. Another study conducted by Vardhan et al. (2015) stated that, if 60% of the aggregates are replaced with recycled glass then the compressive strength is reduced to 34.5%. It was also observed that there was no translucency with 10 mm plates as compared to 6mm plates and on microstructure analysis, it was found that there was incomplete adhesion present at the glass-cement interface.

There was an improvement in the thermal insulation of LTC incorporating polyester-based resin because of the resin's low thermal conductivity testified by Rai & Robinson (2013). In addition, the report noted improvement in the durability of concrete and adhesion properties, the surface of resin can be made rougher.

The overall ratio of transmitted light was influenced by the spacing and number of fibers used it stated by Kabeer and Vyas (2018). 6% of plastic optical fiber performs up to 22% of light transmittance. It was also observed that smaller diameters and spacing of plastic optical fibers had higher light transmittance. Utilization of LTC can reduce the consumption of energy by 20% and the transmittance of light is proportional to the amount of fiber stated by Banu (2016).

2.2 Solar Energy

Energy mitigation policies should be created in tandem with climate resilience and adaptation measures to lessen the severity of climate change's negative impacts. (Cherian et al., 2017). The emission of greenhouse gases contributes very significantly to global climate change and the use of renewable resources to curb this situation can contribute to a great extent. Greenhouse gases emission by India are third highest in the world and their pace is constantly increasing, with the increase in energy consumption per capita we have to adopt certain solutions which include the use of renewable

resources like solar energy, wind energy, etc., (Jaivignesh & Sofi, 2017).

Conventional nonrenewable sources of energy can be replaced by solar energy. Urban air pollution through greenhouse gases can be significantly reduced by the use of rooftop solar panels. Adopting the change and looking at the future perspectives of renewable resources government of India decided to use non-fossil fuel energy and supply 40% of the total consumption by 2030 (Berndt, 2009).

The government of India is putting its faith in solar power and has set a target of installing 100 GW of solar power by 2022. Government officials have divided the goal into two halves: 60 GW for large-scale utility installations and 40 GW for residential roofing photovoltaic, or PV, systems (Raina & Sinha, 2019). The improved capability will also contribute to achieving a goal under the Paris climate agreement. India's renewable energy sector is one of the most attractive in the world because of the country's lofty aspirations and supportive policies and regulations. When considering the prospects for renewable energy adoption in India, according to a new article in The International. The Government's Ministry of Renewable and New Energy has reported that India's solar capacity has grown between 2.6 GW and in excess of 34 GW in just over five and a half years. The potential of renewable energy sources has increased by 226% over the past five years. There was an 80% drop in the price of setting up solar PV plants in India between 2010 and 2018 (Aggarwal, 2014), as reported by the International Renewable Energy Agency (IRENA).

2.3 Bamboo

On a global scale, environmental issues can now progressively constrain growth, industrial practices, and human settlement professions. As a result, finding sustainable materials and renewable technologies has been a global focus. Usage of bamboo will also minimize the need for wood from both native and cultivated forestry.

Bamboo is the renewable commodity that regenerates the fastest. In terms of growth rate and field use, timbers and other species of timbers are incompatible. Besides, it shows outstanding physical, mechanical, and structural properties, such as strength/density and stiffness/density ratios which are superior to that of wood and concrete and equivalent to those of steel (Shen & Zhou, 2020).

Specific methodologies to determine the practical usage have been conducted by many structural engineers and researchers, such as the process of fabrication & analysis of bamboo's mechanical properties with the help of reinforced concrete (Yadav et al., 2016).

By combining a thermoset polymer with raw bamboo rai-sins under pressure, a composite material with controlled

and long-lasting properties was created. This not only assists in maintaining the natural strength of bamboo fibers, but it has also been shown to shield the composite panel from adverse effects on the ecosystem, such as humidity, spores, and pests. This was made possible by casting individual panels ahead of time.

The pre-fabricated panels made up of bamboo showed a tensile strength of over 400MPa and a modulus of elasticity of about 50GPa. Between 100 and 120 MPa the compressible intensity was recorded, while the bending force was up to 200 MPa. Bamboo's tensile strength made it theoretically possible to use in concrete, but disadvantages such as absorbing water, having a low modulus of elasticity, and expanding thermally prevented long-term use. When the bamboo was exposed to the concrete mix, it resulted in excess absorption of water, which caused deterioration and swelling in the reinforced concrete structure.

2.4 Autoclaved Aerated Concrete Blocks

Conventional clay bricks are the most commonly used commodity in India's building and installation industries. Block furnaces have rapidly grown due to accelerated urban brawl and growing interest in construction products, causing genuinely or inadvertently a progression of environmental and medical problems. In 1880, a German named Michaelis was granted a patent for the steam curing procedure, which led to the development of AAC blocks, and in 1889, a Czech named Hoff-man was granted a patent for AERATING concrete made from carbon dioxide (Kumar & Nayal, 2020; Lakshmi et al., 2019).

Porous, non-toxic, reusable, organic, and recyclable, AAC is a perfect alternative. Aircrete, also known as autoclaved aerated concrete, is a construction material available in various sizes and strengths (Thomas, 2007).

During the forecast timeframe, the global market for ACC is expected to increase by 6.0% from USD 18.8 bn in 2020 to USD 25.2 bn in 2025 with a CAGR of 18.8 bn. The AAC industry is growing due to rising urbanization and industrialization, infrastructure expansion, the lightweight construction materials in high demand, as are low-cost housing preferences and a growing focus on green and soundproof buildings (Juan & Zhi, 2019).

The study conducted by Jaiswal et al. (2017) the use of autoclaved aerated concrete for strengthening the soil beneath the slab. In order to prevent sinking, cracking, and the production of an uneven surface, autoclaved aerated concrete is used beneath the soft soil. These buildings save money in the long run because they don't need a costly foundation.

AAC floor slabs and blocks of bonded screed, as well as the AAC blocks used as the inner skins of cavity walls have

performed admirably as construction materials with superb high thermal stability. Even though, serviceability issues such as significant deflections and splitting have been found in installations, possibly due to poor workmanship and a lack of sensitivity to different material properties (Smith & Waterman, 1981).

2.5 Stone Dust

Construction uses natural sand as one of its primary components. However, this demand degrades rivers, causing ecological discord. This is why most of the river has a sand mining ban. Stone dust is the greatest substitute for river sand. Various studies demonstrated that the usage of stone dust in the predation of concrete showed almost the same performance as that of the natural sand.

Torres et al. (2020) conducted experiments using varying percentages of stone dust in place of sand in freshly mixed concrete to better understand the material's behavior. According to the results, increasing the percentage of stone dust to sand in concrete mix improves the material's mechanical qualities. Furthermore, replacement levels of the properties were declined significantly. Zuki et al. (2020) studied the feasibility of the usage of stone dust on soil stabilization. It was stated that, if 50% stone dust is mixed with soil then optimum moisture content can be reduced, which is beneficial for decreasing the water quantity during compaction.

2.6 Ground Granulated Blast Furnace Slag (GGBS)

As a byproduct of iron production, blast-furnace slag (abbreviated GGBS) is a cement-like substance which is having pozzolanic properties that are mostly utilized in concrete (Li et al., 2015). The replacement ratio for concrete structures requiring higher early-age strength is typically 20–30%, whereas the replacement ratio for basement concrete structures requiring average strength is typically 30–50%. GGBS and Portland cement are combined in concrete structures where the greater the percentage of GGBS, the more significantly the concrete properties are affected. Grain size is smaller in GGBS than in Portland cement, and its early strength is lower; however, after 28 days of curing, the material's strength is 20% higher than conventional concrete's (Dhadse et al., 2008; Li et al., 2015).

Kamal (2020) inspected the possibility of utilization of GGBS as a replacement for cement from 0 to 50%. Replacement of cement by GGBS increased the flow of concrete suitable for flowable concrete preparation. The mechanical properties of the concrete showed significant peak values at 20% replacement levels. On average,

replacing 20% of cement with GGBS was suggested as an ideal level of replacement.

2.7 Glass Fiber Reinforced Gypsum (GFRG) Panels

GFRG panel were first launched in Australia, and they are now manufactured in India. GFRG, also known as rapid wall in the industry, is a relatively new building panel. Glass fiber reinforced gypsum (GFRG) wall panel is made of gypsum plaster reinforced with glass fibers. GFRG Panels are made of Phospho Gypsum which is an industrial waste from the fertilizers industry (Kalpana & Mohith, 2020).

The hollow panels are used in load-bearing walls. In situ plain or reinforced concrete may be used to fill the hollow cores inside the walls (Kore & Vyas, 2016). Manpower, expense, and construction time are all reduced as a result of this phase. The use of scarce natural resources such as river sand, water, and farmland is dramatically reduced (Shreyas, 2017) GFRG is especially important to India because it is cost-effective, environmentally friendly or immune to greenhouse impact, and waterproof and fire resistant.

Kore and Vyas (2016) feasibility study on the usage of GGBS in concrete with replacement levels from 0 to 40% by weight of cement with an increment stage of 10%. It may be concluded from this research that, its strength is low at first, but it gradually improves over time. The ideal GGBFS replacement for cementation material has high compressive strength, low-temperature susceptibility, chemical resistance, superlative flowability, good durability, and cost-effectiveness.

Sangeetha et al. (2014) and his team developed the GFRG panels in their institute and constructed a two-storied four-apartment demonstration building. The experiments revealed that the building can withstand gravitational pull and lateral loads as a load-bearing system with sufficient strength, serviceability, durability, and ductility. After successful demonstration, the same was implemented in nearby cities for the construction of affordable housing schemes. The design has been approved by the Bureau of Indian Standards. This technology has the potential to be a long-term sustainable solution for the world's construction sector in terms of affordable housing.

2.8 Precast Concrete

Precast concrete is done by pouring the concrete into a reusable mould, curing it in and happens in a regulated setting, then transporting it to the construction site and erecting it in the desired location (Iucolano et al., 2021). Precast concrete structures have a number of benefits over

cast-in-place concrete structures, including less wet work on the job site, better component quality control, easier construction, and better economic and environmental outcomes (Raghatate, 2012). The use of such technologies will cut down the time required to complete similar projects by up to approximately 60% as compared to conventional construction methods and technology (Sayali & Patil, 2017). Through developing and implementing technologies that minimize greenhouse gas emissions, the cement and concrete industries will make significant contributions to sustainable growth (Peter et al., 2017).

Precast concrete manufacturing has many environmental advantages. Since precise mixture proportions and tighter tolerances are possible, fewer materials are needed. Insulation levels that are suitable for precast concrete sandwich panel walls may be implemented. Since the amounts of constituent materials are closely regulated, less concrete waste is generated (Vaidevi, 2013).

2.9 Fly Ash

Fly ash's relevance and use in concrete has grown to the point that it is now common practice, mostly for the sake of creating a high-strength and durable mix of concrete. The graphic below shows that India is a major producer of fly ash, whose disposal has become a serious environmental problem (Yan et al., 2018).

Variables including collection method and coal-combustion heat determine fly-ash characteristics such as particle size, shape, density, and so on. Fly Ash is a finely divided aggregate that contains primary synthetic elements like SiO_2 , Al_2O_3 , FeO_2 , and CaO (Mahto & Kujure, 2017). The quantity of Fly Ash Produced and Used Worldwide is shown in Fig. 1.

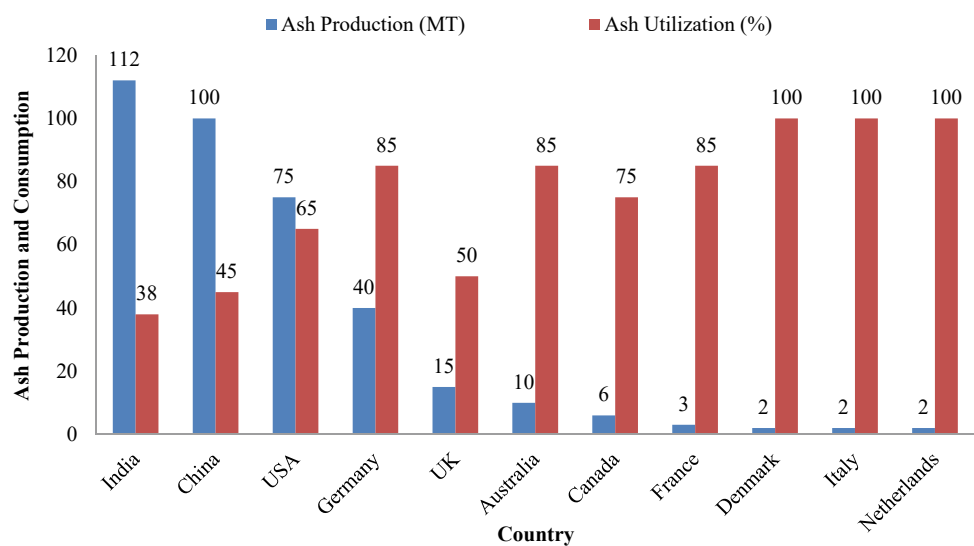
From the recent findings of Berndt (Shen & Zhou, 2013), it was concluded that the replacement of cement constituents by fly ash has been observed to be very helpful. It may be noted that 25% of the substitution of concrete by fly ash enhanced the strength and durability properties of concrete. The use of this material in concrete can help bear environmental issues coming from the thermal industry and help in the removal of the materials from dumping sites.

Multiple experiments on using fly ash in concrete production that are both sustainable and long-lasting were undertaken by Rajaram et al. (2017). The research showed that high-performance concrete with a compressive strength of 80 MPa after 28 days could be made with a water-binder ratio of 0.24 and a concentration of 45% fly ash. This kind of concrete has a decreased heat of hydration and chloride diffusivity than standard cement concrete.

According to Thomas, the optimal amount of fly ash to employ in concrete depends on the building's usage, its exposure, and the curing method (MSME Development Institute Ministry of Micro, Small & Medium Enterprises. Government of India, 2009). Each endeavor has its own optimal fly ash content. If the early-age strength requirements of the project are met and enough moist-curing is guaranteed, then a fly ash concentration of up to 50% may be reasonable for most elements.

Sudarsan (2021) planned to make green concrete, in which fly ash is substituted for cement at rates of up to 60% by weight. There was an increment for long-term cured concretes containing fly ash higher than 30% replacement level for cement, even though there was a drop-in strength at early ages. In addition, it was found that the ideal level of fly ash substitution of cement was more than 15%-20% for greater followability, strength, and other properties of concrete.

Fig. 1 Quantity of fly ash produced and used worldwide (Pagliolico et al., 2015; Yan et al., 2018)



2.10 Marble Powder or Marble Dust

During the production of marble, marble dust is the byproduct and creates environmental pollution on a larger scale. During the processing operation of marble, nearly 50% of the total waste is generated (Harsh Bansal, 2016; Nguyen, 2018). This waste is in the form of quarry waste and during processing in the form of marble slurry. Marble dust is the by-product of the production of marble and creates atmosphere pollution on a massive scale, throughout this cut method nearly twenty-fifth of the initial marble mass is lost within the type of mud that replaces the fine sand in the concrete mixture. Therefore, it's doable to stop the environmental pollution for those reasons wherever marble production is excessive.

According to United Nations Environment Programme (2009), the chemical, physical, and mechanical properties of mortars containing up to 10% marble powder substituted for cement were unaffected. Also, higher cement replacement results in delays in the hydration process, longer initial and final setting times, and the creation of porous microstructures in cement paste, according to the same study. Based on their findings (Mire & Singh, 2017), it appears that marble sludge can substitute for up to 10% of the Portland cement in concrete mixtures. To improve concrete's resilience to permeation, chloride migration, and corrosion, marble was added. However, the dense microstructure of the concrete generated owing to the addition of marble limited its workability. Because of the greater surface area of marble powder, the concrete mixtures were found to be less workable. As a result, it has been claimed that 10% of marble sludge would be used as a partial replacement for cement without affecting hydration products.

Adding 15% marble powder to high-performance concrete improved engineering properties performance, according to Kore et al. (2020). Workability and air content were found to decrease, as well as increased density, when compared to control concrete. At one year after age compared to the control concrete, the authors found that chloride ion penetration resistance had risen and air porosity had decreased by 85%.

Marble powder can boost compressive and flexural strength by 10 and 14% when used in place of cement in up to 10% of the mix, according to Talah et al. (2015). When more than 10% marble powder is used for cement, the flexural and compressive properties decrease by 22.64 and 13.63%, respectively.

2.11 Plastic Concrete

Concrete is the furthestmost utilized substance in this industry, over 25 billion tons are put in every year, plastic

waste is one of the numerous components that contrarily influence the climate (Rana et al., 2016). Issues come from elements, for example, the trouble of waste reusing and restricted reuse. Plastic is a significant sort of strong waste with a solid natural effect. A surge in the total amount of waste generated as a result of a modern lifestyle and technological innovation has led to a dilemma in waste disposal (Tuaum et al., 2018).

Concrete constructed employing recyclable plastics as a substitute for fine and coarse aggregate was tested for its mechanical qualities by Jaivignesh and Sofi (Tuaum et al., 2018). They used a range of percentages, from 0 to 25%, increasing by 5%. According to their findings, concrete's compressive strength decreased by 9% at a 10% replacement level, while it decreased by 13 and 17% at 15% and 20% replacement levels when compared to the control concrete mix. Split tensile strength and flexural strength tests showed a similar pattern. It is known that this decrease in strength primarily of it is primarily due to a weak connection between plastic aggregate and cement. Several other researchers have noted this as well.

However, Subramani et al. discovered that the mechanical behavior of mixes of concrete was enhanced when plastic trash was substituted for standard coarse aggregate. It has been reported that plastic bags can be used in concrete mixes in various percentages, ranging from 0.2 to 0.4 to 0.6 to 0.8 to 1.0% by Arivalagan (2014). It was found that the compressive and tensile strengths were reduced when plastic bags were used as a filler in concrete. BIS 456-2000, on the other hand, allows a 10% reduction in strength. They concluded that more attention should be paid to the concrete mix's behaviour when it is mixed with plastic bags.

3 Shortlisted Factors

An extensive literature survey was carried out to find out the materials for the preparation of the questionnaire survey. These materials were shortlisted based on the different properties of the materials.

- i. Based on these eight variables, a wide variety of surveys were developed.
- ii. Ease of availability at the site.
- iii. Future prospects/usage.
- iv. Percentage of materials used at current working site.
- v. Cost-effectiveness in a project.
- vi. Economic feasibility in accordance with the current market scenario.
- vii. Environmental impact.
- viii. Durability of the materials.
- ix. Recommendation to use material.

3.1 Ease of Availability on Site

Material selection can be influenced by this parameter, so it's critical to pay attention to it. In order to avoid project delays, costs, and energy waste, it is necessary to budget for extended lead times for deliveries.

The cost and installation time can depend upon the availability of the materials. The materials which are available locally can be difficult to transport to other places. In addition to increasing shipping costs, delaying the work also has a negative impact. Shipping costs can be cut in half if the materials are close to the site of the project. Additionally, it saves time and facilitates the completion of tasks.

3.2 Future Prospects/Usage

Before selecting any materials and designing the building, one should consider its reuse or future use of the building and use materials that can be replaced or facilitate adaptation. The adaptability of the materials will contribute to a smaller amount of waste and will result from changing needs or tastes.

3.3 Percentage of Material Used at Present

It is crucial to think about how the building will be used or repurposed in the future when making decisions about the materials used and the layout of the building. Fewer wastes would be generated as a result of the materials' adaptability in response to shifting demands or preferences.

3.4 Cost–Benefit Analysis

The materials that can be used for longer periods and are sustainable are cost efficacy. It is one of the vital factors when choosing materials for construction is to ensure it will safeguard your building.

Material life cycle costs must be taken into account, as well as their initial purchase cost. Maintenance, backup, demolition, and disposal all fall under the umbrella of life cycle costs. Additionally, environmental costs like the release of volatile organic compounds (VOCs) during renovation must always be considered when estimating operational costs.

3.5 Current Market Scenario

Here in the survey, the people were asked to provide ratings of the materials as per their opinion on the basis of the

economic feasibility in the current market scenario for that particular material. Environmental impacts caused by their usage materials that can be reduced and reused, the need for new materials in the future, making them an excellent alternative to non-reusable ones. The materials that are found in the local areas reduce the transportation problem, hence reduction in the emissions. Hence, this data helps us to know the impact the material is causing when being used.

3.6 Durability

For the materials which do not require that much maintenance does not mean it is good for the environment and it could be possible that manufacturing those materials produces a lot of greenhouse gases. Materials that need more maintenance could be producing greenhouse gases way less than the materials that need less maintenance. This is the collective data that summarized the opinion of the person filling the form on whether he or she would recommend using that particular material on site, based on all the factors together through a rating system that was provided.

4 Methodology

This helped us understand the general perception of the materials for the study and how the working professionals perceive their usage.

The research methodology of this study involves a comprehensive analysis of data sets obtained through questionnaire surveys. The research methodology flow is shown in Fig. 2. Various eco-friendly materials were nominated and a thorough literature survey was carried out to determine its sustainability in the construction industry. The eight eco-friendly materials were shortlisted from the extensive literature survey for questionnaire design analysis.

The questionnaire was prepared and spread among industry experts, working professions, and researchers. Using a Likert scale and a defined psychometric scale, we assigned points to each questionnaire based on how environmentally friendly the products were.

- **1** represents 0–20%,
- **2** represent 20–40%
- **3** represent 40–60%
- **4** represent 60–80%, and
- **5** represent 80–100%.

After accumulating data via a questionnaire survey, an analysis of linear regression was performed. The following components were both the focus of the analysis and its predictors.

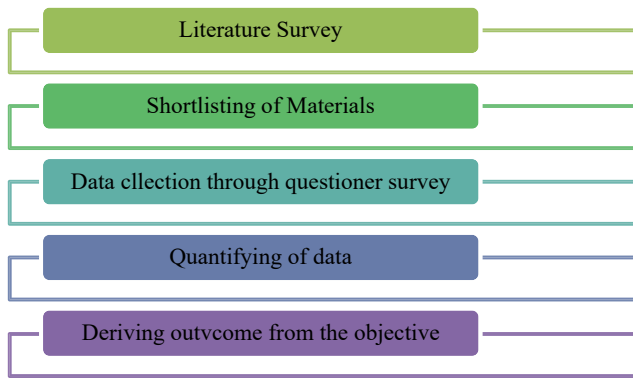


Fig. 2 Research methodology adopted

A. Determinant Factor: Global Effect on Long-Term Sustainability.

Constant B. Predictors: Time-to-Failure; Durability; Percentage of Material Used on Site; Cost-Benefit Analysis; Future Prospects/Use; Availability on Site; Economic Feasibility.

Figure 3 shows the diversification in the age of the respondents, where the majority of the plaintiffs belong to the age group of 24–25 with a combined percentage of 56.3%.

5 Results and Discussion

To analyze the data collected through the questionnaire survey, a statistical analysis model such as Regression Analysis was adopted. As part of statistical modelling, regression analysis is known to evaluate the relationship between the dependent variables and one or more relationships between the independent variable. Linear regression is

one of the most common types of regression analysis. The type of analysis is usually determined by the mathematical evaluation to know which line fits best,

Model summary—R Square—The overall model accounts for 26% of the variance in the overall impact on sustainability.

Coefficients—Each predictor is significant if its significance value is less than or equal to 0.05; otherwise, it is not a significant predictor of overall impact on long-term sustainability.

After considering the aforementioned elements and others, such as the cost, the percentage of material used on-site, the future prospects of the material, and the cost-benefit analysis, etc. In terms of the dependent component of variance in overall influence on sustainability, the model summary from the analysis revealed that Plastic exhibited a maximum of 55% variance, subsequent to LTC (Light Transmitting Concrete) had 50% variance, and marble dust with 33% variance.

An analytical synopsis based on regression is shown in Table 1.

For all of these components except bamboo, the Regression analysis produced a statistically significant result. In the cases of AAC blocks, Marble dust, GFRG panels, and plastic, economic feasibility was a major predictor. Solar panels, fly ash, and plastic each had their own unique availability and percentage of material used at site factors that were highly predictive of their success as building materials. The future potential of marble dust and LTC (Light Transmitting Concrete) was found to be a significant predictor of the material's cumulative impact on sustainability.

Fig. 3 Experience of respondents

Experience
110 responses



Table 1 Analytical synopsis based on regression

Materials	Model synopsis	Significant predictor
Plastic	Five-fifths of the total influence on sustainability can be attributed to the predictors	Percentage of material used at the site economic feasibility
Marble dust	Three-quarters of the whole influence on sustainability can be attributed to the predictors	Future prospects/usage economic feasibility
GFRG	The variables can explain 20% of the total influence on sustainability	Economic feasibility
Autoclaved aerated concrete	The entire effect on sustainability is explained by the predictors, to the tune of 24%	Economic feasibility
Bamboo	There is a 10% total influence on sustainability that can be attributed to the predictors	NIL
Solar panels	The variables can explain 20% of the total influence on sustainability	Availability at site
LTC	Half of the total influence on sustainability can be attributed to the predictors	Future prospects
Fly ash	The whole impact on sustainability is explained by the predictors, but only to the extent of 29%	Percentage of material used

6 Conclusions

Finding a sustainable material replacement is the primary focus of this research. The following inferences were made from the aforementioned research:

- The various alternative materials have the potential to be used in sustainable development which reduces the impact on the environment.
- From the response of the respondents, it was observed that these people are ready to adopt these materials in the construction but they have certain limitations.
- Some contradictory observations about the use of these materials in the constructions were seen from the response of the respondents.
- The regression analysis helped to find the impact on sustainability.
- With a variance of 55%, plastic was the most influential material on sustainability, followed by LTC (Light Transmitting Concrete) with a variance of 50%, and marble dust with a variance of 33%.

Green or sustainable concrete can be fabricated with non-traditional components. Using an alternate method results in a product with greater quality, increasing its value and extending its lifespan. A survey of the many novel techniques currently in use and how they may soon become the standard, such as technological advances that will enhance currently available sustainable solutions for advancing green or sustainable building practices.

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Application of Microsurfacing Technique for Optimizing Maintenance Cost of Rigid Pavements in India

Shruti S. Khot, Virgonda A. Patil, and Sneha P. Madnaik

Abstract

Microsurfacing is a proactive surface treatment that enables the surface to restore and preserve the characteristics of the road surface. It is a mix of polymer-modified asphalt emulsion, graded aggregate, cement, water and additives applied in a semi-liquid state using specialized tools on existing pavement with a thickness of 6–8 mm (Type III). In this paper, the mix design developed in the laboratory and the mix design applied on-site are analysed and the economic analysis of microsurfacing on the rigid pavement having 4 lanes is done. The performance of microsurfacing is studied by considering the skid resistance, roughness and rutting of the road surface. The mix design is followed by the guidelines specified in IRC: SP:81:2008 and ISSA A143. In economic analysis the Internal Rate of Return (IRR) is calculated as per guidelines given in IRC: SP: 30:2009. The EIRR of the project is 20.55% which is higher than 12%. It shows that a proposed project is economically viable.

Keywords

Microsurfacing • Rigid pavement • Emulsion • Internal rate of return

1 Introduction

Microsurfacing is the homogenous mixture of modified asphalt emulsion, well-graded aggregate, cement, water and specified additives (if needed). Basically, the application of microsurfacing is carried out when the mixture is in a semi-liquid condition. Microsurfacing as a wearing coat is a smart approach for resurfacing. In addition to hot mix application, it is cost-effective (Pederson et al., 1988; Watson & Jared, 1998). This offers a smooth surface without interfering with the existing profile. After application, the mixture sets rapidly to give a consistent coat of homogeneous mix material which enables the vehicular movement to restart in less than one hundred and twenty minutes. The criteria for the application of microsurfacing is the pavement on which it is to be applied must be structurally sound, but the surface shows uneven surface, cracks, chipping of aggregate, etc. The main objective of the research is to conduct the technical and economic analysis of microsurfacing on rigid pavement. India exists in the tropical zone, where everyday climatic conditions differ. Concrete is a material that develops high stresses and deforms due to temperature variation. It becomes important to come up with a method and material to accommodate against deformation which will limit it. Using microsurfacing as a wearing course on rigid pavement, mix design is developed. Further, for measurement of the performance of microsurfacing, skid resistance, roughness, surface texture and rutting are taken into consideration.

The economic viability of the project is determined by using the Internal Rate of Return (IRR) method. The economic analysis is followed by the guidelines given by IRC: SP: 30:2009.

The construction cost of rigid pavement is comparatively more but the periodic maintenance cost seems to be less on the contrary construction cost of flexible pavement is comparatively less but maintenance cost observed more. Meanwhile application of microsurfacing on rigid pavement can

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be effectively used to reduce the periodic maintenance cost. In Indian conditions, the use of microsurfacing technique can be proven revolutionary footstep in the upcoming decades.

2 Research Methodology

2.1 Material Collection

1. Emulsion

Modified bitumen emulsion confirming the requirements (as specified in IRC: SP: 81:2008) is used. The emulsion is collected from SMB enterprises in Pune.

2. Aggregate

The gradation of specified aggregate (as per IRC: SP: 81) from the local crusher is used for the particular application.

3. Filler

Ordinary Portland cement as mineral filler is used. The amount of filler material used should range between 0.5 and 2% by dry aggregate weight.

4. Water

The water used should be potable, free from contamination having a pH range of 6–7.

5. Bitumen

For the microsurfacing, the residual bitumen is added by percentage of weight of aggregate.

2.2 Mix Design

Source of material (Table 1).

Proportion of material (Table 2).

Sample calculations

Trial 1

Weight of Aggregate 500 gm

Weight of Cement = 2% of Aggregate

$$= 500 * 2/100 = 10 \text{ gm}$$

Weight of Water = 7% of Aggregate

$$= 500 * 7/100$$

$$= 35 \text{ gm}$$

Weight of Emulsion = 12.5% of Aggregate

$$= 500 * 12.5/100$$

$$= 62.5 \text{ gm}$$

2.3 Test Results of Experimental Mix Design with IRC:SP:81:2008 Mix Design

Test Results of Physical Characteristics of Aggregate Used in Mix Design (Table 3).

Test Results of Physical Characteristics of Bitumen Emulsion used in Mix design (Table 4).

Test Results of Physical Characteristics of Residue of Emulsion (Table 5).

The research findings clear that the properties of aggregate, emulsion, residue of emulsion are approximately the same with some acceptable differences as per IRC: SP:81:2008 and IRC:SP:100:2011. The mix design of microsurfacing is prepared for ensuring the desired strength.

Factors affecting mix design of microsurfacing (IRC: SP:81-2008; White & Hein, 2009).

1. Interlocking properties of aggregate
2. Weather conditions.

Mix design used for micro surfacing and mix design prepared in laboratory (Table 6).

Test Results of Microsurfacing Mix—

As per IRC:SP:81-2008, the mix design of microsurfacing is prepared. While testing the mixture precaution is taken

Table 1 Materials

Sr. No.	Material	Source
1	Emulsion	SMB enterprises, Pune
2	Aggregate	Local crusher plant
3	Filler	Ordinary Portland cement (ultra-tech)
4	Water	River water supplied by the municipal corporation
5	Bitumen	Local HMA plant

Table 2 Mix design

Sr. No.	Mix proportion	Trial 1
1	Aggregate	100%
2	Cement	2%
3	Water	7%
4	Additive	None

Table 3 Test results of aggregate

Sr. No.	Description	Laboratory test results	Requirement as per IRC: SP: 81: 2008
1	Water absorption (%)	0.935	Max. 2
2	Sand equivalent value	86.95	Min.50
3	Moisture content test (%)	1.45	—

Table 4 Test results of Bitumen emulsion

Sr. No.	Description	Laboratory test results	Requirement as per IRC: SP: 81: 2008
1	Residue on 600 microns IS sieve (% by mass)	0.048	0.05, maximum
2	Viscosity by say bolt furol viscometer, at 25 °C in second	21	20–100 s
3	Coagulation of emulsion at low temperature	—	—
4	Storage stability after 24 h, %	0.86	2 Maximum
5	Particle charge, +ve/–ve	+ve	+ve

Table 5 Test results of residue of emulsion

Sr. No.	Description	Laboratory test results	Requirement as per IRC: SP:81:2008
1	Residue by evaporation, %	63.15	60% Min
2	Penetration at 25 °C/100gm/5 s	64.33	40–100
3	Ductility at 27 °C, cm	84.6	50 cm Min
4	Softening point, in °C	85.75	Minimum 57 °C
5	Solubility in trichloroethylene, %	99.50	Minimum 97%

Table 6 Comparison of mix designs (experimental design)

Sr. No.	Mix proportion	Mix design prepared in lab
1	Aggregate	100%
2	Cement	2%
3	Water	7%
4	Additive	None
5	Emulsion	12.5%

about mixing time, adequate amount of aggregate, filler, water and residual bitumen content based on the dry weight of aggregates. Mix time given in Table 7 was determined by the value of set time obtained during laboratory testing. Mix

time of the emulsion depends on the colour obtained when mixed with cement slurry and aggregates into a given proportion. The brown emulsion changes to blackish brown colour. Meanwhile, the value of the set time is obtained by

Table 7 Results of mix design applied on site

Sr. No.	Description	Test results obtained	Requirement as per IRC:SP:81:2008
1	Mix time (s), minimum	190	120
2	Consistency (cm), maximum	2.2	3
3	Wet cohesion, within 30 min; (kg cm), minimum	22	12
4	Wet cohesion, within 60 min; (kg cm), minimum	22	20
5	Wet stripping, pass % minimum	99	90
6	Wet track abrasion loss, (one hour soak); g/m ² maximum	178	538

the minimum time required by microsurfacing to reach the initial setting. In short, the initial setting time of microsurfacing is evaluated to ensure the early use of pavement for vehicular movement. The set time of the designed mix should not be more than 2 h (Fig. 1).

2.4 Economic Analysis of Microsurfacing (for 1 km)

Cost of Rigid pavement and Microsurfacing for 1 km—

Rigid Pavement

Life of pavement = 30 yrs

Initial cost = 14.674 Cr. (As per Economic Survey 2018–19).

Maintenance cost

Annual maintenance = 0.5% of initial cost

$$= 0.12 \text{ Cr.}$$

Periodic maintenance = 3% of initial cost and 5% of WB index

$$= 24 * 0.3(1.05)^{15} = 10 \text{ gm}$$

$$= 14.968 \text{ Cr}$$

Periodic maintenance is done after 15 years.

Microsurfacing on Rigid Pavement

Life rigid pavement = 30 years

Microsurfacing reapplication on pavement = 5 years

Rate of microsurfacing = 200/Sq M (As per DSR)

For 4 lane road of 1 km, the cost of microsurfacing is

$$= 200 \times 17,000$$

$$= 3,400,000$$

For work < 5 lac Sq M, the rate of microsurfacing will be ₹150–180 Sq M.

Also for special jobs, rate of microsurfacing is ₹ 250/Sq M.

Input Parameters for Economic Analysis—

The following are the parameters required for the economic analysis.

Analysis Period

Analysis period includes the construction period as well as the benefit period.

Project Cost

Construction cost considered for economic analysis includes land acquisition, resettlement and rehabilitation, environment and utility shifting cost along with civil construction cost.

Pavement Characteristics

Pavement characteristics that are taken into consideration for economic analysis include the length of the pavement, carriageway width, width of paved shoulders, composition of existing pavement, sub-grade CBR, roughness of the existing road (IRI), structural number and cracking, raveling and other pavement distress parameters.

Routine and Periodic Maintenance

Maintenance cost rates considered in Per Sq m, which includes patching, crack sealing, edge repair, overlay, drainage clearance and markings and installation of damage traffic sign boards, etc.

Traffic Volume Data

AADT (No. of vehicles) on the project road includes motorized and non-motorized vehicles. The vehicles are grouped under motorized vehicles passenger vehicles, freight vehicles, and slow moving vehicles.

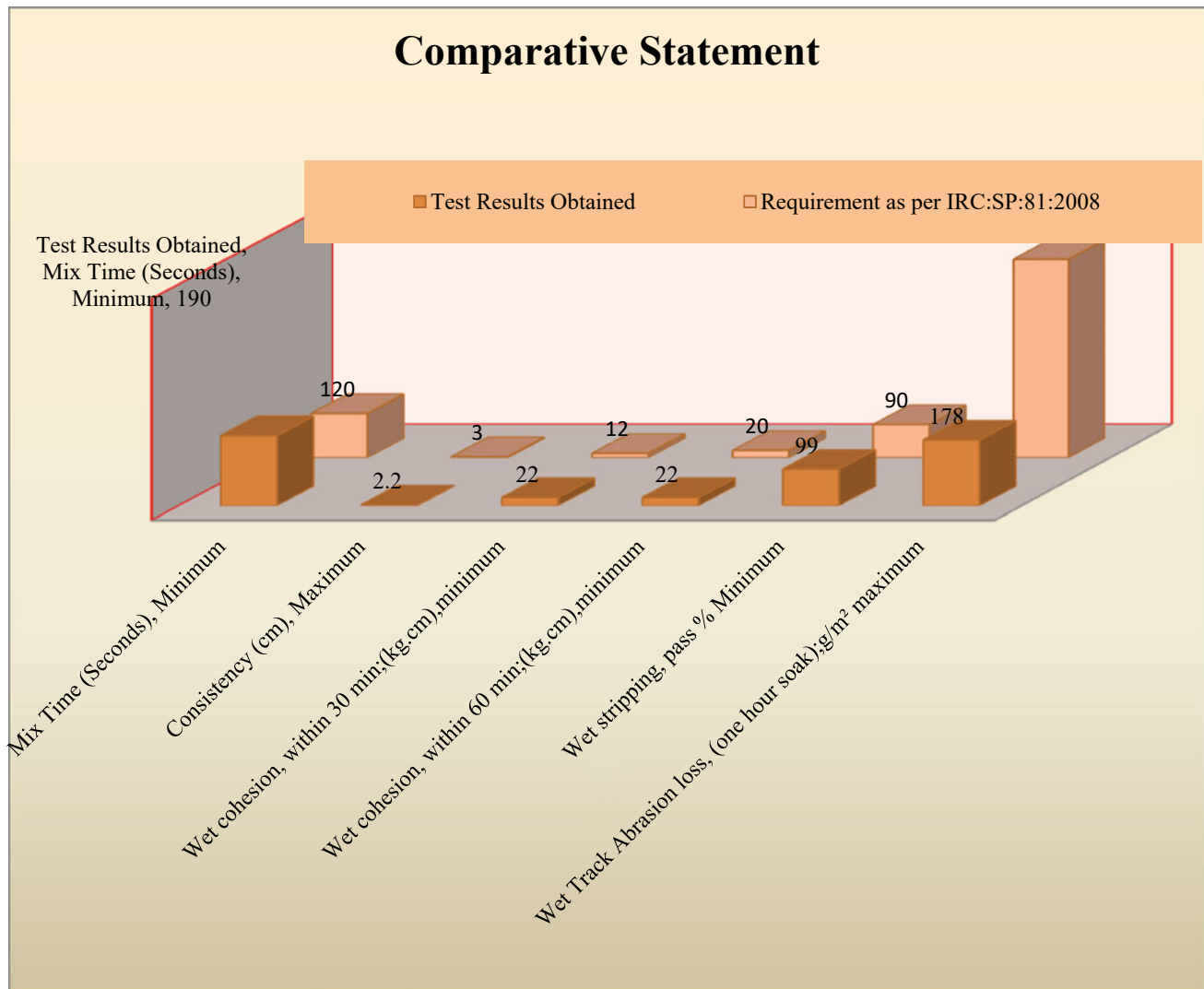


Fig. 1 Comparative statment of mix design obtained on-site

Secondary Data

- Vehicles and tyre prices
- Current fuel price in the project corridor.
Petrol (Rs/Ltr)
Diesel (Rs/Ltr)
Lubricants (Rs/Ltr).

To conduct a traffic volume study, the growth rate of vehicular movement by 9% in terms of PCU/day within the year 2019–2034 is taken into consideration. For the calculation of distance and time-related congestion factor, about 10% of daily traffic is considered. Both these congestion

factors are to be calculated for a rise and fall (RF) value of '10' m/km and roughness (RG) of 3000 mm/Km. for the calculation of traffic, the following data is to be collected.

Sr. No.	Average daily traffic	
1	Car/jeep	1544
2	LCV	800
3	Trucks	605
4	Private bus	400
5	3-axle	250
6	Mav	300

(Traffic is considered as an average of 4 toll locations on NH4)

Sr. No.	Traffic growth rate	
1	Car/jeep	7%
2	LCV	3.5%
3	Trucks	3.25%
4	Private bus	3.00%
5	3-axle	4.0%
8	Mav	4.0%
Sr. No.	PCU factors for various types of vehicle	
1	Car/jeep	1
2	LCV	1.5
3	Trucks	3
4	Private bus	3
5	3-axle	4.5
6	Mav	4.5

(Form IRC: SP: 30-2009, Page NO. 36)

Year	Spread of quantum of investment (in %)
2012–2013	40
2013–2014	30

The separately calculated time and distance-related congestion factors are corrected by using the corrected multiplying factor 0.8. This is to consider the effect of assuming 10 percent of total daily traffic to represent peak hourly traffic for 24 h in the computations of congestion. Total vehicle operating costs are calculated for the above two cases using the economic costs of VOC given in the updated road user cost study conducted by CRR14 and the congestion factors are determined.

3 Discussion

1. A premium quality material should be used for microsurfacing (Ronald & Luis, 2016) for the success of treatment. When microsurfacing technique is carried out in good condition, the average life of microsurfacing lasts for about 7 years (Transportation Research Board, 2010). The performance of microsurfacing is calculated on the basis of roughness, skid resistance, rutting of road.
2. The highest degree of supervision skills are expected during the application of microsurfacing coat on the existing pavement. Meanwhile, agitated and uniform

mixture is poured into the mechanical spreader. Frontal seal should be provided to control the loss of mixture at the road contact point and hinder seal should be provided to ensure the surface texture. Both seals must ensure the proper mixture and free flow of material (Xiao & Xiaoning, 2012).

3. After applying the microsurfacing as a preventive maintenance, the severability of pavement will be increased as the microsurfacing layer is applied on the existing pavement. From the economic analysis, it is proven that microsurfacing is an economically feasible treatment for pavements.

4 Results

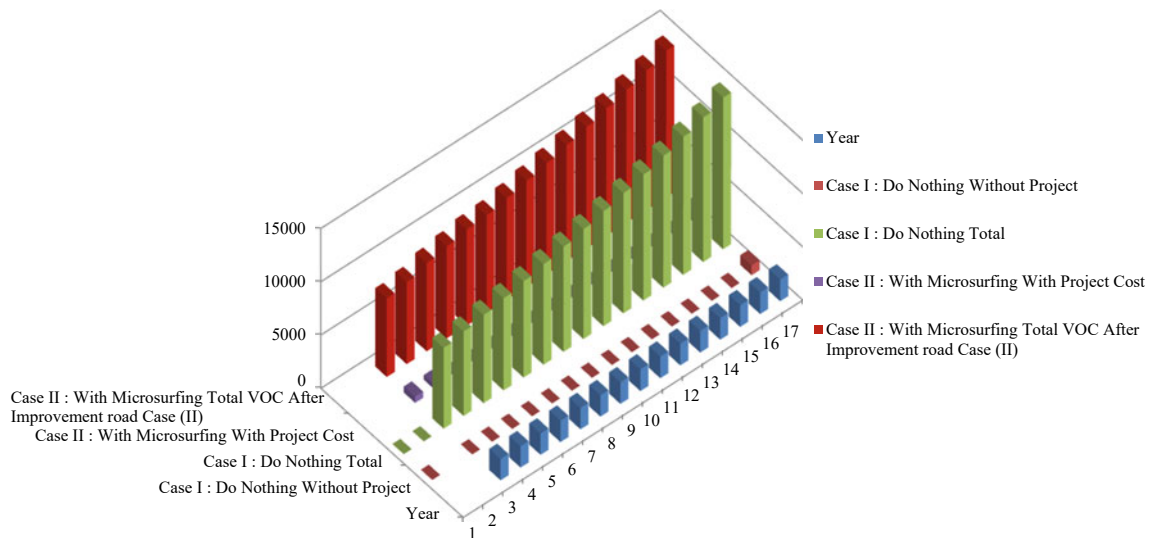
1. As per the IRC:SP:81:2008 (Tentative specifications for slurry seal and microsurfacing), the results calculated for materials are suitable for microsurfacing.
2. Table 8 shows the Economical Internal Rate of Return (EIRR) of the microsurfacing calculated for 1 km.
3. The comparative analysis is carried out for the experimental design and the on-site design. The economic analysis is done for 1 km patch of microsurfacing considering the rate of microsurfacing as per DSR (Fig. 2).

5 Conclusion

Microsurfacing is a pavement preservation and maintenance treatment that can be effectively used to restore the transverse geometry and helps in the improvement of surface texture and driving quality of road. From the analysis, it is clear that the mix design satisfies all the criteria given in IRC: SP: 81: 2008 and ISSA A143. The research findings clear that the average life of microsurfacing is about 6 years. The performance of microsurfacing is measured on the basis of rutting, roughness, and skid resistance of the surface through the field survey, literature, agency of microsurfacing, and various handbooks of microsurfacing. The rate of return for transportation projects in India is desirably about 12%. In the Indian scenario, it is clear that the calculated EIRR of the project is 20.55%, which is higher than 12%. Hence, the investment for the proposed project is economically viable.

Table 8 Economical Internal Rate of Return (EIRR)

Year	Case I: do nothing		Case II: with microsurfacing		Cost stream	Benefit streams	Net benefits
	Without project cost	Total VOC for base case (I)	With project cost	Total VOC after improvement road case (II)			
2020	7.34	7620.88	586.96	7375.18	-579.62	245.70	-333.92
2021	7.34	7949.68	453.58	7692.59	-446.24	257.10	-189.15
2022	7.34	8300.82	13.36	8286.02	-6.02	14.80	8.77
2023	7.34	8666.79	13.36	8641.52	-6.02	25.27	19.25
2024	7.34	9053.93	13.36	9016.47	-6.02	37.46	31.43
2025	7.34	9460.84	13.36	9149.84	-6.02	310.99	304.97
2026	7.34	9886.58	13.36	9560.30	-6.02	326.28	320.26
2027	7.34	10,339.54	13.36	9996.75	-6.02	342.79	336.76
2028	7.34	10,810.32	13.36	10,450.61	-6.02	359.71	353.69
2029	7.34	11,308.66	13.36	10,930.72	-6.02	377.94	371.91
2030	7.34	11,833.59	13.36	11,436.08	-6.02	397.51	391.49
2031	7.34	12,387.36	13.36	11,969.72	-6.02	417.64	411.61
2032	7.34	12,970.45	13.36	12,531.23	-6.02	439.22	433.19
2033	7.34	13,589.34	13.36	13,127.00	-6.02	462.34	456.32
2034	922.40	14,238.84	928.42	13,751.78	-6.02	487.06	481.04
EIRR							20.55%

**Fig. 2** Economical internal rate of return

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Flexural Behaviour of Concrete Beams Embedded with PVC Pipe Sandwiched with Waste Crumbed Rubber

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Abstract

The research paper presented a comprehensive and detailed investigation into the flexural behavior of concrete beams incorporating PVC pipes filled with waste-crumbed rubber. The study aimed to explore the potential of utilizing waste-crumbed rubber as a partial replacement for conventional coarse aggregates in concrete beams, with the addition of PVC pipes as a reinforcement element. To conduct the study, laboratory specimens were prepared using a mix ratio of 1:1.5:3 (M20), and varying proportions of rubber crumbs were incorporated into the concrete mix. The rubber crumbs were carefully placed within PVC encasings, and the concrete beams were subsequently cast. The research team carefully controlled the replacement percentages, which included 1, 3, 5 and 7% of the total volume of coarse aggregate. The primary objective of the investigation was to assess the impact of incorporating waste-crumbed rubber on the flexural strength of the concrete beams. To achieve this, the researchers conducted extensive testing and analysis, focusing on parameters such as compressive strength, flexural strength, and load-deflection behavior of the beams. The results of the study revealed a significant improvement in the flexural behaviour of the concrete beams with the addition of crumbed rubber. As the percentage of rubber content increased up to 5%, the flexural strength of the beams also showed a progressive increase. However,

beyond the 5% threshold, no significant change in flexural strength was observed with further additions of rubber. Specifically, the flexural strengths for conventional beams and PVC-filled beams with rubber were found to be 13.5, 15.3, 16.6, 17.1, and 17.0%, respectively. The findings indicate that incorporating PVC pipes filled with waste-crumbed rubber can effectively enhance the flexural strength of concrete beams. The elastic and resilient nature of rubber particles contributes to the energy absorption capacity of the beams, resulting in improved load-carrying capabilities and resistance to deformation. Additionally, the interlocking of rubber particles with the surrounding matrix material enhances the overall structural integrity of the composite beams. It is evident that there exists an optimal percentage of rubber replacement that provides the maximum benefit in terms of flexural strength enhancement. Beyond this point, further additions of rubber might not yield significant improvements and could potentially lead to practical challenges in workability or density. The study's outcomes underscore the importance of optimizing the rubber content to achieve the desired improvements in concrete beam performance. By selecting the appropriate percentage of rubber replacement, engineers can strike a balance between enhanced flexural strength and other critical mechanical properties. The scope of the study covered a limited range of rubber content percentages, and a more extensive dataset encompassing a wider range of rubber contents would provide a more nuanced understanding of the relationship between rubber filling and beam strength. Moreover, the researchers highlighted the need to explore the long-term durability, environmental impact, and cost-effectiveness of rubber-filled beams. The study presented in the research paper adds valuable insights into the potential of incorporating waste-crumbed rubber in concrete beams, along with PVC pipes as a reinforcement method. The results demonstrate the feasibility of this approach to enhance the flexural strength of concrete

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beams, making them more resilient and durable under cyclic loading. In conclusion, the research showcases the promising possibilities of utilizing waste-crumbed rubber in sustainable construction practices. It emphasizes the importance of carefully optimizing the rubber content to achieve the desired improvements in flexural strength and highlights the need for further research to explore the broader implications of this approach. With continued investigation and refinement, incorporating PVC pipes filled with waste-crumbed rubber could pave the way for more efficient, environmentally friendly, and resilient construction practices.

Keywords

Flexural • Crumb rubber • Encased • Load • Deflection

1 Introduction

Concrete-filled tube (CFT) systems with steel confinement tubes revealed better structural performances in tower buildings, bridges, columns, and pile footings to mitigate gravitational and lateral loads. Concrete-filled steel tube (CFST) and concrete-filled fiberglass-reinforced plastic tube (CFRTP) column systems are the two most popular types of concrete-filled tube (CFT) column systems that have been studied at both the member and system levels. The CFT system has outstanding qualities, including enhanced structural performance, better constructability, and higher project economic feasibility. In the building and construction sectors, cement and aggregate are also necessary components that are always rising in demand to make concrete.

Concrete-filled tube (CFT) systems are innovative structural construction solutions that combine the strength and durability of steel with the compressive capacity of concrete. This composite system consists of a steel tube, acting as the external formwork, encasing a concrete core. The steel tube provides lateral confinement to the concrete, enhancing its load-carrying capacity and ductility. CFT systems are known for their exceptional resilience, making them well-suited for high-rise buildings, bridges, and other structures subjected to significant loads and seismic forces. With their ability to dissipate energy and undergo large deformations without sudden failure, CFT systems offer enhanced safety and reliability in earthquake-prone regions. Moreover, the fire resistance of CFT systems is a notable advantage, as the steel tube shields the concrete core from high temperatures, ensuring structural integrity during fire incidents. Their construction efficiency and reduced material usage make CFT systems an environmentally sustainable choice for modern engineering projects. By utilizing the benefits of

both steel and concrete, these systems optimize the use of materials, reducing the overall environmental impact and contributing to greener and more cost-effective construction practices.

As the field of civil engineering continues to evolve, concrete-filled tube systems stand as a testament to the ingenuity of engineers in developing robust and efficient solutions for the challenges of modern construction. With ongoing research and advancements in design and construction techniques, CFT systems are likely to remain at the forefront of innovative structural engineering, shaping the skylines of cities and ensuring the safety and longevity of vital infrastructure.

Ho et al. (2012) conducted a significant study focusing on the innovative use of waste materials in the construction sector to combat the pressing issue of waste material dumping. Among these materials, waste rubber derived from discarded truck and bicycle tires garnered considerable attention due to its substantial manufacturing volume and the environmental challenges it poses during disposal. Researchers and engineers have explored various applications of waste rubber in construction, such as rubberized asphalt to improve road surfaces, rubberized concrete for enhanced structural elements, erosion control solutions, building insulation, sport surfaces, and rubber mulch for landscaping. Despite the promising benefits, factors like processing costs and environmental impact necessitate further investigation into this environmentally conscious approach (Ho et al., 2012).

In the present study, the coarse aggregate was replaced by crumb rubber in varying proportions. Crumb rubber was obtained by grinding rubber to a size similar to that of coarse aggregate as experimented by Duarte et al. (2016). The PVC tube that is filled with rubber powder is then placed within the beam in such a way that the neutral axis, seismic load-bearing capability, and the dampening effect of the concrete all contact with the midpoint of the PVC tube. The rubberized concrete is subsequently poured into the PVC tube. The PVC tube is then filled with varying amounts of this rubberized concrete. The use of crushed tires as an additive to concrete not only has the potential to end the problem of further exploitation of used tires, but it has also improved the quality of the concrete (Duarte et al., 2016, 2018). Elchalakani et al. (2016) conducted a comprehensive study to explore the impact of rubber powder replacement on the durability and deformability of reinforced concrete used in construction. Their research revealed that incorporating crumb rubber into concrete mixes led to notable improvements in various aspects. Notably, the presence of rubber powder enhanced the material's durability, making it more resistant to degradation over time. Furthermore, the addition of rubber particles contributed to an increased ability of the reinforced concrete to withstand cracking, providing

enhanced structural integrity. Moreover, the rubber's ability to absorb shock waves offered added protection against impact loads, while also dampening acoustic waves, making it a promising option for constructions where vibration and noise control are crucial considerations. The findings from this study highlight the potential benefits of using rubber powder as an environmentally friendly and effective additive in reinforced concrete applications. Further research in this area could provide valuable insights to optimize the utilization of rubber powder in construction for sustainable and resilient infrastructure development. (Elchalakani et al., 2016). The inclusion of rubber powder in concrete-filled steel tubes (CFST) offers a range of additional benefits. Notably, it reduces the material's weight and enhances thermal insulation, making CFST structures lighter and more energy-efficient. Rubber's incorporation also improves the composite's ability to withstand dynamic loads, absorb shock waves, and dampen vibrations, adding resilience to the construction. By pouring concrete into thin-walled rubber tubes, CFST combines the compressive strength of concrete with the energy-dissipating properties of rubber, creating a promising synergy. This innovative approach holds the potential to revolutionize construction practices, paving the way for sustainable and efficient infrastructure solutions. Ongoing research and development will further optimize rubber powder utilization in CFST, ensuring continued progress in construction technology (Atahan & Sevim, 2008; Elchalakani et al., 2018). The recent study conducted by Divahar et al. (2021) delves into the flexural behaviour of concrete beams, focusing on their reinforcement with PVC pipes and waste-crumbed rubber. The researchers observed that the incorporation of PVC pipes had a positive impact on the flexural capacity of the beams. This enhancement was primarily attributed to the improved load-carrying capacity and ductility achieved through the addition of PVC pipes. Furthermore, the inclusion of waste-crumbed rubber in the concrete mix proved beneficial as well. The rubber particles contributed to the beams' increased toughness and energy absorption capacity. Consequently, the beams exhibited enhanced crack resistance and improved durability when subjected to loading and external stresses. This research highlights the potential of utilizing both PVC pipes and waste-crumbed rubber as reinforcement elements in concrete beams. Such findings can significantly influence the design and construction of structures, offering the construction industry more sustainable and resilient solutions. Further exploration of these materials properties and interactions could open up new avenues for optimizing the performance of reinforced concrete elements in various engineering applications (Li et al., 2018). The widespread recognition of incorporating fibres

into concrete mixes stems from its remarkable ability to enhance the material's mechanical properties. By dispersing fibres, such as steel, synthetic polymers, glass, or natural fibres, throughout the concrete matrix, the material's tensile strength is significantly improved, leading to enhanced crack resistance and durability. Fibre-reinforced concrete exhibits increased flexural strength, making it resilient against bending and deflection. It also offers superior energy absorption and impact resistance, ideal for structures subject to dynamic loads and vibrations. Moreover, fibre reinforcement helps control shrinkage cracking, improves dimensional stability, and enhances resistance to high temperatures, freeze-thaw cycles, and spalling. These advantages make fibre-reinforced concrete a compelling choice for robust and reliable construction solutions (Bisht & Ramana, 2019). Hassanli et al. conducted a study on concrete beams reinforced with PVC pipes and waste-crumbed rubber, investigating their flexural performance. The results demonstrated significant enhancements compared to conventional concrete beams. Incorporating PVC pipes increased flexural strength and load-carrying capacity, making the beams more resistant to bending forces. The addition of waste-crumbed rubber acted as a filler, reducing brittleness and improving crack resistance, resulting in greater durability. Notably, the waste rubber also enhanced the beams' ductility, allowing them to deform without fracturing, thereby improving energy absorption and impact resistance. This research sheds light on innovative reinforcement methods to optimize concrete structures, offering potential advancements in construction practices (Hassanli et al., 2017). Hassanli et al. conducted a study aimed at improving the performance of rubber concrete through the application of surface treatment and coating techniques. The researchers explored three coating procedures, which involved using standard cement, blended cement with silica fume, and blended cement combined with sodium silicate to enhance the bonding between rubber and cement. Additionally, two surface treatment methods, namely NaOH and silane coupling Agent, were employed to further enhance the rubber-cement bonding. By utilizing these surface treatment and coating techniques, the modified rubber concrete exhibited improved properties and adhesion, making it a viable material for various applications, including building pavements and structures. This research contributes valuable insights to advance the use of rubber concrete in the construction industry (Guo et al., 2017). Guo et al. conducted an extensive study to explore the potential applications of rubberized polymer concrete (PC). They performed a series of destructive tests, including impact, compression, and splitting tensile tests, alongside non-destructive techniques such as ultrasonic testing, digital signal processing, electrical conductivity analysis, and microstructure analysis. The results indicated that the incorporation of rubber in the polymer concrete decreased its workability while increasing porosity and air content within the mixture. However, it also

resulted in reduced cost and density of the material, along with enhanced ductility, making it more resistant to cracking and deformation. Based on their analysis, the researchers suggested that rubberized PC hold promise for applications in repair and rehabilitation projects. Its improved ductility and other advantageous properties make it a suitable candidate for reinforcing and strengthening existing structures, potentially extending their service life. By uncovering the performance characteristics of rubberized PC through a combination of destructive and non-destructive tests, this study provides valuable insights for engineers and researchers interested in developing innovative and sustainable solutions for construction and infrastructure projects (Jafari & Toufigh, 2017).

Girskas et al. conducted research on the use of waste tyre crumb rubber in concrete, specifically investigating two fractions of the rubber: 2/4 and 4/6. The rubber crumb was incorporated into concrete mixes to replace sand at varying proportions, ranging from 5 to 20%. The testing focused on assessing the concrete's compressive strength, water absorption, and ultrasonic pulse velocity, with the computation of structural performance indices for the concrete samples. The results of the testing indicated a significant decrease in compressive strength, ranging from 68 to 61.3%, when using crumb rubber in place of fine aggregate (sand) in the concrete mixtures. However, the research also revealed that incorporating up to 20% crumb rubber as a replacement for fine aggregate could lead to an anticipated enhancement in the concrete's freeze-thaw resistance (Girskas, 2017). The study focused on evaluating the flexural and splitting tensile strengths of concrete containing PVC pipes filled with rubber powder, as well as the water resistance of crumb rubber concrete when exposed to dicing chemicals. The researchers compared the results of concrete mixes that included rubber powder as an addition, referred to as crumb rubber concrete (CRC), with the results of concrete mixes containing PVC pipes but no rubber powder. The investigation aimed to assess how the incorporation of rubber powder impacted the mechanical properties, such as flexural and splitting tensile strengths, of the concrete. Additionally, the study examined the resistance of CRC to water when subjected to dicing chemicals, likely to simulate environmental conditions or potential chemical exposures in practical applications. By contrasting the performance of CRC with conventional concrete containing PVC pipes, the researchers sought to identify the potential benefits and drawbacks of using rubber powder as an additive in concrete mixes. Such research findings can provide valuable insights for engineers and construction professionals considering the use of rubber powder to enhance the properties of concrete materials in various applications (Alsaif et al., 2018). Elghazouli et al. conducted an experimental study to investigate the cyclic behaviour of reinforced concrete components that

incorporated a significant amount of recycled rubber particles in place of conventional mineral aggregates. The researchers tested thirteen large circular cross-section elements, some with external confinement and others without, subjecting them to various axial loads with different rubber content ratios. The results of the study demonstrated that using rubberized reinforced concrete members, as opposed to conventional reinforced concrete, offers a favourable balance between bending capacity and ductility, especially when exposed to moderate levels of axial stresses. This suggests that the incorporation of rubber particles can enhance the overall performance of the concrete components, making them more resilient and flexible under cyclic loading. The discussions in the research also highlight methods that can be employed to determine the essential design parameters for rubberized reinforced concrete members and underscore the practical implications of the findings. The research's outcomes have significant implications for the practical utilization of rubberized reinforced concrete in various engineering applications, providing insights into its potential benefits and design considerations (Elghazouli et al., 2018). Mendis conducted a study focusing on the flexural behaviour of reinforced beams made from crumbed rubber concrete (CRC) mixtures with comparable compressive strengths. For this research, twelve beams with similar reinforcement configurations and support conditions were constructed using six different CRC mixtures. These beams were subjected to a two-point bending stress test, measuring their flexural responses until failure occurred. Concurrently, tests were performed on the relevant material properties of the constituent materials used in the CRC mixtures. The experimental results were used to compare the beam responses of the CRC mixtures with comparable strengths. Additionally, the study examined whether the design rules used for conventional concrete could be applied to predict the flexural capacities of CRC beams. The research aimed to provide insights into the flexural performance of CRC in comparison to conventional concrete, exploring its potential as a viable alternative in construction applications. By examining the behaviour of CRC beams under bending stress and comparing them to conventional concrete, this study contributes valuable information for engineers and designers seeking innovative and sustainable solutions for reinforced concrete structures (Mendis et al., 2017).

The combination of PVC pipes and waste-crumbed rubber in construction shows promise for sustainable practices, offering the benefits of reduced material consumption and a positive impact on the environment. Nevertheless, to fully understand the potential and practicality of this approach, additional research is essential. Further investigation should focus on assessing the long-term performance and structural behaviour of composite beams made with PVC pipes and crumbed rubber under various loading conditions and environmental exposures.

By subjecting these composite beams to prolonged testing, engineers can gain insights into their durability, resistance to degradation, and ability to withstand different types of stresses over time. Understanding the behaviour of these materials in different environmental conditions, such as exposure to temperature fluctuations, moisture, and chemical agents, is crucial for ensuring their suitability and reliability in real-world applications. Moreover, exploring the economic feasibility and potential challenges in large-scale implementation will be essential for determining the viability of adopting this approach in mainstream construction practices. By addressing these research gaps, we can harness the full potential of PVC pipes and waste-crumbed rubber in construction, advancing sustainable building techniques and contributing to more environmentally conscious infrastructure development.

2 Experimental Investigation

2.1 Materials and Method

In this thorough investigation, the researchers used 53-grade OPC (Ordinary Portland Cement) with a specific gravity of 3.15. The cement's properties were studied in detail, and the preliminary findings indicated an initial setting time of 131 min and a final setting time of 173 min. The initial setting time refers to the time elapsed from the moment water is added to the cement until it begins to lose its plasticity and starts to set. In this case, it took approximately 131 min for the cement to begin its setting process. On the other hand, the final setting time signifies the time required for the cement to fully set and attain its hardened state. The final setting time observed in this investigation was around 173 min. Understanding these setting times is essential in construction, as it allows engineers and workers to plan the timing and sequence of concrete placement, consolidation, and finishing operations effectively. These results provide valuable information for the practical use of the specific cement grade in various construction applications. In the study, the fine aggregates (FA) used were crushed sand, carefully selected to meet the grading zone II requirements specified in IS 4031 (1998) standards. The specific gravity of the crushed sand was determined to be 2.66, and it easily passed through a sieve with a 4.75 mm aperture, indicating its suitability for the desired application. As for the coarse aggregates (CA), uniformly sized 20 mm stones were meticulously chosen, ensuring they complied with the strict standards set by IS 383-1970. The specific gravity of these coarse aggregates was measured at 2.70, indicating their appropriate density and quality for use in the concrete mix. The precise selection and assessment of both fine and coarse aggregates are essential for producing high-quality concrete

with the desired properties. The compliance with relevant standards ensures the consistency and reliability of the construction material, contributing to the durability and performance of the concrete in various engineering applications.

Furthermore, this investigation incorporated crumb rubber, which underwent a rigorous grading and filtering process to align its size with that of the coarse aggregates (20 mm). The crumb rubber exhibited a specific gravity value of 1.15, adding an innovative dimension to the study. It is essential to emphasize that the grading of the coarse aggregates was meticulously verified, confirming the use of single-size aggregates to ensure the integrity of the experimentation. The tubes utilized for the study were thoughtfully crafted from polyvinyl chloride (PVC) and possessed a circular cross-section, boasting an impressive diameter of 50 mm and a substantial length of 700 mm. To ensure the accuracy and reliability of the findings, only standard potable water was deemed suitable for preparing the concrete employed in casting the specimens. This meticulous attention to detail and adherence to standards underscore the robustness of this investigation.

2.2 Mix Proportion

M20 grade of concrete was designed as per IS 456:2000 and used to prepare the test samples. In accordance with the guidelines outlined in IS 456:2000, a concrete mix of M20 grade was meticulously designed and employed to fabricate the test specimens. M20 grade signifies that the concrete possesses a compressive strength of 20 mega Pascal (MPa) after 28 days of curing. The concrete mix was meticulously proportioned with an appropriate blend of cement, fine aggregates, coarse aggregates, and water, ensuring that it meets the specific requirements of the M20 grade. IS 456:2000 is the code of practice established by the Bureau of Indian Standards (BIS) for the design and construction of reinforced concrete structures, and following this standard ensured that the concrete's composition and characteristics were well-suited for the intended application and adhered to industry best practices. The use of M20 grade concrete in preparing the test samples ensures that the structures will exhibit the desired strength and durability properties, instilling confidence in the reliability and quality of the ensuing test results. The properties of Cement and Aggregates are shown in Table 1.

2.3 Preparation of Specimen

The study aimed to investigate the properties and behaviour of concrete specimens, and as part of the experimental

Table 1 Properties of cement and aggregates

Description	Value
Grade of concrete	M20
Grade of cement used	OPC—53 Grade
Specific gravity of cement	3.15
Specific gravity of fine aggregate	2.66
Specific gravity of coarse aggregate	2.68

design, three layers of concrete were cast with identical thicknesses. To ensure uniformity and consistency during the casting process, a specific number of tamping actions were performed on each layer. As depicted in Fig. 1, the concrete was compacted 35 times during the casting process to promote better bonding between the layers and to minimize any potential voids or air pockets within the specimens.

To prepare the specimens, the concrete mixture is placed into a mould, taking care to maintain a consistent depth across the three layers. Between each layer, the concrete was subjected to careful tamping and compaction to achieve an even distribution of the material and to reduce any variations within the cross-section of the specimens. This method ensured that the specimens had a uniform composition and density throughout, which would be essential for accurate and reliable test results.

After casting the specimens, they underwent a curing period of 28 days. This curing process allowed the concrete to gain strength and develop its full potential as the hydration reactions took place. After the curing period, the specimens were dried before being used in the subsequent testing phase. This drying process ensured that the moisture content of the concrete was standardized across all specimens, eliminating any potential confounding factors that could influence the test results. To carry out the testing, it was

crucial to prepare the specimens and testing apparatus properly. It was made sure that the surfaces of the specimens were thoroughly cleaned from any loose sand particles or debris that might have accumulated during the casting and curing stages. Additionally, the rollers and bearings used for applying the load during testing were also cleaned to minimize friction and ensure accurate and consistent results.

During the testing phase, circular steel rollers were employed to provide support for the specimens. These rollers had a specific cross-section with a diameter of 38 mm, ensuring a standardized load application area. This choice of roller design was likely made to create a well-defined and consistent contact point between the load and the specimens. Furthermore, using steel for the rollers enhanced their durability and stability, thus reducing any potential deformation or variability during the testing process. In conclusion, the experiment was conducted meticulously, considering every detail from the casting of the concrete specimens with uniform layers and tamping actions, to the curing and drying process, and finally to the cleaning and preparation of the testing apparatus. Such thoroughness in experimental design is essential to obtain reliable data and draw meaningful conclusions regarding the behaviour and characteristics of the concrete specimens under investigation.

Three rollers which can rotate on their longitudinal axis and one fixed roller were used, where the roller is of length 10 mm more than the width of the test specimen. There were four rollers employed, three of which could rotate around their own axes. The span, or distance between the outer and inner rollers, was '3d', and the latter was d. The system was structured so that the inner rollers were evenly spaced apart compared to the outer rollers. The test object was then perfectly centred inside the apparatus, with its longitudinal axis oriented such that it was transverse to the rollers. The

**Fig. 1** PVC pipe encased inside concrete beam and casting of the specimen

rate of the loading for the 150 mm cube specimens was 4 kN/min, and for the 100 mm specimens 1.80 kN/min.

2.4 Test for Flexural Strength Test

In this research work, the specimens are tested with a Universal Testing Machine (UTM) with a load capacity of 1000 kN. The experimental setup encompassed a meticulously calibrated one-point bending configuration, renowned for its precision in appraising the flexural performance of materials and structural elements. To ensure precise quantification of vertical deflection, a high-precision dial gauge was judiciously affixed at the mid-span of each beam, facilitating real-time monitoring of deflection responses throughout the entire experimental duration.

With utmost diligence, a meticulously crafted experimental design was implemented, subjecting diverse beam specimens to rigorous testing regimens. A comprehensive tabular representation was methodically compiled, synthesizing pertinent findings and observations from multiple tests, thereby imparting a holistic overview of the beams' dynamic response under diverse loading conditions. Each test iteration underwent rigorous scrutiny from the inception of initial loading to the eventual fracture of the beams, elucidating their mechanical integrity and failure behaviour in intricate detail. A pivotal facet of this study encompassed a systematic examination of crack initiation and propagation vis-à-vis the escalating applied load. Scrutinizing the genesis of primary fissures, and closely monitoring their evolution and dissemination throughout the loading process furnished valuable insights into fracture mechanisms, thus informing a meticulous analysis of failure modes.

The loading protocol, thoughtfully engineered to ensure methodical execution, guaranteed a uniform and incrementally progressive force application. Ongoing deflection measurements were meticulously recorded, thereby facilitating the construction of comprehensive load versus deflection curves. Rigorous adherence to data acquisition protocols ensured the timely capture of critical events, thus circumventing any data lacunae. Load application persisted until the threshold of failure, wherein beams were poised on the precipice of complete structural collapse. This meticulous approach assured an incisive evaluation of their ultimate load-carrying capacities and resilience under duress, rendering an exhaustive understanding of their structural viability. Throughout the testing campaign, stringent safety measures were scrupulously observed to safeguard personnel and UTM integrity. Analytical precision was upheld in the meticulous parsing of data, culminating in graphical load versus deflection representations, efficaciously encapsulating beams' responsive behaviour under applied loads, thus offering pivotal insights for discerning further analyses. In



Fig. 2 Flexural strength test

summation, this scholarly inquiry epitomized an exhaustive exploration of beam behaviour by leveraging cutting-edge Universal Testing Machine technology. The seamless integration of precise data collection, methodical analysis, and advanced equipment enabled a comprehensive appraisal of mechanical attributes, load-bearing capacities, and failure mechanisms. The erudition gleaned from this study holds considerable significance in engineering practice, endowing profound implications for the design and construction of diverse structural configurations. The flexural strength test is shown in Fig. 2.

3 Discussions on Test Results

3.1 Compressive and Flexural Strength

The potential strength of the concrete specimens is assessed by the compressive and flexural strength under the considered conditions. Compression, tension and flexural strength tests were performed as per the standard procedures and the observed reading were evaluated to understand the characteristics of the materials and the system. Various percentages of crumbled rubber such as 0, 1, 3, 5 and 7 percentages with respect to the weight of aggregate are added to the concrete mix and the specimens are designated appropriately (Aravind Raj et al., 2020; Sangeetha et al., 2019).

Table 2 presents the influence of crumbled rubber content on the mechanical properties, specifically flexural and compressive strength, of beams. This research is of

particular interest due to the growing interest in sustainable construction practices and the recycling of waste materials. The table showcases the results for different percentages of crumbled rubber incorporated into the beams, allowing for an insightful comparison against conventional beams without any rubber filling.

In terms of flexural strength, the data demonstrates a consistent improvement as the crumbled rubber content increases. Conventional beams show a flexural strength of 13.7 MPa, while the beams filled with 1% crumbled rubber exhibit a noticeable increase to 15.3 MPa, representing a relative enhancement of approximately 11.7%. As the rubber content further rises to 3, 5, and 7%, the flexural strength continues to increase, reaching values of 16.6, 17.1, and 17.0 MPa, respectively. These values indicate a substantial improvement in flexural strength compared to conventional beams, with relative enhancements of about 21.9, 24.1, and 23.4%, respectively, at each corresponding rubber percentage. The influence of crumbled rubber on compressive strength follows a similar pattern. Conventional beams demonstrate a compressive strength of 20 MPa. Upon adding 1% crumbled rubber, the compressive strength rises to 22 MPa, representing a relative increase of 10%. As the rubber content increases to 3%, the compressive strength jumps to 27 MPa, exhibiting a remarkable improvement of 35%. Further incorporation of crumbled rubber at 5 and 7% maintains the compressive strength at 30 MPa, providing a consistent 50% enhancement compared to conventional beams.

The increasing flexural and compressive strength observed with higher crumbled rubber content in the composite beams can be attributed to the beneficial properties of rubber particles. The elastic and resilient nature of rubber contributes to enhanced energy absorption capacity, leading to improved load-carrying capabilities and resistance to deformation in the beams. Moreover, the interlocking of rubber particles with the surrounding matrix material enhances the overall structural integrity of the composite beams.

While the data presented in the table is compelling, it is important to acknowledge the need for further investigation.

The current tabulation covers specific percentages of crumbled rubber, and a more extensive dataset encompassing a wider range of rubber contents would provide a more nuanced understanding of the relationship between rubber filling and beam strength.

Additionally, exploring the long-term durability, environmental impact, and cost-effectiveness of rubber-filled beams would be valuable for assessing the feasibility and sustainability of this innovative construction approach. Such comprehensive research will contribute to advancing knowledge in the field of sustainable construction materials and practices, providing valuable insights for engineers and researchers seeking to develop eco-friendly and resilient structures.

Based on the test results, it was observed that replacing up to 5% of the conventional aggregates with crumb rubber resulted in good compressive and flexural strength, as shown in Figs. 3 and 4. These figures likely depict the trends of compressive and flexural strengths at different replacement percentages of crumb rubber in the concrete mix. The findings indicate that a small percentage of crumb rubber inclusion can positively impact the mechanical properties of the concrete, leading to satisfactory compressive and flexural strengths. This suggests that the addition of crumb rubber as a partial replacement for conventional aggregates is a promising approach for enhancing the concrete's performance without compromising its overall strength.

It is important to note that the optimal replacement percentage may vary depending on the specific application and desired concrete properties. Further research and experimentation may be needed to determine the most suitable replacement level for different engineering scenarios, ensuring a balance between performance and sustainability in concrete construction.

3.2 Load Versus Deflection

The load–deflection relationship in a structural system exhibits a linear trend until a specific threshold is attained. This behaviour was investigated through a series of

Table 2 Flexural and compressive strength of crumbled rubber at different percentage

Crumbled rubber percentage	Flexural strength		Compressive strength	
	Conventional beam	Crumbled rubber filled	Conventional beam	Crumbled rubber filled
0	13.7	–	20	–
1	–	15.3	–	22
3	–	16.6	–	27
5	–	17.1	–	30
7	–	17.0	–	30

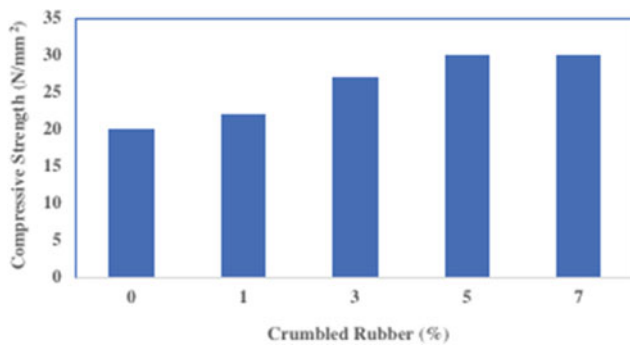


Fig. 3 Compressive strength versus crumbled rubber

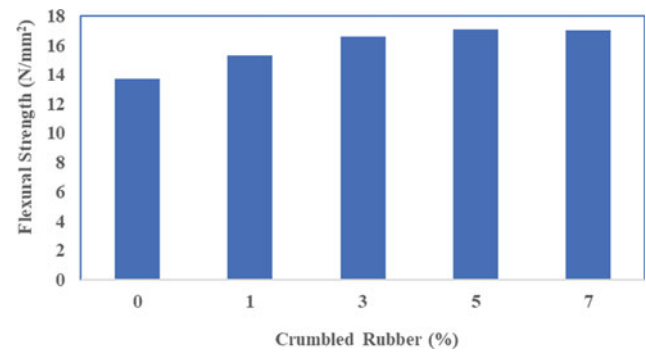


Fig. 4 Flexural strength versus crumbled rubber

experiments, and the findings are presented in Table 3. The table showcases load values and their corresponding deflections for various percentages of rubber additions to the structural material. The collected data illuminates a clear direct proportionality between the applied load and the resulting deflection, providing strong evidence for a linear relationship. This linear behaviour signifies that as the load increases, the deflection also increases proportionally within the observed range. However, it is important to note that beyond a certain threshold, the linear trend might deviate, possibly due to the onset of non-linear deformations or failure mechanisms in the structural system. This study's results have significant implications for structural design, as understanding the load–deflection relationship is critical for predicting the performance and safety of the system under different loading conditions.

Table 3 represents a set of data points showcasing the relationship between the percentage of crumbled rubber and the maximum load applied in kilonewtons (kN). It appears to be a study or experiment focusing on the impact of varying amounts of crumbled rubber on the load-bearing capacity of a particular material or structure.

The data shows five data points, where each row represents a different percentage of crumbled rubber mixed with a specific material or composite, and the corresponding maximum load that the material can withstand before failure. Here is a description of the tabulation:

Table 3 Load attained for various percentages of crumbled rubber

Crumbled rubber (%)	Maximum load (KN)
0	20
1	22.8
3	24.3
5	32
7	31

1. At 0% crumbled rubber content, the material could sustain a maximum load of 20 kilonewtons (KN). This data point likely serves as a baseline or reference for comparison.
2. When the crumbled rubber content was increased to 1%, the material's maximum load increased to 22.8 kilonewtons (KN). This suggests that the addition of even a small percentage of crumbled rubber has a positive effect on the material's load-bearing capacity.
3. With 3% crumbled rubber content, the material's maximum load further increased to 24.3 kilonewtons (KN). This demonstrates a trend of incremental improvement in load resistance as the percentage of crumbled rubber is raised.
4. At 5% crumbled rubber content, there was a significant jump in the material's maximum load to 32 kilonewtons (KN). This indicates a notable enhancement in the material's strength and ability to withstand heavier loads.
5. However, at 7% crumbled rubber content, there seems to be a slight decrease in the material's maximum load, which dropped to 31 kilonewtons (KN). This anomaly could be a result of various factors, such as the specific properties of the crumbled rubber used or the nature of the material and its interactions with higher rubber concentrations.

The data from the study indicates that incorporating crumbled rubber into the material mix generally results in an improvement in the load-bearing capabilities of the material, at least up to a certain threshold or percentage of rubber content. This enhancement can be attributed to the beneficial properties of rubber particles, such as their elastic and resilient nature, which contribute to improved energy absorption and structural integrity.

However, as with any material modification, there might be a point of diminishing returns or potential complications to consider. Beyond a certain percentage of crumbled rubber, there could be challenges related to workability, density, or

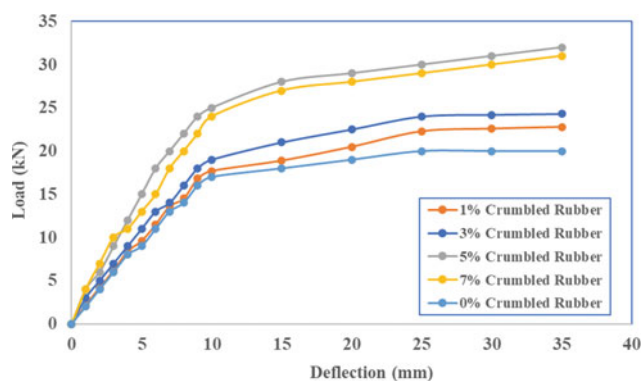


Fig. 5 Load-deflection curve for varying percentages of crumbed rubber

other mechanical properties that need to be carefully evaluated. To draw conclusive insights and optimize the material's composition for specific applications, further in-depth analysis and experimentation are required. It would be essential to explore a wider range of rubber content levels and assess how different percentages affect the material's overall performance, durability, and long-term behaviour.

Moreover, considering factors like environmental impact, cost-effectiveness, and sustainability is crucial when implementing crumbed rubber in construction materials. By conducting comprehensive research and continuously refining the mix design, engineers can determine the ideal balance of crumbed rubber to achieve both enhanced load-bearing capabilities and sustainable construction practices. Load-deflection Curve for varying percentages of crumbed rubber is shown in Fig. 5.

4 Conclusions

The experimental examination of hollow core reinforced concrete (RC) beams with PVC pipes filled with rubber powder yielded significant findings. These beams demonstrated superior flexural behavior compared to traditional RC beams. Notably, at a rubber content of 5%, the compressive strength of these beams reached an impressive 30 N/mm², showing a remarkable 50% improvement over traditional concrete.

Similarly, at the same 5% rubber concentration, the flexural strength of the beams reached 17.1 N/mm², representing a notable 24.8% improvement over traditional RC beams. Furthermore, the study revealed that the maximum load capacity of the beams with 5% rubber content was 60% higher than that of ordinary beams without rubber. These findings highlight the positive impact of incorporating rubber powder into the concrete mix with PVC pipes. The addition of rubber particles appears to enhance the compressive and flexural strengths of the beams significantly,

contributing to their superior load-carrying capabilities. These results open up promising possibilities for using such composite beams in various construction applications, potentially leading to more efficient and sustainable building practices. The inclusion of hollow PVC pipes in the low-stress area of the reinforced concrete beams is responsible for the increased strength. Despite the absence of concrete in the hollow core, this arrangement increases the overall strength of the beams. To achieve optimum performance, the hollow core is sized to sit 160 mm below the neutral axis from the top. Surprisingly, the inclusion of hollow pipes doesn't necessitate any extra work or building time. The amount of concrete that is replaced in the beams determines the cost and weight reduction. The effectiveness of the concrete savings increases with the length and depth of the beam.

This suggests that hollow reinforced concrete beams have the potential to optimize weight and reduce costs in a variety of construction projects. Additionally, the use of hollow reinforced concrete beams is consistent with environmentally friendly building techniques because they reduce the amount of concrete used and the amount of carbon dioxide released during cement manufacture. This makes a bigger contribution to ecologically friendly and sustainable construction methods. These results demonstrate the potential of hollow core RC beams with PVC pipes filled with rubber powder for enhancing structural performance, lowering material consumption, and boosting green building techniques. Additional advantages and uses for these novel beams may be discovered with more investigation and study in this field.

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Strength and Micro-structural Investigation on Geopolymer Concrete Developing with Reuse of Demolition Waste

E. Madhumithra and S. Kanchidurai

Abstract

This paper considers the depletion of mineral resources from the earth and global warming, so recycling construction and demolition waste (CDW) to develop geopolymer concrete (GPC) works is carried out. In this attempt, 80% of washed brick (BW) and concrete (CW) waste is reused to prepare GPC. Firstly, the X-ray fluorescence (XRF) analysis summarises the chemical composition in BW and CW. The alkaline activation 12 molarity sodium hydroxide and Na₂SiO₃ with an activator ratio of 1:1.5 was used to prepare concrete specimens. From CDW, the BW 0–40% was replaced to prepare GPC, and the CW 0–60% was replaced. The combination of BW and CW of up to 80% is used to prepare GPC. The compressive strength test, mode-I fracture toughness test and impact resistance test were done to analyse the GPC strength. Based on trial mix results, the optimum replacement percentage was 30% for washed BW and 50% for washed CW. The SEM analysis examines the internal bonding of the particles in GPC.

Keywords

Demolition waste • Recycled material • XRF • Concrete • SEM • Sustainability • Circular economy

1 Introduction

Nowadays, there are large-scale changes in human lifestyle, climate, transportation and technology. Because of the rapid development of buildings and infrastructures, the existing

are demolished or renovated. Due to this, the vast CDW are landfilled or facing difficulties to dispose of. At the same time, we need more materials for the construction. Hence, recycling CDW is the most feasible idea for a clean environment. Shoukat Alim Khan investigated GPC with the replacement of CDW, the optimum percentage of the waste is replaced for GPC from the roof tile 35% and hollow brick 34%, the reuse process mainly protects the environment from enfeeblement of natural resources (Khan et al., 2022). Zheng et al. calculated that certain large nations produce around 10 billion metric tonnes of CDW waste annually. Due to its extensive urbanization and urban renewal programmes, China makes up about 3 billion metric tonnes of this total (Zheng et al., 2017). Yunxin Xue checked the suitability of the washed recycled sand from CDW for construction and found that the fine recycled sand can perfectly replace the quarry dust sand (Xue et al., 2022). Oluwarotim and Joshua tried to get high-strength concrete from recycled brick and calcined clay. The brick particles were crushed and replaced by 0–50% for fine aggregates. Also, the calcinated clay was replaced by up to 10% to cast concrete specimens; the optimum dosage was suggested at 10% for brick and calcinated clay (Olofinnade & Ogara, 2021). Kirubajiny examined the geopolymer foam concrete with brick waste, and the added alkali improved mechanical properties. Also, the compressive strength increased by 2.45 times more than the standard foam concrete (Pasupathy et al., 2021). The evolution of rheology properties of brick waste, mortar brick waste and dust powder from construction demolition waste is significant to recycling. The CDW properties analysis separating the wastes is highly related to the concrete strength, especially the SiO₂, Al₂O₃, CaO, Fe₂O₃ and alkali properties (Duan et al., 2020). Furthermore, the alkali-activated process is a valuable and good alternative to cement. Since executing the polymerization process, the CDW, red clay brick and other wastes can be converted into concrete (Robayo et al., 2016).

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Concerning CDW, separation is a time-consuming process, but separating brick waste as a fine aggregate of 1–2 mm and concrete debris as a coarse aggregate of 10–20 mm may be an easy process, and the same is considered in this research work. The ceramic tile waste of up to 40% from CDW is also a good substitution for cement (Li et al., 2020). Xinpeng et al. presented the development of ultra-high-performance concrete from CDW, a maximum of 50% of materials were replaced for cement, and 19% were replaced for a fine aggregate (Wang et al., 2019). In the famous research, the structural member, especially the flexural member also cast with the replacement of CDW. All tested specimens with CDW show higher strength than the control specimen, and from the failure of the beam, the model shows that the average crack width was minimum (Aldemir et al., 2022). From the CDW, the concrete can be effectively reused to make ultra-high-performance concrete. The concrete waste converts into powder form, then the concrete powder is replaced by up to 30% to develop the high-performance GPC, and it can achieve up to 128 MPa compressive strength (He et al., 2022).

Similarly, Fatih et al. investigated recycled CDW aggregate such as concrete pipes, paver blocks and kerbs. The research has given promising results for recycling waste materials, and the results show there is a considerable increment in strength. Also, adding fine particles like fly ash, GGBS and silica fume may improve the solidness of the GPC (Arenas et al., 2017; Ozalp et al., 2016). The 100% reuse of CDW is easily achieved to make concrete and pavers blocks (Sabai et al., 2013). Processing like washing and chemical treatment of CDW is vital to recycling.

Figure 1 shows that the 30-year-old college building in the SASTRA Deemed to be a university was demolished. The construction solid waste is almost 200 tonnes produced. Maximum destruction is used for landfilling, and a small quantity is used for this research. The reinforcing steel is separated from concrete and sold to a steel plant for recycling. Therefore, the vast amount of waste that must be recycled by developing concrete is perfect for the environment and circular economy. Hence, the main objective of this study is to convert the CDW to fine or coarse aggregate.

2 Materials and Methods

2.1 CDW Materials

The CDW was collected from 30-year-old demolished building. From CDW, the BW and CW were washed and dried at the normal temperature for two days as shown in Fig. 2. The washed BW particle which is passed in 2.36 mm and retained in a 1.18 mm sieve was taken to prepare the GPC concrete specimen. Also, the CW size of 10–20 mm



Fig. 1 CDW from 30 years old university building

was taken to cast the specimen. XRF (X-ray fluorescent) analysis was used to understand the micro characteristics of BW and CW. The chemical composition of the CDW materials is listed in Table 1.

2.2 Ground Granulated Blast-Furnace Slag (GGBS)

Usually, GGBS will be the perfect partial replacement for cement. The particle size of GGBS was measured as 13.4 μm . Calcium oxide, silicon dioxide and aluminum oxide are the primary compositions, containing almost 45, 32 and 14%, respectively. GGBS by-product from steel manufacturing is shown in Fig. 3.

2.3 Alkali Activators

In this experiment, alkaline activator solutions included sodium hydroxide in pellet form and Na_2SiO_3 . Na_2SiO_3 comprising NaOH upgraded the geo-polymerization reaction. In geo-polymer concrete alkaline activator was prepared by mole concentration for NaOH (480 g pellets) of 12 M. Sodium hydroxide pellets were dissolved in water to create a one-litre solution, while the sodium hydroxide & sodium silicate (Na_2SiO_3) solutions were prepared. Both alkaline NaOH and Na_2SiO_3 were mixed in a ratio of 1:1.5 for all three concrete combinations. The GPC preparation is shown in Fig. 4.

2.4 GPC Mix Ratio and Specimen Preparation

Geopolymer concrete was prepared by mixing GGBS with normal river sand with a specific gravity of 2.65. The alkaline activation used 12 M NaOH and Na_2SiO_3 at an

Fig. 2 Demolished BW and CW processed materials



Table 1 Chemical composition of BW and CW

Element	SiO ₂	CaO	Al ₂ O ₃	Na ₂ O	MgO	SO ₃	K ₂ O	TiO ₂	Fe ₂ O ₃
BW in %	56.4	15.6	10.3	9.5	4.4	1.2	1.0	0.9	0.4
CW in %	46.1	20.7	15.7	9.5	4.2	1.1	0.9	0.9	0.4



Fig. 3 GGBS by-product from steel manufacturing

activator ratio of 1:1.5 in the concrete mix. The concrete mix was prepared by mixing the GGBS with recycled aggregate at ratios of 20–60% with a difference of 10%, along with a superplasticizer of 1% used in concrete concerning the weight of GGBS. There were 118 numbers of specimens cast. At the same time, alkali activators were mixed with the concrete paste, finally obtaining the optimum mixed proportions shown in Table 2.

2.5 Compressive Strength Test

The compressive strength test was performed with a compression testing machine with 3000kN capacity. The 100 × 100 × 100 mm size specimens were cast with natural materials as control specimens from CDW. Specifically, BW replacement alone made with 10, 20, 30 and 40%. And, from CDW, specifically CW replacement alone made with 10, 20, 30, 40, 50 and 60%, and the best combination of BW and CW replacement were cast. After casting, all the specimen was air-cured for up to 28 days. Totally 84 specimens were cast and tested. The seven days and 28 days compressive strength were tested. The speed of the testing was kept at 100 kN per minute. Figure 5 shows the experimental setup of the compressive strength test. The natural aggregate was used for the control specimen with a 12 M geo polymer mix as used for all other mixes.

2.6 Opening Mode Fracture Toughness Test

The Mode-I fracture toughness test was performed with a universal testing machine with 1000 kN capacity. The speed of the testing was maintained at 10 kN per minute. 12 Edge-Notched Disc Bend (ENDB) specimens were cast. The experiment was designed as the best results obtained

Fig. 4 Polymerization process**Table 2** GPC mix characteristics in kg/m³ for alkali activator with 12 M

Mix	GGBS	CA*	Concrete waste	FA*	Brick waste	Superplasticizer in percent
Control	490	1160	—	580	—	1
Optimum mix ratio	490	754	406	406	174	1

* CA—coarse aggregate, FA—fine aggregate

**Fig. 5** Compressive strength test of GPC cube under testing equipment

from compressive testing mix combination, specimens with BW 30%, CW 50% and a combination of 80% of BW and CW was cast. The ENDB specimen was prepared as 50 mm in depth, 150 mm in diameter and 16 mm crack notch. For opening mode fracture, the stress intensity factor K_I derived from Irwin formulation (Baratta & Katz, 2001; Eghbali et al., 2019; Xie et al., 2022) as specified in Eq. 1. The experimental setup is shown in Fig. 6.

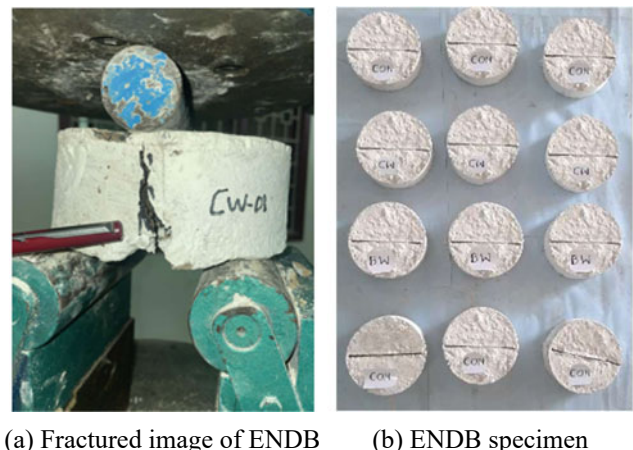
$$\sigma = 6P_{cr}S/RB^2 \quad (1)$$

$$K_{If} = \sigma\sqrt{\pi a} \times Y_1 \quad (2)$$

σ = Stress, P_{cr} = Critical load, S = Spacing, R = radius of ENDB specimen, B = thickness of ENDB specimen, a = notch depth, Geometric factor, $Y_1 = 0.323$.

2.7 Drop Weight Impact Test

Concrete capacity to endure repeated impact loads is referred to as impact resistance. Figure 7 shows the impact test experimental setup. The energy required to split the specimen into two or more parts is used to calculate this load

**Fig. 6** Mode-I fracture of ENDB specimen experimental setup

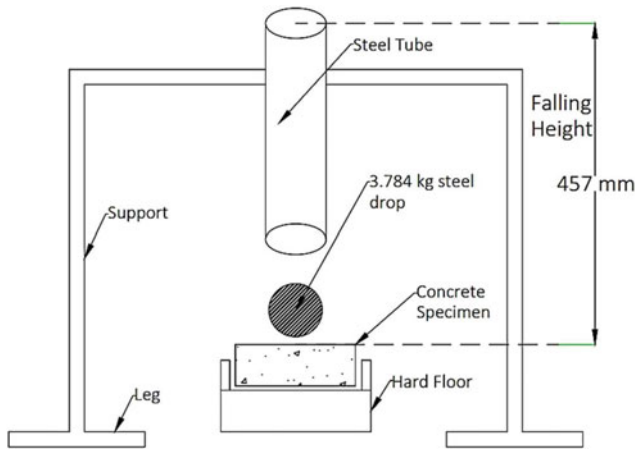


Fig. 7 Schematic diagram of impact test

(Eq. 3). Many impact test methodologies under various specifications are available to assess the impact resistance of geo-polymer concrete. The standard disc size used in this experiment was a diameter of about 150 mm and a height of 63.5 mm, which were collected for the impact study and put through the ACI 544-2R test (ACI 544.2R-89, 2009; Murali et al., 2022). The samples were initially set up on a holder. A 3.748 kg metal ball was repeatedly dropped on the specimens from a height of 457 mm. The number of blows needed to start a visible crack was noted. The total number of blows is required to get a complete fracture also taken for impact strength consideration.

$$U = (mgh) \times N \quad (3)$$

where m = mass g = gravity, h = 457 mm, N = numbers of impact

2.8 Scanning Electron Microscope (SEM)

SEM analyzes the concrete crystalline structure. The microscopy has an approximate $\times 500$ resolution and a magnitude range of 2 mm to 2 μ m. A small concrete sample is used for testing, taken from the cube specimen's middle core and polished into a smooth surface. Alternatively, the sample is collected and ground into a fine powder before being used for testing. Following the test results analysis, the material's microscopic structure can also be examined, as well as the bonding between the materials.

3 Results and Discussions

3.1 Compressive Stress Development of CDW Recycled GPC

Compressive loads are gradually applied to the concrete $100 \times 100 \times 100$ mm blocks. The ratio of maximum applied and cross-sectional area calculates the compressive stresses. 12 molarity GPC concrete control specimen was compared to the recycled aggregate mixed samples. The detailed compressive strength test results are shown in Table 3. The average of the three control specimens' compressive strength was 43.52 MPa; no model crossed the highest value than the control specimen, whereas the specimen ID BW20 + CW20 and BW30 + CW50 reached a very close compressive strength value to the control specimen. Here we can note that the BW replacement is more than 30% in GPC, and the CW replacement is more than 50% showing less attainment of compressive strength in GPC. Hence we can conclude that a maximum of 30% in

Table 3 Comparison of average compressive strength of CDW-replaced GPC

Sl. no	Specimen ID	BW in %	CW in %	Comp. stress in MPa (7 days)	Comp. stress in MPa (28 days)
1	Control	0	0	25.41	43.52
2	BW20	20	0	23.95	39.69
3	BW30	30	0	23.56	41.14
4	BW40	40	0	23.71	30.61
5	CW20	0	20	25.43	38.78
6	CW30	0	30	25.25	41.02
7	CW40	0	40	24.15	42.43
8	CW50	0	50	25.43	42.12
9	CW60	0	30	24.16	28.23
10	BW20 + CW20	20	20	25.23	38.40
11	BW30 + CW30	30	30	25.40	43.32
12	BW40 + CW40	40	40	21.71	30.52
13	BW30 + CW50	30	50	24.41	43.01
14	BW30 + CW60	30	60	17.86	29.70

Table 4 Comparison of fracture toughness between control to CDW contains GPC

Sl. no	Mix Id	Peak load in kN	Stress in MPa	KIf MPa m ^{0.5}	Avg. fracture toughness (MPa m ^{0.5})
1	FRC-01	7.75	35.34	2.56	
2	FRC-02	11.25	51.30	3.71	3.25
3	FRC-03	10.50	47.88	3.47	
4	FBW30-01	7.90	36.02	2.61	
5	FBW30-02	9.30	42.41	3.07	2.86
6	FBW30-03	8.75	39.90	2.89	
7	FCW50-01	8.17	37.26	2.70	
8	FCW50-02	9.27	42.27	3.06	2.78
9	FCW50-03	7.83	35.70	2.58	
10	FBW30 + FCW50-01	12.00	54.72	3.96	
11	FBW30 + FCW50-02	8.00	36.48	2.64	
12	FBW30 + FCW50-03	9.20	41.95	3.04	3.21

BW and 50% in CW might attain a promising result in using CDW. We can see almost 60% of early strength attainment of all GPC specimens.

BW and 50% CW mixed in GPC obtained stress intensity factor 3.21 MPa m^{0.5} which is very less about 1.24% compared to the control specimen. All fractured specimens took almost the same time for complete fracture.

3.2 Fracture Toughness of GPC (Opening Mode)

Totally, twelve numbers ENDB specimen was cast and tested for comparison. The results of the fractured specimens are shown in Table 4. In that three control specimens obtained 3.25 MPa m^{0.5} average stress intensity factor, which is slightly higher than the control specimen. Whereas the ENDB specimen with BW replaced 30% obtained 2.86 MPa m^{0.5} similarly the CW 50% alone obtained 2.78 MPa m^{0.5} stress intensity factor. The specimen 30% of

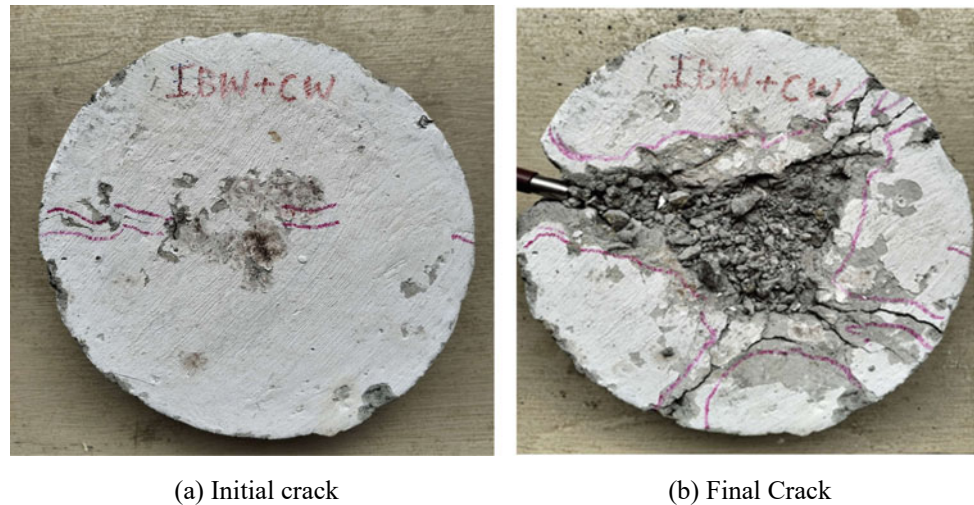
3.3 Drop Weight Impact Resistance of CDW Contains GPC

Table 5 shows the obtained impact energy of a 50 mm thickness disc specimen. The average result of the impact energy of the control specimen was 281.9 J. It was slightly higher than CDW-used GPC specimens. The optimum mix of CDW with GPC found that BW is 30% and the CW is 50%. The average of mix IBW30 + ICW50 was only 4%

Table 5 Results of drop weight impact test

Sl. no	Specimen Id	BW in %	CW in %	No. of drops		Impact energy		Avg. impact energy (J)
				First crack	Final crack	First crack	Final crack	
1	IC-01	0	0	13	17	215.57	281.90	
2	IC-02	0	0	14	16	232.15	265.32	
3	IC-03	0	0	15	18	248.73	298.48	254.26
4	IBW-01	30	0	13	15	215.57	248.73	
5	IBW-02	30	0	14	15	232.15	248.73	
6	IBW-03	30	0	12	16	198.99	265.32	243.21
7	ICW-01	0	50	11	12	182.41	198.99	
8	ICW-02	0	50	14	16	232.15	265.32	
9	ICW-03	0	50	15	16	248.73	265.32	270.84
10	IBW30 + ICW50-01	30	50	16	18	265.32	298.48	
11	IBW30 + ICW50-02	30	50	12	16	198.99	265.32	
12	IBW30 + ICW50-03	30	50	14	15	232.15	248.73	

Fig. 8 Impact resistance of GPC disc specimen on different failure stage



less strength obtained than the control specimen. Hence, it might be concluded that the lesser percentage of a mix of CDW to the GPC may receive no difference in impact strength. Figure 8 shows the cracked surface of the impact specimen.

3.4 Scanning Electron Microscopy (SEM) Analysis

SEM images were taken from the fractured surface of GPC after experimentation. The 28 days of well-formed GPC parts are analyzed. From SEM images, it was observed that the C-S-H (calcium silicate hydrate) formation, ettringite (E) early hydration process of the concrete, calcium hydroxide (CH) formation, crystallization, bonding and debonding nature and micro cracks. Figure 9 shows the SEM image for all specimens. Figure 9i, ii shows the control mix GPC specimen; it was well noted that the control mix GPC has a primary hydration level of ettringite crystal formation; this referred to the initial geopolymer formation stage. Also, the slate layer formation in GPC was noted; this many small layers formation represents the resistance scattered on all surfaces.

Similarly, Fig. 9iii, iv shows the specimen are cast by BW 30% replacement; it can be categorized as the well C-S-H gel formation, but the large potholes were present. The usage of washed concrete shows the crystal-clear CH formation in Fig. 9v, vi. It is claimed that the replaced materials were good in obtaining the strength and durability of concrete. Finally, the BW30 + CW50 specimens show minimized microcracks and debonding after failure; Fig. 9vii, viii represents that there are no significant differences

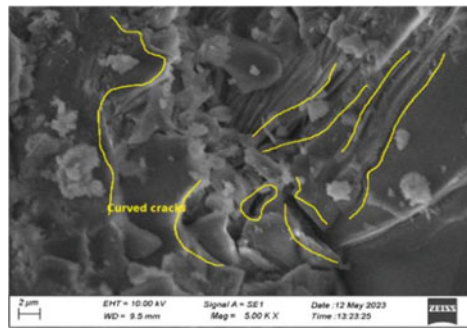
when compared to the control specimen; even the BW and CW replacement had less slate formation and cracks and strong in CH and CSH gel formation.

4 Conclusions

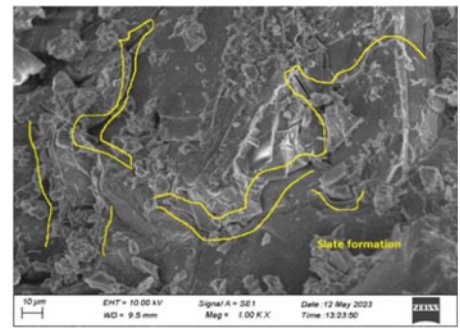
This current research represents the possible ways to recycle the CDW. The promising results related to sustainability are listed below.

- The GPC concrete made by CDW is highly possible with 100% of recycling, as assessed from this experimental study.
- Replacing up to 30% of washed brick waste to develop GPC gives almost equal strength to the control specimen. Similarly, adding 50% of washed concrete waste as coarse aggregate provides better results than GPC made from natural materials.
- The maximum compressive strength of BW30 + CW50 is achieved at 43 MPa, which is 1.2% less than the control specimen. Hence the suggestion for future works is when replacing more CDW, and research needs to move towards refinement of the CDW and changes in the molarities on GPC.
- The fracture toughness and impact resistance of the optimum dosage CDW replaced GPC specimens varies just 1–4% from the control specimen.
- The SEM image shows that the micro cracks, ettringite formation and formation of dense gel in the BW and CW added sample lead to improved performance in concrete. The image depicts a concrete area that is exceptionally dense.

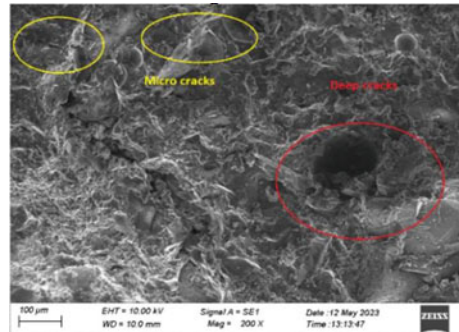
Fig. 9 Scanning electron microscopy images



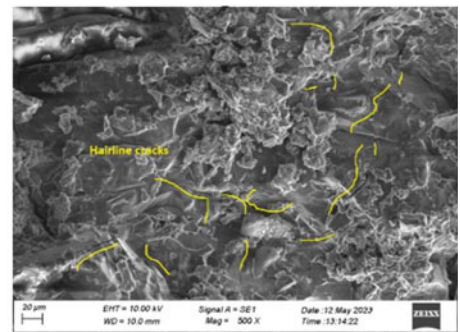
(i) GPC control specimen cracks



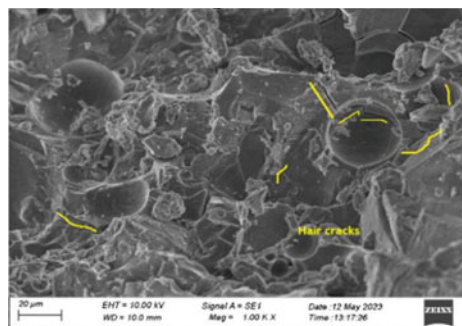
(ii) GPC control specimen slate form



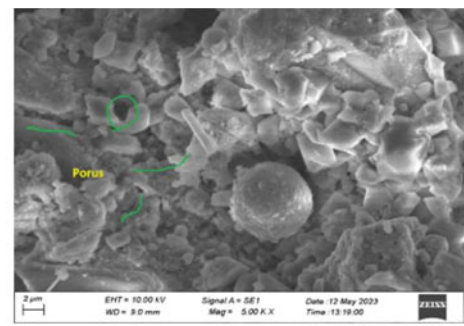
(iii) BW30 GPC crystallized structure deep cracks



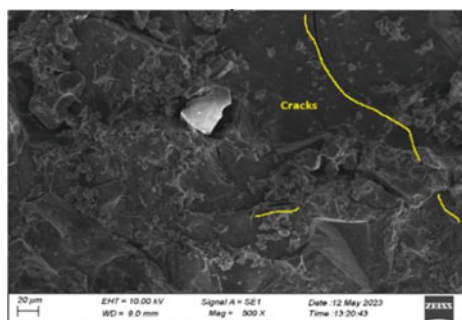
(iv) BW30 GPC hair line micro cracks



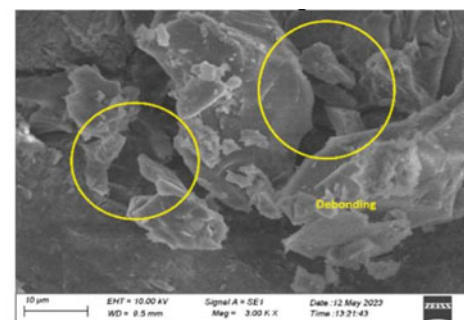
(v) CW 50 GPC crystal structure



(vi) CW 50 GPC micro pores



(vii) BW30+CW50 GPC cracks



(viii) BW30+CW50 GPC debonding

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Progressive Investigation on Utilisation of Steel Slag and Silica Sand as Partial Replacements for Coarse and Fine Aggregate in Concrete

Pravin Prakash Chate and Ajay K. Gaikwad

Abstract

Waste disposal research is recently focused on analysing industrial waste for economic, environmental, and technological reasons. Steel slag, which has a rougher surface than natural aggregates, is a denser waste product of the steel foundry and allows for greater particle conformance to the cement matrix. Due to silica sand's ability to fill tiny spaces, the pores in concrete are reduced by increasing the density of the concrete. This research study aims to partially replace coarse aggregate and sand (fine aggregate) with steel slag and silica sand, respectively. Here, the replacement is carried out in various portions, such as 10, 20, 30, and 40%, and its impact on the characteristics of concrete is also examined. According to the study's findings, silica sand and steel slag may be used effectively as coarse and fine aggregate with up to 30% swapping and a noticeable improvement in strength.

Keywords

Concrete • Steel slag • Silica sand • Partial replacement • Coarse aggregates • Fine aggregates

1 Introduction

All across the globe, natural sand and aggregate are often utilised as construction materials. The utilisation of manufacturing and farm waste as an alternative source of raw materials for industries is a topic that is being investigated by researchers recently. As industrial wastes like fly ash, silica sand, and slag from steel (as shown in Fig. 1a, b) are used as additional materials in the constructing field, this waste utilisation would not only be economical but would also result in environmental pollution management.

On precious land, hundreds of tonnes of garbage are dumped annually. The issue will be resolved if individuals start using these waste products. The potential applications of discarded steel slag as an alternative for coarse aggregate and silica sand as an alternative for fine aggregate in concrete were the focus of this investigation.

2 Literature Reviews

2.1 Amin et al., “Experimental Investigation on Static/Dynamic Response and γ/n Shielding of Different Sustainable Concrete Mixtures” (Amin et al., 2023)

This study analyses how recycling waste materials such as coarse and fine aggregates could generate sustainable concrete that may have innovative both static and dynamic performance as well as radiation attenuation strengths. Crushed stone aggregates and silica sand might be replaced by grinding scale and steel slag, correspondingly, in the manufacturing of concrete, to solve this problem. Experimental research was done on the characteristics of fresh and cured concrete. The main evaluable qualities in this investigation's work were the workability of concrete, strengths of concrete such as compressive, tensile, and flexural, impact resistance, and linear attenuation capacity. The results of this

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Fig. 1 a Steel slag and b silica sand (source <https://www.archdaily.com>)



study demonstrated that, in addition to its significant environmental advantages and economic accessibility, using steel slag and mill scale in concrete fabrication could result in superior static and dynamic performance by a maximum of 81.67 and 178.39%, respectively, compared with standard concrete.

2.2 Lai et al., “Effect of Fillers on the Mechanical Properties and Durability of Steel Slag Concrete” (Lai et al., 2022)

Here, researchers investigated that, the impact of pozzolanic fillers on the mechanical properties and durability of steel slag-containing concrete has only been the subject of an extremely limited number of studies. A systematic and scientific experiment was done to generate 29 concrete mixes with steel slag partially or entirely replacing natural aggregates and FA/SF partially replacing cement in an equivalent volume in order to close this research gap and encourage the usage of steel slag. All specimens underwent tests for slump, wet packing density (WPD), 7-, 28-, 91-, and 182-day compressive strength and lifespan in terms of total charge passed, as well as the depth of chloride ion penetration in the rapid chloride permeability test. X-ray diffraction (XRD) was utilised as well to identify the chemical structure of the concrete. According to test results, the porous nature of the slag caused a reduction in the slump of steel slag concrete. Additionally, the compressive strength of concrete was boosted by the inclusion of steel slag. The strength of steel slag concrete might be increased further by including SF to replace some of the cement. Due to the denser and more impermeable microstructure of concrete, which increased the resistance of chloride ion penetrability, the total charge passed at the given composition of aggregates and filler type and the depth of chloride ion penetration of steel slag concrete dropped as the WPD got up.

2.3 Anifowose et al., “Influence of Water Cement Ratios on the Optimum Use of Steel Slag in Concrete” (Anifowose, 2022)

The best way to substitute crushed stone with Prism Nigeria Slag (PNS) in the process of making concrete was investigated in this investigation with respect to the effect of water-cement ratios. Crushed stone was substituted by PNS by 0, 40, 50, and 60%. It was determined to utilise a 1:2:4 mix ratio with a water content of 0.4, 0.5, 0.6, and 0.7. Test specimens were cast, and they were given a 7- and 28-day water cure. With raised in w/c, the behaviour of the hardened concrete consistently exhibits decreasing compressive and split tensile strengths. For all w/c, 60% PNS replacement proved to be the ideal replacement at 28 days of cure for the strength of compression. However, it was found that the split tensile strength replacement that worked best for water cement ratio of 0.4, 0.6, and 0.7 was 60% PNS, whereas the replacement that worked best for w/c of 0.5 was 40% PNS. According to the study, using a 1:2:4 mix ratio and 60% PNS with a water content of 0.4 would end up resulting in concrete with higher compressive and split tensile strengths than standard concrete.

2.4 Chen et al., “Study on the Application Mechanism and Mechanics of Steel Slag in Composite Cementitious Materials” (Chen et al., 2020)

This research looks into for massive use and manufacturing of cement and concrete cause a fast rise in carbon dioxide emissions, necessitating the urgent development of cement substitutes in order to manufacture green cement and concrete. This study examines the viability of preparing cementitious materials from steel slag (SS) and granulated blast furnace slag (GBFS). Through the application of backscattered electron microscopy and X-ray diffraction, the

mineral phases of SS are identified and examined. The composite impact of SS-GBFS is analysed and contrasted by evaluating the compressive strength of mortar samples. Results indicate that SS may substitute cement by 10–30%, and the generated binary cementitious material has longer-lasting strength than cement. A 50% cement replacement is possible with SS and GBFS. Because SS and GBFS work together to strengthen cementitious materials, the strength of the ternary cementitious material SS-GBFA-Cement is greater than that of SS-Cement.

2.5 Sakthidoss et al., “A Study on High Strength Geopolymer Concrete with Alumina-Silica Materials Using Manufacturing Sand” (Sakthidoss & Senniappan, 2020)

This effort is mainly focused on making high-strength concrete using sustainable resources instead of cement in order to find a solution to the stated challenges. Specifically, powdered fly ash, slag from ground-granulated blast furnaces (GGBS), manufacturing sand (M Sand), crush aggregate from stones and alkaline solution are utilised in geopolymer concrete to achieve this. For the purposes of this experiment, extremely strong geopolymer concrete that was used with and without manufacturing sand was taken into consideration. The results are compared to high-strength cement concrete together with and instead of factory sand. In this investigation, M Sand is employed exclusively in place of river sand. Concrete is strengthened by adding manufacturing sand, which has a better gradation.

2.6 Sharba, “The Efficiency of Steel Slag and Recycled Concrete Aggregate on the Strength Properties of Concrete” (Sharba, 2019)

The impact of replacing the natural aggregate in concrete with recycled concrete aggregate (RCA) and steel slag (SS) was investigated through experimental experiments. In landfills, recyclable materials such as SS, a by-product of the steel-making process, and concrete shards, a by-product of demolition work, are discarded. These waste products are regarded as non-biodegradable and harm the environment. They have developed into such qualities for potential all-natural aggregate substitutes in the making of concrete. SS and RCA were both chemically and physically characterised in the current investigation. SS and RCA were used as partial replacements for (sand) fine aggregate and (gravel) coarse aggregate, respectively, in the next stage of the work plan. After completing the sieve analysis in accordance with American Concrete Institute guidelines, the proportions of

SS and RCA were estimated based on the particle size criteria. In proportions of 0, 15, 25, 35, and 45% by weight, these two replacement materials were employed to replace the natural aggregate in M40-grade concrete. The performance of the resultant mixes was compared to that of the original M40-grade concrete. Compressive strength, flexural strength, and split tensile strength of the concrete mixes were all examined for comparison. The findings demonstrated that adding SS increased the mechanical characteristics of the RCA-containing concrete. Additionally, a mixture that contained 15% recycled aggregate from concrete and 25% steel slag achieved the most impressive results.

2.7 Mahmood et al., “Effect of Sand Replacement by Silica Sand on Strength of Fibres Reinforced Foamed Concrete” (Mahmood et al., 2019)

In this investigation, three (1200 kg/m^3) foamed concrete mixtures composed of standard sand (particle size 2.36), traditional sand (particle size 0.5 mm), and silica sand (particle size 0.5 mm) were prepared to investigate the effects of sand type and particle grading. In order to investigate the impact of extra fibres and their lengths on the strength of foamed concrete, three additional (1200 kg/m^3) mixes of foamed concrete that were reinforced with Polypropylene fibres of various lengths (12, 18, and 30 mm) were added as reinforcement (0.5% of volume). Absolute volume was used to create the examined mixes, and pre-foamed foam was used to create the foamed concrete mixtures. Silica sand was found to help increase compressive and splitting tensile strengths when conventional sand was replaced with it. Decreases in the traditional sand's particle size from 2.36 to 0.5 mm were also associated with an improvement in strength. Additionally, as compared to mixes without fibres, reinforced foamed concrete containing polypropylene fibres had the highest strengths. The strongest impact on the strength of foamed concrete comes from the combination of silica sand and polypropylene fibres.

2.8 Depaa et al., “Experimental Study on Steel Slag as Coarse Aggregate in Concrete” (Depaa & Felix Kala, 2017)

In this study, replacing the coarse aggregate in concrete with steel slag is proposed. Steel slag was utilised as a replacement for coarse aggregate in concrete cube, cylinder, and prism moulds up to 100%, and the compressive strength characteristic was explored. The appropriate replacement for coarse stone fragments with slag from steel is 80%, according to the findings of the strength in compression tests.

2.9 Ravikumar et al., “Experimental Investigation on Replacement of Steel Slag as Coarse Aggregate in Concrete” (Ravikumar et al., 2015)

This study evaluated the impact of substituting steel slag for the usual coarse aggregate in concrete to determine how such changes affected the properties of the material. Because concrete is used more than any other substance in the world, its usage cannot be avoided. At the same time, however, aggregate is becoming increasingly scarce. Construction companies have embraced industrial waste since it helps to cut down on the use of natural resources. For many years, products like fly ash, silica fume, and steel slag were regarded as waste materials. They have been effectively utilised in the concrete industry for both partial and complete substitution. For the purposes of this study, concrete of the M20, M30, M40, and M50 grades was taken into consideration for a W/C ratio of 0.55, 0.45, 0.37, and 0.32, respectively, for the substitution of coarse aggregate at 30%, 60%, and 100% by steel slag. According to this study, all concrete grades have a 5 to 10% increase in compressive strength. All concrete grades have a 4–8% improvement in split tensile strength. For all grades, the flexural strength of concrete increases by around 2 to 6%. Steel slag may replace up to 60% of the cement in all concrete grades. Strength is significantly reduced when steel slag completely replaces the material.

2.10 Vishnumanohar, “Performance of Normal Concrete with Eco Sand (Finely Graded Silica) as Fine Aggregate, International Journal of Engineering Science Invention” (Vishnumanohar, 2014)

A study on the strength and durability of using “Finely Graded Silica” (Eco Sand), a waste product from the process of making cement, as a partial substitute for fine aggregate in concrete was conducted in this area. This research involves testing to determine the physical and chemical characteristics of finely graded silica as well as partially substituting this fine-graded silica with fine aggregate (15, 30, 45, and 60%). For the replacement, M25 and M40 concrete is used as a mix. $150 \times 150 \times 150$ mm concrete cubes of sizes were created for the compression test, and they were put to the test after 3, 7, 28, and 90 days. The results of the experimental study showed that a 15% replacement level is the ideal amount.

3 Objectives

- To analyse the workability and slump tests of freshly poured concrete for M25 grade concrete mix.
 - To analyse the hardened concrete's characteristics, including its flexural, tensile, and compressive strength for concrete of the M25 mix grade.
 - To estimate an optimum percentage of coarse and finer aggregate replacement with steel slag and silica sand for M25 grade of concrete.
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- ## 4 Methodology and Details of Experimental Work
- Making a combination of steel slag with natural coarse aggregate and silica sand with natural fine aggregate.
 - 90% natural fine aggregate + 10% silica sand and 90% natural coarse aggregate + 10% steel slag.
 - 80% natural fine aggregate + 20% silica sand and 80% natural coarse aggregate + 20% steel slag.
 - 70% natural fine aggregate + 30% silica sand and 70% natural coarse aggregate + 30% steel slag.
 - 60% natural fine aggregate + 40% silica sand and 60% natural coarse aggregate + 40% steel slag.
 - Preparing moulds of cubes $150 \times 150 \times 150$ mm for testing of compressive strength with various combinations of steel slag with natural aggregate and silica sand with natural sand.
 - Preparing moulds of cylinder 150×300 mm for testing of split tensile strength with various combinations of steel slag with natural aggregate and silica sand with natural sand.
 - Preparing moulds of beam $500 \times 100 \times 100$ mm for testing of flexural strength with various combinations of steel slag with natural aggregate and silica sand with natural sand.
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- ## 4.1 Materials
- Cement: 43 grades of OPC (Ordinary Portland Cement) were utilised throughout all parts of the work. A 3.15 specific gravity for cement was noted.
 - Fine aggregate: The entire project used finer aggregates that were made of fine sand from rivers with an average density of 2.65 and a maximum particle size of 4.75 mm.
 - Coarse aggregate: The coarse aggregates utilised were an angular-shaped machine-crushed stone that went through a 20 mm IS sieve and was kept on a 4.75 mm IS sieve with a specific gravity of 2.9.
 - Steel slag: Utilised as coarse aggregate with an angular shape that passes through a 20 mm IS sieve and is retained on a 12.5 mm IS sieve with a specific gravity of 3.6.

- Silica sand: As a partial replacement for the finest aggregate, silica sand is utilised in concrete. Silica sand has a specific density of 2.7.

4.2 Tests on Materials

4.2.1 Impact Test

The aggregate impact value is utilised to determine the durability of the aggregate. This test provides a relative estimate of the aggregate's resistance to a rapid load. For this test, an aggregate impact value apparatus is used. Figure 2 depicts the device, which comprises a steel test mould and a falling hammer. The arrangement of the vertical guides permits the hammer to move easily between them such that its bottom portion is above and systematically connected with the mould. The aggregate impact value of the given sample is 36% which means the aggregate have a high impact value and can be used in some concrete for wearing surface.

4.2.2 Crushing Value Test

We utilised steel slag aggregate that is sieved by using a 20 mm sieve and then kept on a 12.5 mm screen for performing the crushing test. We carried steel slag aggregate through a crushing test refer to Fig. 3 and the results showed that it had a crushing value of 44.63, which is acceptable for use in buildings. Additionally, we are partially replacing the coarser aggregates in concrete with steel slag, which will increase the strength of the concrete.

4.2.3 Sieve Analysis of Natural Sand

In order to calculate the design of concrete mixtures, a sieve analysis of natural sand is used. 4.75, 2.36, 1.18 mm, 600, 300, and 150 μ are the four different sand zone kinds according to the proportion of sand that passes through sieves. From the following observations, shown in Table 1, the sand is of Zone II as per IS 383-2016.

4.3 Tests on Concrete

4.3.1 Slump Cone Test

The concrete slumping test, also known as the slump cone test (Fig. 4), is used to determine if a concrete mix that has been manufactured in a laboratory or on the building site can be used in actual construction projects. Concrete slump tests are carried out from batch to batch in order to ensure that the concrete is of an equivalent level during the construction process. The easiest, cheapest, and fastest approach to determine if the concrete is workable is to do a slump test. This has led to its widespread usage for workability testing since 1922.

4.3.2 Compressive Strength Test

The test for compression (refers Fig. 5) is the one that is carried out frequently on hardened concrete, in part because it is easy to do and because it is frequently used as an indicator of both the concrete's calibre and its other properties. The capacity of a substance or a structure to withstand or resist compression is known as compressive strength. Compressive strength is the ability of a material to tolerate

Fig. 2 Impact value test apparatus (source <https://www.civilalliedgyan.com/2020/03/aggregate-impact-value-test.htm>)

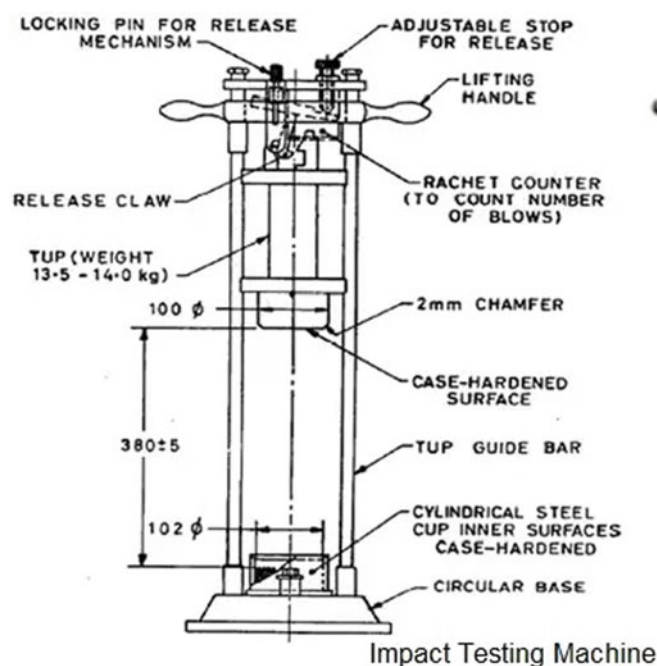




Fig. 3 Crushing value test apparatus (Testing at Concrete Technology Lab. NHCE Parli V.)

degradation in its natural state of cracks and fissures. The characteristic strength of concrete cubes 150 mm in size is used to calculate the compressive strength of concrete after 28 days.

4.3.3 Split Tensile Test

Tensile strength, or the ability to endure tearing or splitting under stress, is a property of concrete. The amount and type of cracks in concrete structures are affected by it. Cracks develop when tensile forces exceed the tensile strength of the concrete. The tensile strength of typical concrete is substantially lower than compressive strength. This implies that tensile-stressed concrete structures must be reinforced with steel or other materials having a high tensile strength. Indirect methods are used because it is difficult to assess the tensile strength of concrete directly. The two preferred indirect methods are split tensile strength and flexural

Table 1 Sand sieve analysis

Sieve sizes	Weight retained in grams	Percentage passing
10.00 mm	00.0	100.00
4.75 mm	95.1	90.49
2.36 mm	154.0	75.09
1.18 mm	194.5	55.64
600 μ	73.0	48.34
300 μ	190.5	29.29
150 μ	214.5	7.84
Pan	78.4	-

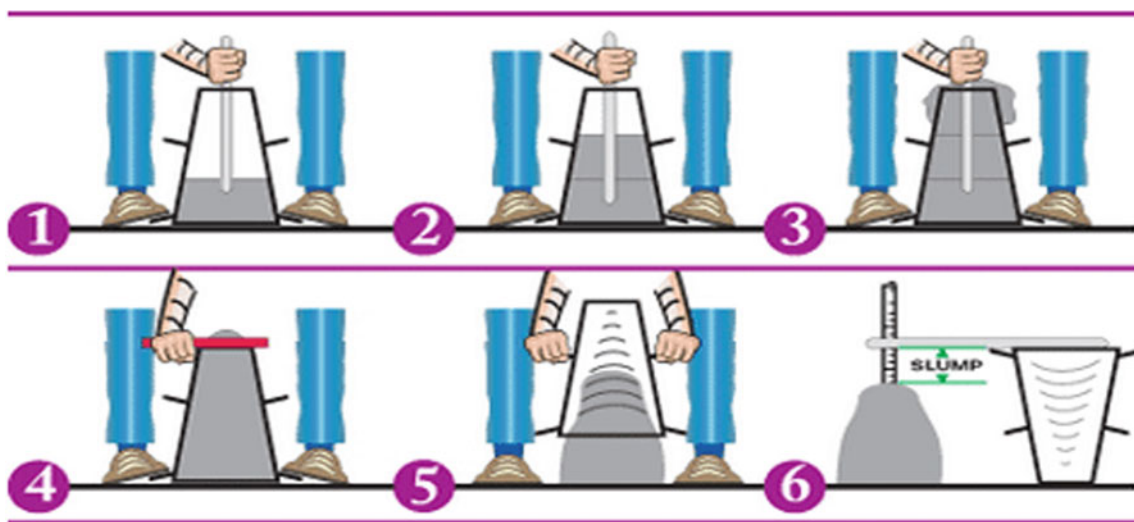


Fig. 4 Slump cone test on concrete (<https://theconstructor.org/concrete/concrete-slump-test/1558/>)



Fig. 5 Compressive test on concrete (<https://www.forconstructionpros.com/>)

strength, respectively. To assess the splitting tensile strength of concrete, cylinders made of concrete are subjected to a split tensile test. A typical cylindrical specimen is placed horizontally for this test, and force is applied uniformly on its surface until a vertical fracture develops across its diameter. Test samples deteriorate across the axial path of the applied force, and as the longitudinal compressive force grows, tensile stress increases. All that is needed for this simple test is a standard cylindrical sample for testing and a loading apparatus as shown in Fig. 6.

4.3.4 Flexural Strength Test

Another type of indirect tension test is the flexural test, also known as the modulus of rupture. In order to establish an absolute bending moment in the structure of the beam test specimen under stress, this approach entails applying two loads to it that are equally distanced from the centre. This is done until the largest fibre of the beam object receives the

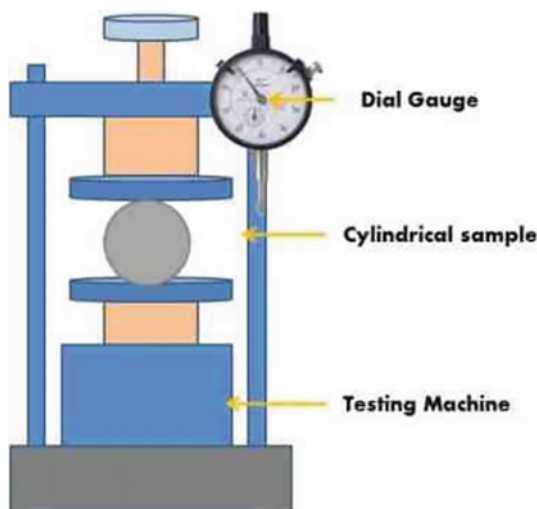


Fig. 6 Experimental setup for split tensile test on concrete (source <https://civiconcepts.com>)

maximum stress of tensile. The following image, Fig. 7, depicts the experimental test setup. The neutral axis, which is located in the top half of the beam, is compressed, whereas the neutral axis is located in the lower half of the beam, which is subjected to strain. In addition, it is presumed that the stress varies linearly in a triangle pattern along the section, when the true stress distribution should vary parabolically. As a result, the flexural test's measurement of tensile strength is 50–100% greater than the tensile test for concrete itself. Additionally, only the fibre at the bottom of the specimen is subjected to the highest tensile stress during this test, indicating that the specimen's bottom is the sole place where the largest stress is concentrated. There isn't a consistent distribution of stresses as a result. Despite this, this test is frequently employed because to its straightforward experimental test setup and straightforward specimen casting.

5 Results and Discussions

This method looks at the effects of substituting steel slag for coarser aggregate and silica sand for finer aggregate on various concrete properties, such as compressible strength, tensile strength at splits and torsional strength. As shown in Tables 2, 3 and 4.

- From Fig. 8, in the case of the compressible strength of concrete cubes, it is noted that strength has been raised up to 30% substitution of steel slag and silica sand by 24.66% compared to conventional concrete cubes for 28 days, and then the graph begins to decrease from 40%.
- From Fig. 9, in the split tensile test of the cylinder, it has been investigated that the strength increased up to 30% replacement of steel slag and silica sand by 23.67%

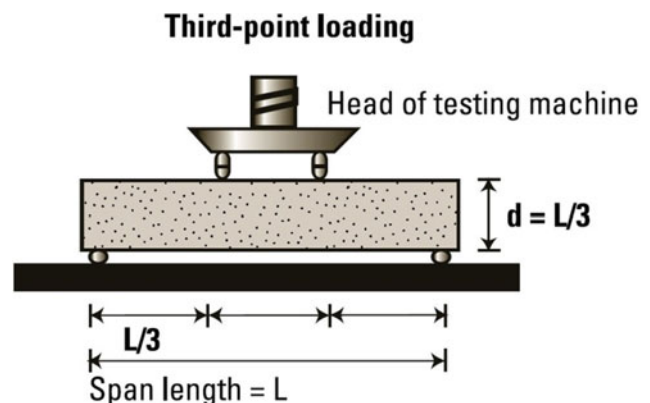


Fig. 7 Experimental setup for flexural test on concrete (source <https://theconstructor.org/>)

Table 2 The result of the compressive strength test

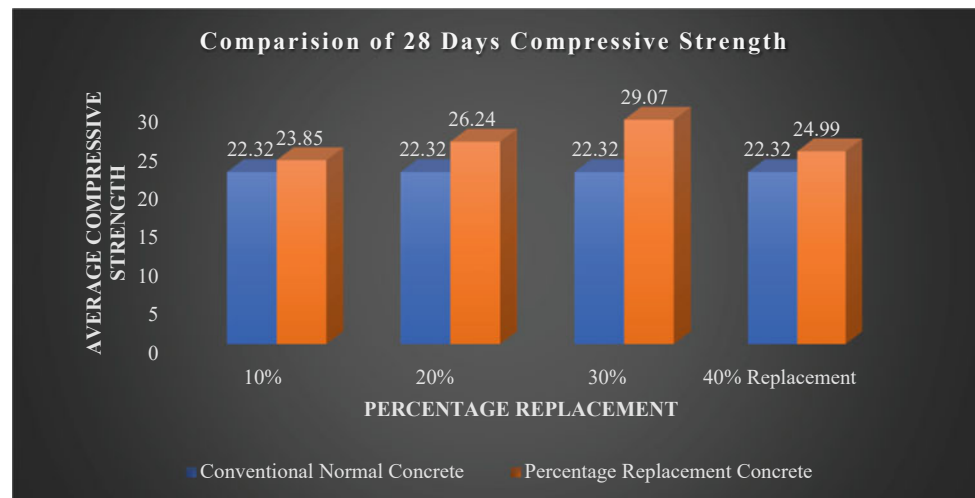
Sr. No	Weight of cube in Kg (28 days)	7 days compressive strength (N/mm ²)	Average 7 days compressive strength (N/mm ²)	28 days compressive strength (N/mm ²)	Average 28 days compressive strength (N/mm ²)
0% replacement (conventional normal concrete)					
1	8.9	18.67	18.82	22.66	23.32
	8.9	19.11		24.10	
	8.8	18.67		23.21	
10% replacement					
2	8.6	23.11	22.23	24.00	23.85
	8.7	22.22		22.22	
	8.7	21.26		24.45	
20% replacement					
3	8.6	23.11	22.23	25.37	26.24
	8.8	24.44		26.46	
	8.7	23.95		26.89	
30% replacement					
4	9.2	25.88	25.30	29.66	29.07
	9.1	24.67		28.22	
	9.1	25.36		29.34	
40% replacement					
5	8.4	22.78	22.48	25.13	24.99
	8.5	21.98		24.88	
	8.5	22.68		24.97	

Table 3 The result of the split tensile strength test

Sr. No	Weight of cylinder in Kg (28 days)	7 days strength (N/mm ²)	Average 7 days strength (N/mm ²)	28 days strength (N/mm ²)	Average 28 days strength (N/mm ²)
0% replacement (conventional normal concrete)					
1	13.6	2.54	2.44	3.28	3.38
	13.5	2.40		3.38	
	13.7	2.40		3.50	
10% replacement					
2	13.7	2.89	2.99	3.52	3.52
	13.8	3.09		3.45	
	13.8	2.98		3.59	
20% replacement					
3	13.8	3.11	3.17	3.67	3.62
	13.8	3.21		3.61	
	13.9	3.19		3.59	
30% replacement					
4	13.6	3.82	3.88	4.14	4.18
	13.7	3.89		4.23	
	13.7	3.95		4.19	
40% replacement					
5	12.9	3.25	3.20	3.54	3.51
	12.9	3.12		3.47	
	12.8	3.24		3.52	

Table 4 The result of the flexural strength test

Sr. No	Weight of cylinder in Kg (28 days)	7 days strength (N/mm ²)	Average 7 days Strength (N/mm ²)	28 days strength (N/mm ²)	Average 28 days Strength (N/mm ²)
0% replacement (conventional normal concrete)					
1	13.00	11.15	10.45	11.60	11.25
	13.10	09.70		10.95	
	13.10	10.50		11.20	
10% replacement					
2	13.50	10.25	10.52	10.95	11.30
	13.60	10.50		11.25	
	13.60	10.80		11.70	
20% replacement					
3	13.70	10.65	10.50	11.20	11.45
	13.70	10.55		11.45	
	13.60	10.30		11.70	
30% replacement					
4	13.70	11.20	11.49	11.75	12.00
	13.90	11.55		12.00	
	13.70	11.70		12.25	
40% replacement					
5	13.40	09.65	09.67	10.30	10.67
	13.50	09.90		11.15	
	13.40	09.45		10.55	

Fig. 8 Comparison of compressive strength for all percentage replacements with conventional concrete

compared to the conventional concrete cylinder of 28 days, and then the graph decreases from 40%.

From Fig. 10, for flexural strength of beams, it is observed that the strength of concrete beams raised up to 30% replacement of steel slag and silica sand by 6.67% compared to conventional concrete beams for 28 days, and then the graph decreased from 40%.

6 Conclusion

The combination of silica sand and steel slag in concrete produced workable concrete that had good fresh concrete properties. When compared to normal concrete, steel slag and silica sand replacements have increased compressive strength by 24.66% up to 30% replacement. Compared to the

Fig. 9 Comparison of split tensile strength for all percentage replacements with conventional concrete

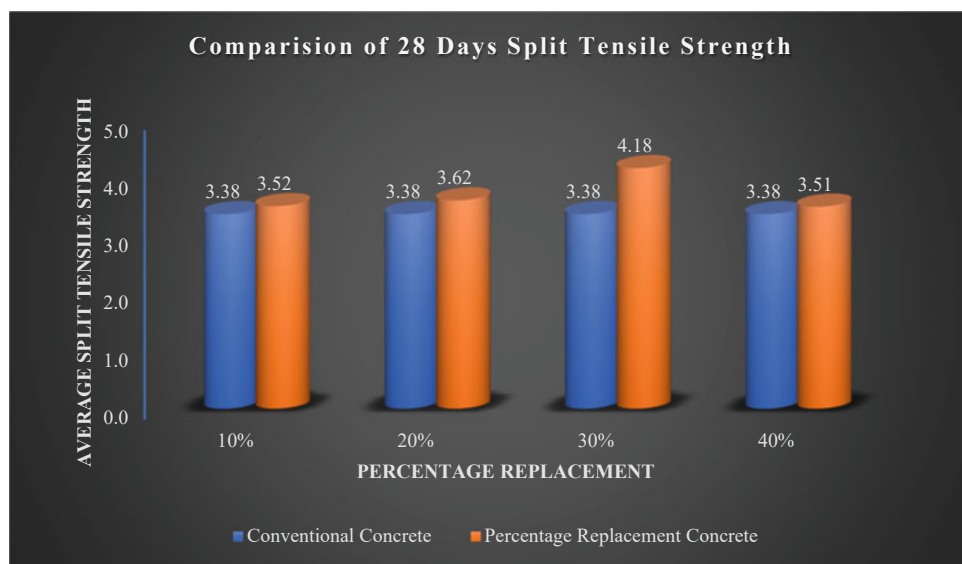
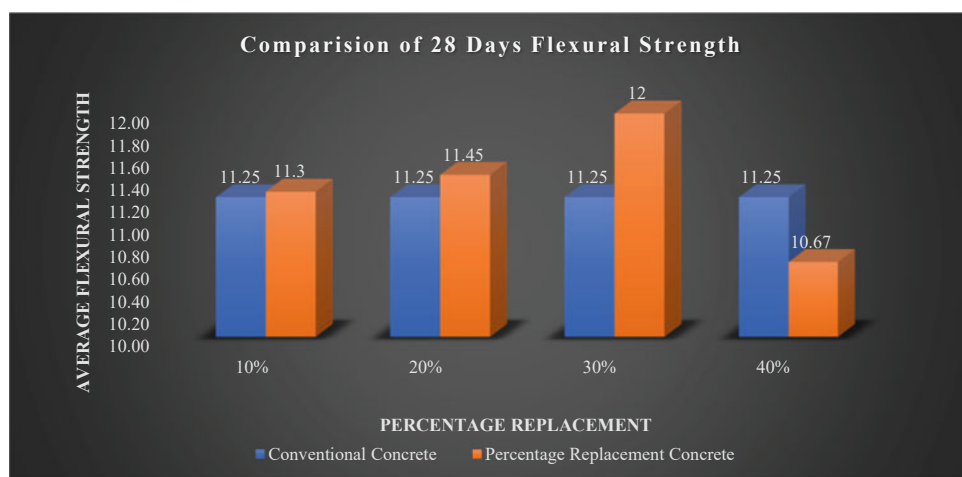


Fig. 10 Comparison of flexural strength for all percentage replacements with conventional concrete



normal concrete cylinder of 28 days, it may be observed that the split tensile strength has risen by up to 30% and that silica sand and steel slag replacement has increased by 23.67%. Flexural strength was observed to increase by up to 30% over conventional concrete beams over a period of 28 days when steel slag and silica sand were replaced. According to the findings, the ideal amount of coarse and fine aggregate replacement with steel slag and silica sand for concrete of the M25 grade is 30%.

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A Study on the Relationship Between the Physical, Hydrological and Mechanical Properties of Pervious Concrete

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Abstract

During the rainy season, urban roads are affected by the stagnation of stormwater on the surface course which poses a major concern for road users. Pervious concrete or no-fines concrete is a special type of concrete that usually does not contain fine aggregates. The purpose of eliminating fine aggregates completely is to achieve effective drainage of stormwater when used in the construction of rigid pavements. The structure of pervious concrete comprises increased voids or pores compared to conventional concrete which promotes water permeability. However, the permeability of pervious concrete is achieved at the cost of reduced mechanical strength properties. Hence, pervious concrete design should be capable of balancing their porosity and structural strength as per the site requirement. This chapter discusses a detailed overview of the engineering properties of pervious concrete based on the studies by previous research works. Moreover, this chapter is aimed at reviewing the major design parameters of pervious concrete such as density, permeability, compressive strength, split tensile strength, flexural strength and abrasion resistance. In addition to this, the interdependencies of the properties are also investigated to understand their level of dependence on the performance of pervious concrete. The porosity of the pervious concrete was observed to define its hydrological and mechanical strength properties of pervious concrete.

Keywords

Compressive strength • Flexural strength • Pervious concrete • Porosity • Permeability • Density

1 Introduction

As a significant element of civil infrastructure, stormwater management systems play a major role in transitioning from urban conventional drainage systems to urban sustainable drainage systems with the help of Pervious concrete (Ibrahim et al., 2014; Sauri & Palau-Rof, 2017). It has the property of faster infiltration of water due to its own character of higher permeability (Sandoval et al., 2017). The application of pervious concrete is limited to a narrow range compared to conventional concrete due to the use of zero fine aggregates and a low binding material proportion which poses challenges to its durability and strength (Akand et al., 2016). In other words, pervious concrete is susceptible to the decrement of strength due to its higher void content and it is also subjected to ravelling. The failure under loading occurs predominantly in the interfacial zone between aggregates and paste due to thin bonding between aggregates (Agar-Ozbek et al., 2013; Ibrahim & Abdul Razak, 2016; Lori et al., 2019). Moreover, the strength development of pervious concrete varies with that of ordinary concrete due to its porosity (Bright Singh & Murugan, 2022a; Peng et al., 2018). Studies on pervious concrete report compressive and flexural strength of pervious concrete as a function of water cement ratio (w/c), aggregate cement ratio (ACR) and aggregate sizes and gradation (Bright Singh & Murugan, 2022b; Deo & Neithalath, 2011). Unlike ordinary concrete, w/c ratio, mixing and compaction were ascertained by trials in the case of pervious concrete (Yao et al., 2018). Clogging of pores of pervious concrete takes place with the presence of excess paste which in turn increases the compressive strength of concrete (Sonebi et al., 2016). In order to achieve

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the desired properties, extensive care should be taken in maintaining the consistency of the cement paste during the moulding of specimens (Yao et al., 2018; Seeni et al., 2023). The quality or efficiency of pervious concrete can be determined by performing basic properties tests namely inter-connected porosity test (Sonebi et al., 2016), unit weight measurement (Leon Raj & Chockalingam, 2020), water absorption measurement, water permeability tests (Wu et al., 2016), compressive strength tests, split tensile strength tests, flexural strength test (Brake et al., 2016), surface abrasion measurement (Leon Raj & Chockalingam, 2020) and frost resistance tests (Yao et al., 2018). Pervious concrete mixes with porosity of 15–19% resulted in a permeability value of 1 mm/s and a compressive strength of 22 MPa (Yahia & Kabagire, 2014). However, it was proven that the factors relating to aggregate proportions and properties such as gradation, size and composition tend to have much influence on the void content and the permeability of the concrete than the change in compaction effort (Crouch et al., 2007). The use of supplementary cementitious materials and polymers yields pervious concrete with compressive strength in the range of 32–46 MPa termed High Strength Pervious Concrete (Chen et al., 2013). On the other hand, Lori et al. (2019) reported pervious concrete with flexural strength in the range of 3 to 3.8 MPa as High Strength Pervious Concrete. A balance of material composition is essential in the mix design of pervious concrete in order to ensure optimum mechanical strength, permeability and other durability properties (Sonebi et al., 2016). The paper presents the interdependency and inter variabilities of properties of pervious concrete mixes based on the existing literature. In this study, the relation between parameters such as permeability and the porosity with the mechanical strength of the pervious concrete is reviewed from the literature, consolidated and presented in the upcoming sections.

2 Permeability and Porosity

Permeability of porous concrete is highly correlated with the connected porosity than the total porosity (Zhong & Wille, 2015). Permeability varies linearly with the connected porosity (Kuo et al., 2013), especially in the void ratio range of 15–30% (Bhutta et al., 2012). 1/10th of the connected porosity value equals the permeability coefficient expressed in cm/s (Kuo et al., 2013). Cui et al. (2017) reported that the permeability increases with the increase in the porosity values representing a positive correlation using a polynomial function. An increase in permeability occurs with the increase in void content irrespective of the size of aggregates and the percentage of fine aggregates (Maguesvari & Narasimha, 2013). Moreover, no considerable effect on the permeability can be observed due to changes in the type of

aggregates (Sriravindrarajah et al., 2012). Decreasing the porosity values results in the filling up of connected voids resulting in reduced permeability coefficient values. Chandrappa and Biligiri (2016) established relations between permeability and porosity at various heads which indicates a higher correlation in the case of high heads. Due to the compaction, the top and bottom most layers of the concrete show less permeability in comparison with the middle layer even though the overall porosity remains constant (Costa et al., 2018). Relationship between permeability and porosity was established by Sandoval et al. (2017) for both falling head and constant head method. Relationship between porosity and permeability expressed by various researchers show negative or positive residual values of permeability even at 0% porosity (Sandoval et al., 2019). Understanding the range in which the expression can be deployed becomes essential. Sandoval et al. (2019) proposed correlation of porosity and permeability based on Darcy law and Bernoulli's law. Table 1 lists the relationship established by researchers between permeability and porosity.

3 Compressive Strength and Permeability

Understanding the relationship between compressive strength and permeability is essential to maintain a balance of the hydrological properties and mechanical properties (Cui et al., 2017). Decrement in compressive strength can be observed with the increment in permeability values which is backed by the increase in void ratio (Aliabdo et al., 2018). Permeability of pervious concrete is highly affected by the compressive strength of the concrete (Aliabdo et al., 2018). This is due to the higher pore-filling paste ratio required for high compressive strength which hinders the permeability of water (Kuo et al., 2013). Table 2 lists the relations between compressive strength and permeability.

4 Compressive Strength and Porosity

Increment in voids of pervious concrete decreases the compressive strength (Aliabdo et al., 2018; Peng et al., 2018). An inverse relationship between compressive strength and porosity is observed by Liu et al. (Liu et al., 2018b). The variation of compressive strength with respect to void ratio or porosity behaves similarly to that of porous brittle material due to the brittle cement paste (Chindaprasirt et al., 2008; Öz, 2018). Cui et al. (2017) obtained a relationship between compressive strength and porosity using Lorentzian function. Variation of the relationship between compressive strength and porosity based on the aggregate to cementitious material ratio is determined by Al-sallami et al. (2020). Aggregate type has a considerable effect on the

Table 1 Dependence of permeability on porosity

Author	Relation	R ²	Remarks
Nguyen et al. (2014)*	$k_f = 1.077n - 28.88$	0.83	
Nguyen et al. (2014)*	$k_c = 0.564n - 15.20$	0.91	
Bhutta et al. (2012)*	$k_f = 2.927(\text{voidratio}) - 49.7$	0.75	
Chandrappa and Biligiri (2016)*	$k_f = 6 \times 10^{-5} n^{3.628}$	0.92	Initial Head of 16 cm
	$k_f = 7 \times 10^{-5} n^{3.598}$	0.92	Initial Head of 21 cm
	$k_f = 7 \times 10^{-5} n^{3.579}$	0.93	Initial Head of 26 cm
	$k_f = 7 \times 10^{-5} n^{3.568}$	0.93	Initial Head of 31 cm
	$k_f = 6 \times 10^{-5} n^{3.557}$	0.93	Initial Head of 39 cm
	$k_f = 7 \times 10^{-5} n^{3.534}$	0.93	Initial Head of 44 cm
	$k_f = 7 \times 10^{-5} n^{3.518}$	0.93	Initial Head of 49 cm
Cheng et al. (2011) *	$k_c = 0.0436n + 2.44$		Cement paste
	$k_c = 0.14n + 1.1$		Styrene-butadiene latex (SBL) modified paste
El-Hassan et al. (2019)*	$k_f = 0.331e^{-0.1897n}$	0.99	
Ghashghaei and Hassani (2016)*	$k_f = 129.71n - 38.023$	0.99	Coarse Pervious concrete
	$k_f = 77.44n - 19.234$	0.96	Fine Pervious concrete
Kuo et al. (2013)#	$k_c = 0.1n_c$	0.63	
Sandoval et al. (2017) *	$k_c = 0.0003n^{3.29}$	0.98	
	$k_f = 0.0591n^{1.09}$	0.98	
Sriravindrarajah et al. (2012)*	$k_f = 1.93e^{0.075n}$	0.93	
Li et al. (2021)*	$k_c = 2.98e^{0.06n_c} - 3.05$	0.96	
	$k_c = 2.85e^{0.07n_c} - 3.01$	0.97	Submerged specimen
Emiko et al. (2013)*	$k_c = 17.312k^{0.0882}$	0.26	
Liu et al. (2018a)*	$k_c = 47.91n - 4.20$	0.94	
	$k_c = 52.17n_c - 3.38$	0.93	
Liu et al. (2018b)*	$k_c = 0.030n^2 - 0.676n + 4.615$	0.97	
Luck et al. (2006)	$k_c = 1.31n - 20.44$	0.81	k in lit/s/m ²
Lund et al. (2014)#	$k_c = 36.99e^{0.21n}$		12 cm head
	$k_c = 35.97e^{0.21n}$		30 cm head
	$k_c = 35.05e^{0.20n}$		Average head
El-maaty (2016)*	$k_f = 1.4419e^{0.0527(\text{voidratio})}$	0.86	
Muthaiyan and Thirumalai (2017)#	$k_f = 0.0926n_e - 1.0474$	0.66	
	$k_f = 0.0716n_e - 0.6847$	0.95	10% Fly ash replacement
	$k_f = 0.1157n_e - 1.3821$	0.96	20% Fly ash replacement
Peng et al. (2018)*	$k_c = 0.028e^{0.194n_c}$	0.99	
Tabatabaeian et al. (2019)*	$k_f = 0.4223(\text{voidratio}) + 1.3843$	0.70	
Tijani et al. (2019)*	$k_f = 0.02e^{0.25n}$	0.99	
Magesvari and Narasimha (2013)#	$k_f = 0.067e^{7.246n}$	0.84	
Zhong and Wille (2015)*	$k_c = 0.32n_c - 3.11$	0.87	
	$k_c = 0.40n - 6.88$	0.67	
Lim et al. (2013)	$n = 6.0597k_c^{0.4831}$	0.91	
Bonicelli et al. (2015)*	$k_f = 1.2628n - 11.197$	0.72	
Elizondo-Martinez et al. (2019)#	$k_f = 0.7931n - 20.768$	0.85	ACI 522R-10 (Committee, 2010)
	$k_f = 0.2088n - 3.6496$	0.94	PCD

(continued)

Table 1 (continued)

Author	Relation	R ²	Remarks
Costa et al. (2018) #	$k_f = 9.538n - 1.9217$	0.40	Core specimens
	$k_f = 26.742n - 5.5733$	0.98	Casted specimens
Cui et al. (2017)#	$k_c = 28.358n^2 - 4.5n + 0.381$	0.96	Based on the polynomial function
	$k_c = 35.37223(\frac{n^3}{(1-n)^2})$	0.86	Based on the Carman-Kozeny function
Khankhaje et al. (2016)*	$k = 1.162n - 20.08$	0.90	
Sonebi et al. (2016)#	$k = 0.04e^{0.15(\text{voidratio})}$	0.82	

* represents k in mm/s; # represents k in cm/s; k —co-efficient of permeability; n —porosity; k_c —co-efficient of permeability by constant head method; k_f —co-efficient of permeability by falling head method; n_c —connected porosity or effective porosity

Table 2 Relationship between compressive strength (f_c) and permeability

Author	Relation	R ²	Remarks
Aliabdo et al. (2018)#	$f_c = 2.2346k_f^{1.847}$	0.72	
Nguyen et al. (2014)*	$k_f = -0.3384f_c + 8.4657$	0.96	
	$k_c = -0.6235f_c + 14.98$	0.89	
Kuo et al. (2013)#	$k_c = -0.34f_c + 4.94$	0.72	
Oz (2018)#	$f_c = 21.89e^{-1.297k_f}$	0.92	
Lim et al. (2013) (2013)*	$f_c = 31.753k_c^{-0.292}$	0.28	
Yazici and Mardani-Aghabaglou (2017)	$f_c = 0.0158p^2 - 2.6929p + 120.59$	0.90	p = rate of water passed from the sample in %
Cui et al. (2017)*	$f_c = 12.525 + \frac{740.26}{\pi} \times \frac{1.673}{4(k_c + 0.778)^2 + 2.799}$	0.93	

* represents k in mm/s; # represents k in cm/s; k —co-efficient of permeability; k_c —co-efficient of permeability by constant head method; k_f —co-efficient of permeability by falling head method

relationship between compressive strength and porosity (Gaedicke et al., 2016). Regardless of the compaction method and paste content, the compressive strength reduces by 50% for every 10% increase in porosity (Deo & Neithalath, 2011). For the same porosity, uniform gradation of aggregates resulted in improved compressive strength (Crouch et al., 2007). Various equations relating to the effect of porosity on the compressive strength of pervious concrete are tabulated in Table 3.

5 Flexural Strength and Porosity

Hariyadi and Tamai (2015) state that a linear relationship between flexural strength and porosity exists for a porosity range of 25–35%. Flexural strength decreases by 25% with an increase in the porosity of the concrete from 15 to 25% (Liu et al., 2018b). Table 4 shows the variation of flexural strength with respect to the change in porosity of concrete.

6 Split Tensile Strength and Porosity

The exponential equation is used by Gaedicke et al. (2016) to represent the relationship between the split tensile strength and porosity values for all aggregate types and specimen types. Split tensile strength decreases with the increase in voids (Kevern et al., 2009). Splitting tensile strength of the cored specimen is lesser than that of the casted specimen due to the disturbance caused by the drilling process (Gaedicke et al., 2016). Table 5 lists the expressions representing the relationship between split tensile strength and porosity.

7 Density and Porosity

Density has a direct relationship with porosity, the higher the porosity the lesser the density of the concrete. El-Hassan et al. (2019) termed porosity as the predominant factor which

Table 3 Influence of porosity on compressive strength

Author	Relation	R ²	Remarks
Aliabdo et al. (2018)	$f_c = -0.9511(\text{voidratio}) + 25.659$	0.78	
Al-sallami et al. (2020)	$f_c = 42.133e^{-0.061n}$	0.99	For ACR = 6
	$f_c = 49.481e^{-0.068n}$	0.99	For ACR = 8
	$f_c = 48.33e^{-0.072n}$	0.95	For ACR = 10
Chindaprasirt et al. (2008)	$f_c = 152e^{-0.084n}$	0.96	
Elizondo-Martinez et al. (2019)	$f_c = -0.8323n + 27.811$	0.81	Proposed porous concrete design
	$f_c = -0.8102n + 28.205$	0.25	ACI design
Gaedicke et al. (2016)	$f_c = 48.112e^{-0.063n}$		For gravel
	$f_c = 40.565e^{-0.053n}$		For limestone
	$f_c = 37.965e^{-0.057n}$		For recycled aggregate blend
	$f_c = 41.229e^{-0.056n}$	0.82	For all specimens
	$f_c = 28.010e^{-0.047n}$	0.81	For cores
Nguyen et al. (2014)	$f_c = -1.6769n + 70.248$	0.87	
Bhutta et al. (2012)	$f_c = -1.2863(\text{voidratio}) + 46.692$	0.90	
Deo and Neithalath (2011)	$f_c = 98.32e^{-9.11n}$	0.77	
Hariyadi and Tamai (2015)	$f_c = -0.8312n + 37.617$		
Oz (2018)	$f_c = 79.96e^{-0.1035(\text{voidratio})}$	0.92	
Sriravindrarajah et al. (2012)	$f_c = 70.2e^{-0.066n}$	0.91	Natural Aggregates
	$f_c = 22.2e^{-0.052n}$	0.91	Recycled concrete aggregates
Lian et al. (2011)	$f_c = 231.44e^{-0.09n}$	0.90	
Lim et al. (2013)	$n = 65.531f_c^{0.404}$	0.79	
Liu et al. (2018a)	$f_c = -60.05n + 32.21$	0.78	
El-maaty (2016)	$f_c = 43.648e^{-0.0413(\text{voidratio})}$	0.64	
Muthaiyan and Thirumalai (2017)	$f_c = 56.838e^{-0.076n}$	0.80	Pervious cement concrete
	$f_c = 47.538e^{-0.072n}$	0.81	Pervious fly ash—cement concrete (10% fly ash replacement)
	$f_c = 41.302e^{-0.076n}$	0.84	Pervious fly ash—cement concrete (20% fly ash replacement)
Peng et al. (2018)	$f_c = 230.1e^{-0.121n_e}$	0.98	
Tabatabaeian et al. (2019)	$f_c = -2.3277(\text{voidratio}) + 121.63$	0.64	High-performance pervious concrete
Tijani et al. (2019)	$f_c = 0.54n^2 - 26.18n + 326.22$	0.88	
Maguesvari and Narasimha (2013)	$f_c = 330.4e^{-8.86n}$	0.94	
Wang et al. (2019)	$f_c = -1.813n + 62.91$	0.91	
Zhong and Wille (2015)	$f_c = -3.46n + 127$		High-performance pervious concrete
	$f_c = -1.07n + 41$		Pervious concrete

(continued)

Table 3 (continued)

Author	Relation	R ²	Remarks
Zhong and Wille (2016)	$f_c = -3.15n + 118$	0.60	Ultra-high strength matrix (UHSM)
	$f_c = -1.58n + 60$	0.97	High-strength matrix (HSM)
	$f_c = -1.07n + 41$	0.99	Normal strength matrix (NSM)
	$f_c = -2.52n + 116$	0.99	UHSM with an aggregate size of 1.19 mm
	$f_c = -2.57n + 101$	1.00	UHSM with an aggregate size of 2.38 mm
	$f_c = -2.61n + 94$	1.00	UHSM with an aggregate size of 4.75 mm
Crouch et al. (2007)	$f_c = -1.6902n_e + 67.789$	0.92	Mix A—Standard Mix
	$f_c = -1.6244n_e + 69.624$	0.99	Mix B—Uniform gradation
	$f_c = -1.2685n_e + 56.223$	0.99	Mix C—Uniform gradation with aggregate content of 58.7–61.7%
	$f_c = -1.2249n_e + 52.092$	0.99	Mix D—Uniform gradation with a maximum aggregate size of 19.5 mm (58.7–61.7%)
Lim et al. (2013)	$f_c = 63.579e^{-0.068n}$	0.93	
Cui et al. (2017)	$f_c = 10.156 + \frac{2566.466}{\pi} \frac{10.161}{4(n-0.453)^2 + 103.246}$	0.95	
Khankhaje et al. (2016)	$f_c = -0.615n + 23.50$	0.94	

n —porosity; n_e —effective or connected porosity; f_c —compressive strength at 28 days in MPa

Table 4 Dependence of flexural strength on porosity

Author	Relation	R ²	Remarks
Hariyadi and Tamai (2015)	$f_r = -0.0812n_e + 4.426$		
Liu et al. (2018a)	$f_r = -12.58n + 6.45$	0.71	
El-maaty (2016)	$f_r = 7.0441e^{-0.0511(\text{voidratio})}$	0.58	
Crouch et al. (2007)	$f_r = -29.205n_e + 1214.9$	0.38	f_r in psi
Cui et al. (2017)	$f_r = 1.979 + \frac{1283.830}{\pi} \times \frac{21.371}{4(p + 4.904)^2 + 456.720}$	0.83	

f_r —flexural strength at 28 days in MPa; n_e —effective porosity; n —porosity

Table 5 Dependence of split tensile strength on porosity

Author	Relation	R ²	Remarks
Bonicelli et al. (2015)	$f_t = -0.0282n + 1.7894$	0.23	
Elizondo-Martinez et al. (2019)	$f_t = -0.0521n + 2.2896$	0.65	Proposed porous concrete design
	$f_t = -0.0549n + 2.332$	0.19	ACI design
Gaedicke et al. (2016)	$f_t = 4.791e^{-0.048n}$		For recycled aggregate blend
	$f_t = 5.210e^{-0.055n}$		For gravel
	$f_t = 4.085e^{-0.043n}$		For limestone
	$f_t = 3.993e^{-0.046n}$	0.74	For core specimen
	$f_t = 4.695e^{-0.049n}$	0.78	All specimen type
Kevern et al. (2009)	$f_t = -0.0626n + 3.267$	0.77	7 days cured specimen
El-maaty (2016)	$f_t = 5.5831e^{-0.0747n}$	0.59	
Crouch et al. (2007)	$f_t = -18.418n + 776.27$	0.78	In psi

f_t —split tensile strength at 28 days in MPa; n —porosity

Table 6 Influence of porosity on the density of concrete

Author	Relation	R ²	Remarks
El-Hassan et al. (2019)	$\rho = 2150 - 22.5n$	0.92	
Kevern et al. (2009)	$\rho = 2409 - 19.4n$	0.96	
Cheng et al. (2011)	$\rho = 2748 - 33.734n$		
Liu et al. (2018a)	$\rho = 2440 - 2738n_e$	0.91	
	$\rho = 2491 - 2550n$	0.94	
Luck et al. (2006)	$\rho = 2387 - 20.41n$	0.89	
El-maaty (2016)	$\rho = 2623.6 - 23.017e$	0.96	
Rangelov et al. (2016)	$\rho = 2147.2 - 4.4n$	0.27	Control
	$\rho = 2528.8 - 23.1n$	0.97	CCFCM specimen
Tijani et al. (2019)	$\rho = 4635 - 4.44n^2 - 218.80n$	0.98	
Rodin et al. (2018)	$\rho = 2308 - 1646.7n$	0.92	CrPc0
	$\rho = 2445.7 - 2303.4n$	0.98	CrPc3
	$\rho = 2360.7 - 2158.2n$	0.94	CrPc4
	$\rho = 2323 - 2016.4n$	0.95	CrPc5
Costa et al. (2018)	$\rho = 2429.6 - 1755.6n$	0.98	Casted specimen
	$\rho = 2513.3 - 2186.4n$	0.89	Cored specimen
Sonebi et al. (2016)	$\rho = 2566.7 - 33.3e$	0.87	

ρ —density of concrete in kg/m³; n —porosity; n_e —effective porosity, e —Void ratio

influences the hardened density of pervious concrete. The addition of GGBS in place of cement decreases the porosity which in turn improves the density of concrete. This proves the influence of porosity on the density of concrete. El-maaty (2016) developed a negative linear relationship between the density and porosity i.e. the decrease in density with an increase in porosity. Similarly, negative linear expressions are established by Rodin et al. (2018) for carbon fiber-reinforced pervious concrete (CrPc) as shown in Table 6. Liu et al. (2018b) describe that the density of pervious concrete decreases by 28.6 kg/m³ for a 1% increase in total porosity. Among the investigated literature, most of the studies observed a linear relationship between density and porosity. The relationship between density and porosity is highly influenced by the compaction method (Costa et al., 2018).

8 Flexural Strength and Compressive Strength

In order to estimate the flexural strength of pervious concrete by experimenting with only the compressive strength values, the correlation between flexural strength and compressive strength is essential (Hariyadi & Tamai, 2015). Flexural strength of pervious concrete increases from 12 to 42% (27% on average) with the increase of its compressive strength based on a square root relationship (Aliabdo et al., 2018). Shah and Ahmad (1985) recommend a power greater than the square root for achieving the best fit between flexural strength and compressive strength. The ratio of flexural

strength to compressive strength lies in the average range of 12.5% and 18% which shows that the use of recycled aggregates increases this range due to major decrease in compressive strength, whereas the addition of GGBS improves the matrix strength as well as the aggregate interfacial bond (El-Hassan et al., 2019). IS 12727-1989 (1989) states that flexural strength pertains to 23% of the compressive strength. Kuo et al. (2013) reported flexural strength as 1/4th of the compressive strength value. Figure 1 gives the graphical representation of the variation of flexural strength with respect to the compressive strength values for the relations mentioned in Table 7.

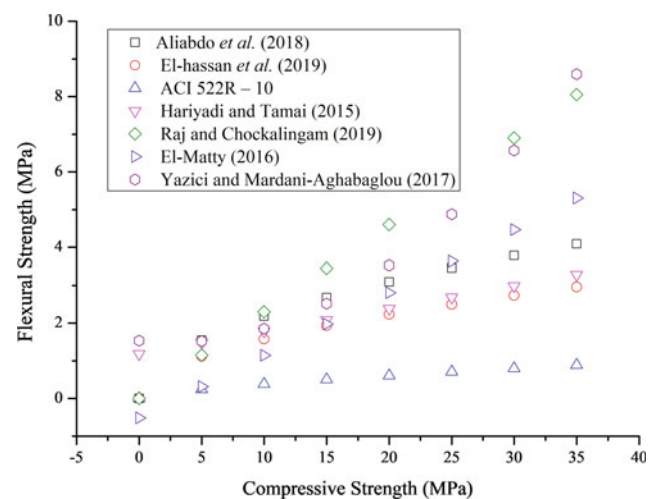
**Fig. 1** Flexural strength versus compressive strength

Table 7 Relationship between flexural strength and compressive strength

Author	Relation	R ²	Remarks
Aliabdo et al. (2018)	$f_r = 0.6915f_c^{0.5}$	0.65	
El-Hassan et al. (2019)	$f_r = 0.50f_c^{0.5}$	0.97	
ACI 522R-10 (2010)	$f_r = 0.083 f_c^{2/3}$		
Hariyadi and Tamai (2015)	$f_r = 0.0601f_c + 1.1844$		
Raj and Chockalingam (2020)	$f_r = 0.23f_c$		Based on IS 12727-1989
Lim et al. (2013)	$f_c = 8.0233e^{0.2124f_r}$	0.34	
El-maaty (2016)	$f_r = 0.1661f_c - 0.5118$	0.99	
Yazici and Mardani-Aghabaglou (2017)	$f_r = 0.0068f_c^2 - 0.0363f_c + 1.537$	0.99	
Shah and Ahmad (1985)	$f_r = 2.3f_c^{0.6667}$		
Crouch et al. (2007)*	$f_r = 7.5f_c^{0.5}$		

f_r —flexural strength at 28 days in MPa; f_c —compressive strength at 28 days in MPa; *—in psi.

9 Split Tensile Strength and Compressive Strength

El-maaty (2016) states that the rate of increase of both flexural and split tensile strength with the increase in compressive strength follows a similar trend. Splitting tensile strength of pervious concrete pertains to an average of 20% of compressive strength ranging from 5 to 35% (Aliabdo et al., 2018). Split tensile strength pertains to 12–15% of the value of compressive strength (Bonicelli et al., 2015) which is close to the IS 12727-1989 (1989) specification (16%). A similar range of 10–14.2% was reported by Ghafoori and Dhutta (1995). Kuo et al. (2013) mention the split tensile strength as 1/9th of the compressive strength values. This is in line with the finding of Crouch et al. (2007) which reveals that the ratio of split tensile strength to compressive strength lies in the range of 8–14% based on the type of aggregates used. El-Hassan et al. (2019) determined that the split tensile strength lies in the range of 10.5 and 15.4% of its compressive strength which increases with the increase in the proportion of recycled aggregates. This varying percentage is mainly due to the higher influence of recycled aggregates on the compressive strength than on the split tensile strength. Moreover, the ratio is found to decrease with increasing strength and age (Shah & Ahmad, 1985). The slope of the relationship curve will be higher in case of higher variation between compressive and split tensile strength for the same porosity as observed in Fig. 2 for recycled aggregate pervious concrete mixtures (Gaedicke et al., 2016). Table 8 shows the various relations established between split tensile strength and compressive strength.

10 Compressive Strength and Density

In general, compressive strength increases with the increase in the density of the concrete (Fig. 3). This is obvious from the comparison of compressive strength and density of pervious and conventional concrete. Based on the experiment by Lori et al. (2021), increase in mechanical properties of concrete can be related to the increase in density of concrete. Mere extrapolation of the relationship above the experimented values does not result in appropriate results as shown in Fig. 3. Hence, it is recommended to undertake future research focusing on identifying the relation between compressive strength and density of pervious concrete.

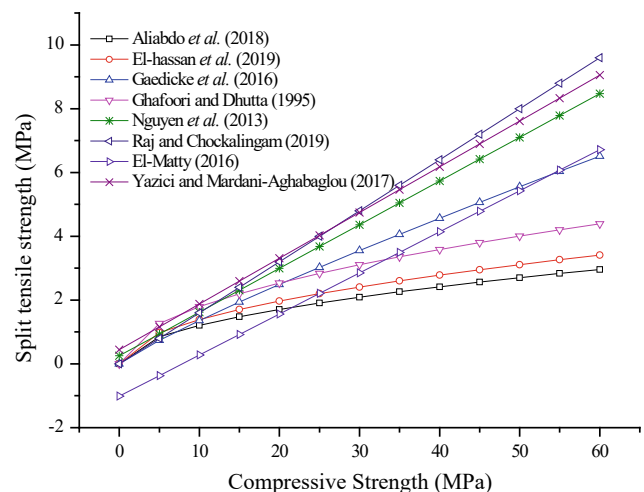
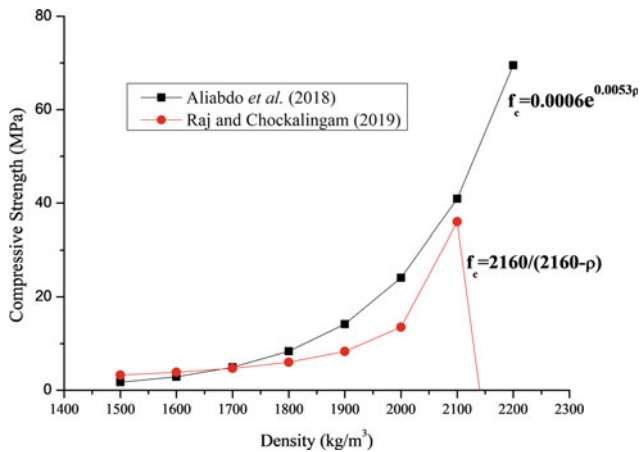
**Fig. 2** Split tensile strength versus compressive strength

Table 8 Relationship between split tensile strength and compressive strength

Author	Relation	R ²	Remarks
Aliabdo et al. (2018)	$f_t = 0.382f_c^{0.5}$	0.45	
El-Hassan et al. (2019)	$f_t = 0.44f_c^{0.5}$	0.92	
Gaedicke et al. (2016)	$f_t = 0.224f_c^{0.842}$		Recycled aggregate
	$f_t = 0.177f_c^{0.873}$		Gravel
	$f_t = 0.203f_c^{0.811}$		Limestone
	$f_t = 0.181f_c^{0.875}$		All aggregates
	$f_t = 0.153f_c^{0.979}$		All specimen type
Ghafoori and Dhutta (1995)	$f_t = 5.67f_c^{0.5}$	0.92	At 28 days in psi
	$f_t = 5.90f_c^{0.5}$		At 60 days in psi
	$f_t = 6.15f_c^{0.5}$		At 90 days in psi
Nguyen et al. (2014)	$f_t = 0.137f_c + 0.253$	0.85	
Raj and Chockalingam (2020)	$f_t = 0.16f_c$		Based on IS 12727-1989
El-maaty (2016)	$f_t = 0.1288f_c - 1.0121$	0.97	
Yazici and Mardani-Aghabaglou (2017)	$f_t = 0.1434f_c + 0.4458$	0.99	
Shah and Ahmad (1985)*	$f_t = 4.34f_c^{0.55}$		
Khankhaje et al. (2016)	$f_t = 0.213f_c - 0.372$	0.37	
Zaetang et al. (2015)	$f_t = 0.179f_c^{0.85}$	0.91	
	$f_t = 0.56f_c^{0.5}$		

f_t —split tensile strength at 28 days in MPa; f_c —compressive strength at 28 days in MPa; *—in psi

**Fig. 3** Compressive strength versus density

11 Conclusion

The review of various literature related to the volumetric, mechanical and hydrological properties reveals a promising future by indicating the possibility of producing pervious concrete suitable for high-intensity and heavy-loaded traffic. The study on the inter-relationship between the properties of concrete helps in understanding the interdependence of design factors and achieving the balance between the mechanical strengths and hydrological properties of pervious concrete.

Following are the key conclusions that can be drawn from the study:

Porosity: Effective porosity predominantly defines the hydrological, mechanical and durability properties of pervious concrete. An increase in porosity improves permeability by compromising mechanical properties. The relationship between porosity and other properties revealed that porosity defines almost all properties of pervious concrete.

Permeability: Permeability is highly influenced by effective porosity and thus factors that influences porosity have a similar effect on permeability as well. Standardized method for permeability measurement (either by falling head or constant head) becomes essential universally for comparing permeability of different mixes under uniform conditions.

Compressive Strength: Compressive strength is highly dependent on the strength, thickness and volume of paste which fills the voids between aggregates and is thus influenced by design factors such as cement content, w/cm, ACR, size of aggregates, sand fraction and aggregate gradation. In general, factors which improve porosity decreases compressive strength.

Flexural strength: Factors which influences the compressive strength also affects the flexural strength due to their direct

relation. With the variations in the mix properties, Flexural strength ranges between 12 and 18% of its compressive strength.

Split tensile strength: Effect of porosity will be higher on split tensile strength due to the propagation of tensile cracks through the pores. Split tensile strength pertains to nearly 10–15 and 65% of compressive strength and flexural strength respectively depending on the mix parameters.

Density: Density of pervious concrete ranges from 60 to 85% of conventional concrete density attributed by its pore structure. Density of pervious concrete predominantly depends on the method of compaction, density of aggregates, porosity and the properties of paste.

Pervious concrete holds key to the mitigation of various problem related to the effective management of stormwater. The current study can act as a platform that provides an extensive list of the relationship between properties of pervious concrete. Moreover, the study emphasises the establishment of the relationship between the major properties of pervious concrete in future studies to understand the influence of various design parameters and in identifying the possibilities of producing high-performance pervious concrete as per the site requirements.

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Ensemble Learning in Concrete Engineering: Towards Reliable Strength Estimation for Concrete Quality Assurance

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Abstract

Predicting the strength properties of concrete is a complex problem as it involves many variables, such as the type and amount of cement, aggregates, admixtures, the water-cement ratio, the age of the concrete, and the curing conditions. In general, Machine Learning (ML) techniques such as regression analysis, support vector machines, decision trees, and neural networks are widely utilized for concrete strength prediction by training the models on available datasets to learn the relationship between the input features and the target output (i.e., strength properties) and then used to make predictions on new data. The traditional ML algorithms lack offering precise predictions due to their inability to capture the complex relationships between the input and output variables. In order to improve the efficiency of the model, it is proposed to implement ensemble learning techniques such as Random Forest, AdaBoost, Gradient Boost, and XGBoost algorithms for clear-cut strength prediction. As ensemble models work by combining different learning techniques, it promises to enhance the model performance in terms of accuracy and efficiency. The ensemble models are trained and tested on two

different datasets. The one that is readily available in the UCI repository and the other one is created with the laboratory results. From the result analysis, it is identified that XGBoost outperforms the other learning models with improved accuracy—92% for dataset 1, 89% for dataset 2, and decreased statistical error—MAE, MSE, RMSE.

Keywords

Concrete strength properties • Ensemble learning techniques • Bagging • Boosting • Machine learning algorithms

1 Introduction

Recent years have witnessed the utilization of Machine Learning (ML) algorithms in various platforms for autonomously understanding and evaluating complex data. ML provides valuable insights for solving complex challenges and generates effective solutions. For example, in the areas of social science, biotechnology, and ecology, Machine Learning (ML) models are incorporated to analyze complex big data challenges and identify useful data patterns. ML is also used to develop prediction models for predicting climatic changes. This emerging technology has the potential to be incorporated into the civil engineering domain to perform data interpretation.

Concrete is the most commonly used building material, which is well-known for its durability and adaptability. Most of the time, the strength of the concrete is influenced by the materials used, its preparation process and the environment. The factors that influence concrete strength are the water-to-cement ratio and the curing environment. The number of variables, including the quality and quantity of the components, curing conditions, and climatic considerations play a crucial role in assuring the safety and durability of concrete structures. The overall strength and durability of

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concrete in various applications are significantly influenced by all these strength qualities.

Compressive strength determines the extreme quantity of strength a material can withstand before fracturing. It is widely measured in concrete objects such as column beams, where compressive load plays a pivotal role. Tensile strength measures the ability of concrete to resist tension or stretching forces. Concrete is generally weaker in tension than in compression, and tensile strength is an important consideration in applications where the concrete is subjected to tensile loads, such as in beams or slabs. Flexural strength measures the ability of concrete to resist bending or flexing forces. It is important in applications where the concrete is subjected to bending loads, such as in beams or lintels.

Among the above-mentioned applications, the proposed work implements advanced machine learning algorithms such as ensemble learning models to predict the strength properties of the concrete such as compressive strength, split tensile strength, and flexural strength.

The rest of the paper is organized as follows: literature survey, machine learning vs. ensemble learning techniques, data collection, implementation of ensemble techniques, results and discussion, conclusion, and future work.

2 Background and Related Works

2.1 Literature Survey

Nowadays, a variety of scientific issues are predicted using machine learning approaches such as decision trees (DT), artificial neural networks (ANN), support vector machines (SVM), genetic algorithms, and deep learning (DL) structures (Foucquier et al., 2013). The architecture of SVM is such that it can cope with the nonlinear regression issues in a better way to overcome the shortness of these approaches (Lv et al., 2013). It can obtain a superior global optimal result rather than a local optimum and has a well-generalized ability. The random forest (RF) and decision tree (DT) operate like a tree structure and employ roots and nodes to forecast the results, respectively (Dou et al., 2019). Although RF chooses feature variables from a random set of options within the parameters that determine the number of prediction trees, DT employs a full database with the variable of interest.

After the forecast is averaged and related to the largest number of votes, it is shown to be correct. The Darwinian evolution process is mimicked by one of the most recent ML computer-based algorithms, called GEP (Zhang & Tsai, 2003). It uses a tree of expression types to represent the nonlinear connection. It is common practice to employ machine learning (ML) techniques to bring out hidden patterns, data, and relationships from huge databases. Yet, this

technique makes use of machine learning, statistical analysis, database technology, and database technology. Prediction and modeling both employ two different strategies. One of them is a standard approach situated on a single separate model, and another is known as the ensemble algorithm approach (Chou & Pham, 2013).

For many years, the performance of many metrics has been predicted using machine learning methods. Yet, in recent years, there has been a noticeable trend towards their increased usage in civil engineering. It's because they can forecast mechanical qualities with a high degree of precision. While nonlinear characteristics are more precise than linear characteristics, machine learning (ML) algorithms follow a similar basic concept to conventional algorithms. The investigation of the mechanical characteristics of concrete frequently employs artificial neural networks (ANN), decision trees (DT), support vector machines (SVM), random forests (RF), gene expression programming (GEP), and deep learning (DL) (Salehi & Burgueño, 2018). For the shear strength prediction of the steel fiber reinforced concrete beams, Rahman et al. (2021) employed eleven methods.

To estimate the mechanical characteristics of the silica fume concrete, Behnood and Golafrshani (2018) employed an ANN with an optimizer known as a multi-objective grey wolf (MOGW). For the prediction of concrete compressive strength, Güçlüer et al. (2021) employed DT, ANN, SVR, and LR. The compressive strength and tensile strength of waste concrete were predicted using the ANN approach of Getahun et al. (2018). Ling et al.'s (2019) prediction of the compressive strength of concrete in maritime environments was evaluated against ANN and DT models. Using a variety of machine learning techniques, Yaseen et al.'s (2018) prediction of the compressive strength of lightweight foamed concrete. The durability of reinforced concrete buildings was also evaluated by Taffese and Sistonen (2017) using a machine learning method.

Machine learning has been used by Yokoyama and Matsumoto (2017) to create an autonomous fracture detector for concrete constructions. Deep learning was employed to detect cracks while learning data from snapshots of concrete samples was utilized for learning. The accuracy of the machine learning models has been evaluated by Ben Chaabene et al. (2020). To further forecast the interfacial bond strength of fibre-reinforced polymers (FRPs) and concrete, Su et al. (2021) employ SVM and ANN. Several ML algorithms can predict the mechanical characteristics of concrete with accuracy. For the prediction of various concrete qualities, the ANN, DT, SVM, GEP, and other ensemble ML techniques are the most often used.

Iqbal et al.'s (2020) use of the GEP approach to forecasting the mechanical characteristics of green concrete including waste foundry sand serves as an example of the model's successful application to prediction. The study by

Behnood and Golafshani (2018) used an ANN technique to predict the mechanical characteristics of sustainable concrete made from foundry sand. According to research, any type of concrete may be accurately predicted using the ANN approach. In order to estimate mechanical characteristics from microstructure pictures in the fiber-reinforced polymer, Sun et al. (2020) utilized a typical neural network. It was mentioned that using trained models might help locate probable damage sites in fiber-reinforced polymers.

The performance evaluation of ANN and SVM algorithms for the prediction of concrete's compressive strength was the foundation of Akande et al.'s (2014) work. In comparison to the ANN technique, the study showed that the SVM strategy performed marginally better in terms of advancement. Since it requires a lot of physical labor and time in the laboratory to produce the required results, concrete's mechanical characteristics prediction is the most common. To forecast the C-S of concrete using recycled coarse aggregate, Ahmad et al. (2021a) used gene expression programming (GEP) and artificial neural networks (ANN). As compared to the ANN model, it was claimed that the GEP model was more accurate in making predictions.

The ANN model performed satisfactorily in terms of forecasting in Song et al.'s (2021) research, which was based on the use of the ANN technique to predict the C-S of ceramic waste-based concrete. The use of supervised ML systems to forecast the C-S of concrete at high temperatures was demonstrated by Ahmad et al. (2021b). For the prediction of both C-S and tensile strength, Nguyen et al. (2021) used a variety of machine learning (ML) techniques, and it was suggested that the gradient boosting regressor (GBR) and extreme gradient boosting (XGBoost) approaches were superior to support vector machine (SVM) and multilayer perceptron (MLP). According to Kaloop et al.'s (2020) research, which was based on the C-S prediction of high-performance concrete, a high R^2 value denotes the greater performance of the model.

According to earlier studies on these algorithms, ensemble approaches appear to be more accurate than traditional individual ML models (Galar et al., 2012). Using training data, ensemble learning algorithms are primarily used to first train the base learners aka weak learners, who are subsequently integrated into strong learners (Gomes et al., 2017).

2.2 Machine Learning Versus Ensemble Learning Techniques

Machine learning and ensemble learning are the subfields of artificial intelligence, but they differ in their approach and methodology. In machine learning, the learning model is trained on a large set of labeled data points, and then uses that training to impose predictions on new, unlabeled data

points. In contrast, ensemble learning techniques combine multiple machine learning models, each of which has different strengths and weaknesses. The idea of ensemble learning is that by combining several models, the overall accuracy of the predictions can be improved (Galar et al., 2012). This approach can be particularly effective for predicting concrete strength properties because it can account for the variability and uncertainty in the data. Ensemble learning techniques can be divided into two categories:

2.2.1 Bagging

In bagging, multiple models are trained independently on random portions of the training samples. The final estimation is obtained by averaging the estimations of all the independent models. Random forest is an example of a bagging ensemble technique. Bagging model is shown in Fig. 1.

2.2.2 Boosting

In boosting, the learners are trained sequentially, and each learner is trained to correct the mistakes made by the previous learner. The final output is obtained by combining the estimations of all the individual learners, with more weight given to the more accurate models. AdaBoost and Gradient Boosting are examples of boosting ensemble techniques (Fig. 2).

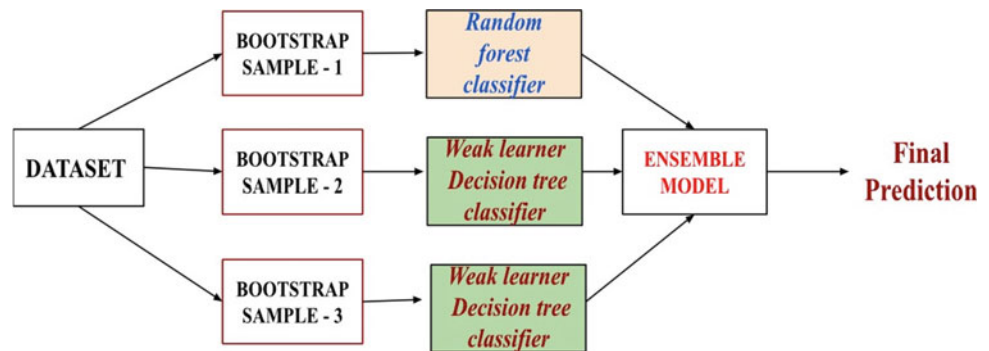
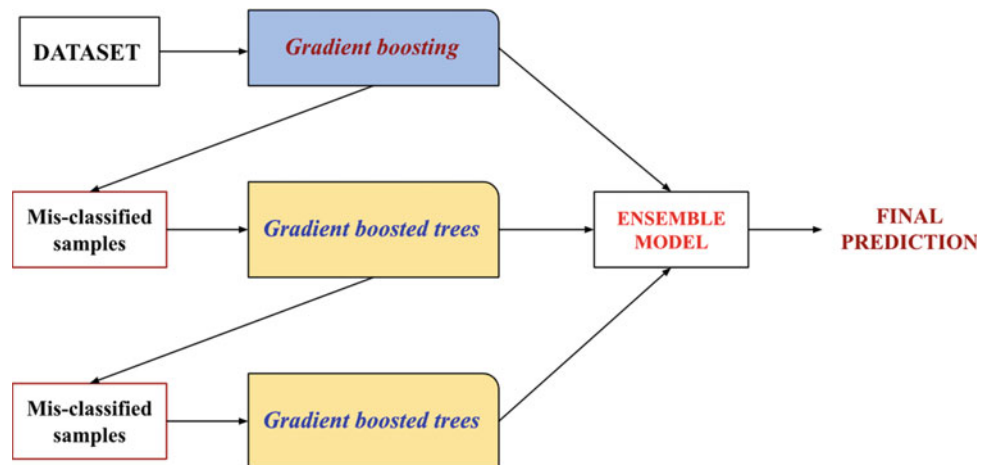
The proposed work implements different ensemble approaches such as random forest, AdaBoost, Gradient Boost and XGBoost algorithms, and the most suitable algorithm for strength prediction is identified by the decreased statistical error (MSE, RMSE, MAE).

3 Implementation of Ensemble Learning Techniques

3.1 Data Collection

The proposed ensemble model is trained and tested with two different datasets, each with a combination of a different set of input features.

The dataset 1 is collected from experimental results obtained from the laboratory. The compressive strength, tensile strength, and flexural strength of concrete are obtained for three different grades of concrete M15, M20, and M25 with ratios of 1:2:4, 1:1.5:3, and 1:1:2. For the prescribed mix proportion the recycled aggregate is incorporated as a partial replacement with 5, 10, 15, 20% of fine aggregate. There are 180 numbers of instances with 6 attributes. The attributes are quantity of coarse aggregate, fine aggregate, cement, recycled aggregate, water-cement ratio, and curing period. The dataset is trained to predict the concrete compressive strength, tensile strength, and flexural strength under the influence of the 6 attributes.

Fig. 1 Bagging model**Fig. 2** Boosting model

The dataset 2 titled concrete compressive strength is considered for strength prediction and is available in the UCI machine learning repository (<https://archive.ics.uci.edu/ml/datasets/Concrete+Compressive+Strength>). There are 1030 numbers of instances with 9 attributes. The attributes are cement, blast furnace slag, fly ash, water, superplasticizer, coarse, fine aggregate, age and concrete compressive strength (predictor). The dataset is trained to predict the concrete compressive strength under the influence of the 8 attributes.

3.2 Ensemble Models Chosen for Implementation

The architecture for the proposed system is shown in Fig. 3. Based on the literature survey the algorithms such as random forest, AdaBoost, gradient Boost, and XGBoost are chosen for implementation.

3.2.1 Random Forest

In this model, during the training process, several decision trees are created. The forecasting made by each individual tree is combined to arrive at the ultimate prediction. This

process varies for classification as well as regression problems. In case of classification problems, the voting technique is adopted and the class with the majority of votes is chosen as the forecasted class value. On the other hand, in the case of regression problems, the mean value of the outcomes is computed to predict the final output. This technique is called ensemble learning due to the fact that it combines multiple outcomes to make a definitive decision.

3.2.2 AdaBoost (Adaptive Boosting)

This is a type of ensemble method in which several weak learners are fused together to build a powerful forecasting model. In the AdaBoost regression model, every sample in the training process is associated with weight parameters. The weak regression model then learns from the set of samples with weighted parameters to make effective predictions with minimized errors. These weak regression models exist in the form of decision trees which are basically binary trees. These kinds of models with binary decision trees are known as the stumps in ensemble techniques. After every iteration, the associated weight parameters are updated based on the error exhibited by the weak learner. The algorithm for the AdaBoost model is presented in Fig. 4.

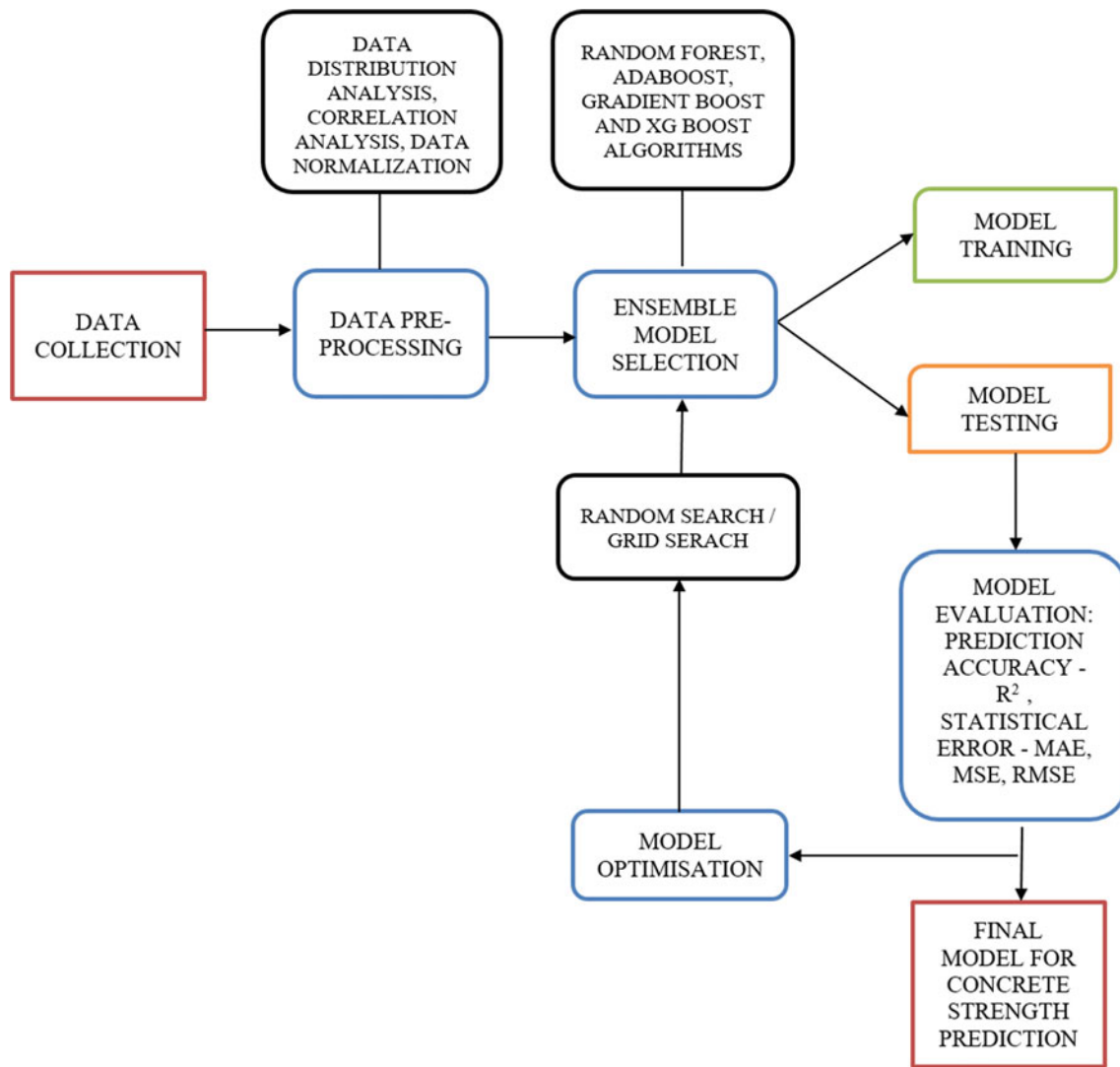


Fig. 3 Proposed ensemble model for concrete strength prediction

3.2.3 Gradient Boosting

This is a type of ensemble technique in which the gradient descent method is used to minimize the errors by optimizing the deviation between the actual and expected predictions which are known as residuals. For every iteration of the algorithm, a gradient is calculated and employed to modify the model parameters to decrease the loss. This model is trained in such a way that the residuals from the preceding model are reduced in the new model. This process is executed in several iterations until the loss is lessened to an admissible level. The algorithm for gradient boosting is presented in Fig. 5.

3.2.4 XGBoost (Extreme Gradient Boosting)

This is another important technique under ensemble methods which makes efficient predictions by employing decision trees as the base learners. This algorithm is capable enough

to handle the intricate and dynamic association between the input as well as target variables, which in this research is highly essential to model the complicated nature of concrete. It can also identify the most important variables (features) for predicting concrete strength, which helps to enhance the mix ratio of concrete and improve its strength properties. XGBoost has regularization techniques that can help prevent overfitting, which is important for ensuring that the learning model can generalize well to new samples. The drawbacks of the decision tree algorithm are improved by the XGBoost algorithm. From the literature survey, it is evident that XGBoost can estimate concrete strength properties, in a precise manner compared to traditional regression algorithms. As such, XGBoost is a promising technique for estimating the strength properties of concrete and improving the construction of concrete structures.

Fig. 4 AdaBoost algorithm**Algorithm 1:** Adaboost algorithm

Step 1: Consider dataset with T samples, compute weight for each sample as

$$wt_a = \frac{1}{T}.$$

Step 2: for x=1 to X:

- Split the dataset based on weights $wt_a^{(x)}$ to produce the samples are training process such as j_a .
- Assign a classifier C_x using j_a .
- Calculate $\gamma = \frac{\sum_{k \neq C_x(j_a)} wt_a^{(x)}}{\sum_k wt_a^{(x)}}$ where k is the truth value of target and $wt_a^{(x)}$ is the weight associated with a for the iteration x.
- Determine $\delta_x = \frac{1}{2} \ln \frac{1-\gamma}{\gamma}$
- Modify weights as $wt_a^{(x+1)} = wt_a^{(x)} e^{-\delta_x k C_x(j)}$.

Step 3: Compute new predictions as $C(x) = \text{sign}[\sum_{x=1}^X \delta_x C_x(j)]$.

Fig. 5 Gradient boosting algorithm**Algorithm 1:** Gradient Boosting algorithm

Step 1: Initialize model as $C_0(a) = \underset{x=1}{\operatorname{argmin}} \sum_{x=1}^N H(b_x, \alpha)$

Step 2: for i=1 to I:

- Calculate residuals as $rs_d = - \left[\frac{\delta H(b_x, C(a_x))}{\delta C(a_x)} \right]_{C(a)=C_{i-1}(a)}$ for $x = 1, \dots, N$
- Trees are trained with features a to reduce residuals, rs_d
- Compute multiplier $\theta_m = \underset{x=1}{\operatorname{argmin}} \sum_{x=1}^N H(b_x, C_{i-1}(a_x) + \theta f_i(a_x))$
- Update model as $C_i(a) = C_{i-1}(a) + \theta_m f_i(a)$

Step 3: Output $C_i(a)$.

4 Results and Discussion

The datasets are collected and the learning models are trained to estimate the concrete strength by implementing the above ensemble algorithms. Jupyter Notebook/Google Colab is used to develop the ensemble models and are validated against the two datasets. Initially, the distribution in

the datasets is analyzed and checked for missing values, errors and outliers by performing standardization, normalization and correlation analysis. The attributes with an increased number of outliers are identified using box plots and the relationship between the attributes is determined using heat maps. The datasets are broken into training sets and testing sets in the proportion 70:30, 70% of the dataset will be used to train the models and the rest of the dataset

will be utilized to test the extent to which the models have learned to predict the concrete strength. In ensemble learning, the predictions of multiple base models are combined to make more error-free predictions. Therefore, during training, the weak learners are trained on a subset of the training data, with different subsets used for each model in the ensemble as mentioned in Figs. 2 and 3. In the Random Forest algorithm, a bagging approach is followed, where weak learners are used to create an ensemble of decision trees that work together to make more accurate predictions than any individual tree. Specifically, each individual tree in the forest is a weak learner, which is again trained on a bootstrapped sample of the training data with a random set of features assessed at each and every split. Finally, the predictions of all base learners are combined through simple averaging, which will provide the final prediction for strength prediction.

In AdaBoost, Gradient Boost, XGBoost, boosting approach is followed, where base learners are trained sequentially, with each learner trying to correct the mistakes made by the previous learners. The training data is weighted, and the base learners are trained on different versions of the data, where the weights are adjusted based on the performance of the previous learners. The final result is obtained by integrating the results of all base learners, typically using a weighted sum. AdaBoost and Gradient Boosting, iteratively create base learners that focus on the previously misclassified instances, gradually improving the overall model's accuracy (Mienye & Sun, 2022).

During model selection, the chosen hyperparameters are fine-tuned, in order to improve and generalize the models' behavior on unseen data. The goal of hyperparameter tuning is to search for the best fusion of hyperparameter values that maximizes the model's efficiency. In the proposed work, random search is used for hyperparameter tuning that systematically searches through a predefined grid of hyperparameter values to find the optimal combination—{'n_estimators': 400, 'min_samples_split': 2, 'min_samples_leaf': 4, 'max_features': 'sqrt', 'max_depth': 40, 'bootstrap': True} that maximizes or minimizes the chosen evaluation metric such as R^2 , MAE, MSE, and RMSE. The hyperparameters utilized for the ensemble models are: {'n_estimators': n_estimators, 'max_features': max_features, 'max_depth': max_depth, 'min_samples_split': min_samples_split, 'min_samples_leaf': min_samples_leaf, 'bootstrap': bootstrap}. The results obtained for the ensemble model are validated with the statistical parameters— R^2 , MAE, MSE, and RMSE.

R^2 refers to the coefficient of determination that implies how well the predicted values fit when compared to the actual values. Higher values of R^2 indicate the model most efficient model. $\hat{y}$ – predicted value of y , $\bar{y}$ – mean value of y

$$R^2 = 1 - \frac{\sum_i (y_i - \hat{y}_i)^2}{\sum_i (y_i - \bar{y})^2} \quad (1)$$

MAE refers to the Mean Absolute Error, which represents the difference between actual values and predicted values obtained by averaging the total difference over the data points.

$$MAE = \frac{1}{n} \sum_{i=1}^n |y_i - \hat{y}_i| \quad (2)$$

MSE refers to the Mean Squared Error, which represents the difference between actual values and predicted values obtained by squaring the mean difference over the data points.

$$MSE = \frac{1}{n} \sum_{i=1}^n (y_i - \hat{y}_i)^2 \quad (3)$$

RMSE refers to the Root Mean Squared Error, which represents the difference between actual values and predicted values obtained by squaring the mean difference over the data points.

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (y_i - \hat{y}_i)^2} \quad (4)$$

The performance of the model for the two datasets is compared between the results obtained before and after hyperparameter tuning. The result analysis depicts that XGBoosting outperforms all the ensemble models. The results are mentioned in the following Tables 1 and 2.

The execution time for the chosen datasets is also considered by modifying the hyperparameters. The average execution time taken by XGBoost is 0.30 s, with n_estimator = 400 and max_depth = 40 as the sample hyperparameter in the parameter grid. Thus the set of ensemble models used in the proposed system are feasible and efficient in estimating the different concrete strength characteristics and are validated against the laboratory results and the available datasets.

5 Conclusion and Future Research

In this study, ensemble Machine Learning algorithms are used to anticipate the mechanical characteristics of concrete with recycled coarse aggregate, including compressive strength, tensile strength, and flexural strength. For the purpose of prediction, Random Forest, AdaBoost, Gradient boosting, and XGBoost techniques were utilized. The Spyder framework was employed to develop programs in Python to execute the necessary models for empirical investigation. To

Table 1 Results before adjusting the hyperparameters

Algorithm	Statistical measure	Dataset-1	Dataset-2
Random forest	R^2	0.81	0.83
	MAE	13.1	17.8
	MSE	40.7	33.1
	RMSE	19.3	21.8
AdaBoost	R^2	0.84	0.81
	MAE	11.3	14.9
	MSE	33.7	32.4
	RMSE	14.3	14.8
Gradient boosting	R^2	0.87	0.85
	MAE	10.5	13.6
	MSE	32	28.9
	RMSE	12.2	16.1
XGBoost	R^2	0.90	0.87
	MAE	10	13
	MSE	15.6	19.1
	RMSE	11.1	14.7

Table 2 Results after adjusting the hyperparameters

Algorithm	Statistical measure	Dataset-1	Dataset-2
Random forest	R^2	0.87	0.85
	MAE	8.5	14.1
	MSE	32.4	29.3
	RMSE	12.7	20
AdaBoost	R^2	0.88	0.82
	MAE	7.6	11
	MSE	30.4	30.7
	RMSE	10.3	13.1
Gradient boosting	R^2	0.90	0.86
	MAE	3.5	11.9
	MSE	29	26.1
	RMSE	10.7	14
XGBoost	R^2	0.92	0.89
	MAE	3.6	11.8
	MSE	18.31	17
	RMSE	9.47	12.5

verify the accuracy of each used model, statistical evaluations in the form of various errors such as Mean Absolute Error, Mean Squared Error, and Root Mean Squared Error were determined. The prediction of the strength properties of concrete is significantly improved with reduced variance using the ensemble machine learning algorithm, XGBoost. Contrary to the values of R^2 for Random Forest, AdaBoost, and Gradient Boosting which are 0.87, 0.88, 0.90 for dataset

1 and 0.85, 0.82, 0.86 for dataset 2, XGBoost regressor provides a coefficient correlation R^2 values of 0.92 for dataset 1 and 0.89 for dataset 2. The XGBoost regressor's higher R^2 values for the prediction of strength properties relate to the model's excellent accuracy. According to the statistical assessments, the XGBoost technique performs superior to the other considered algorithms, as demonstrated by the lower values of the statistical errors.

The significance of these methods in civil engineering is illustrated by the remarkable degree of accuracy between the predicted and actual results. Ensemble Machine Learning techniques are becoming more and more popular as their utilization produces high-precision outcomes and reduces the physical approach of the operational job while minimizing the overall project cost as well. The present research can be extended to examine and evaluate the outcomes of different machine learning algorithms as well as to minimize the errors, by considering more factors such as k-fold cross-validation, regularization, the sample points, the kind of medium used, the number of samples, environmental exposures, curing conditions, substrate concentration, and elevation in the model parameters. Additionally, several deep learning techniques including artificial neural networks, deep neural networks and multilayer perceptrons can also be explored to improve the effectiveness of strength prediction.

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Effect of Leading-Edge Shapes in NACA2421 Aerofoil with Different Angles of Attacks

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Abstract

The profile and aerofoil geometry of the blade affect the aerodynamic effectiveness of a wing or wind turbine. Generally, wing/wind turbine manufacturing purely focuses on materials, reliability, blade performance and cost. In research this work, to investigate the three different shapes of leading-edge the following radius such as Elliptical, Circular and Conical shapes on the aerodynamics efficiency is considered for the wind turbine or even the airfoils of the wing. In accordance with the current research, NACA2421 airfoil is considered for the study. In the wind tunnel, the impact of three leading-edge profile airfoils has been examined with the help of three component force balance instruments at various angles of attack such as 0° , 5° , 10° , 15° , -5° , -10° , -15° respectively. The target of the task is to find out the lift coefficient and drag coefficient at different leading-edge radii of NACA 2421 aerofoil and compared the results of the Elliptical, Circular, Cone leading edge of the aerofoil with standard baseline airfoil.

Keywords

Aerofoil • Wind tunnel • Leading edge radius • NACA 2421 • Lift Co-efficient • Drag Co-efficient • Angles of attack

1 Introduction

To understand the consequences of leading-edge radius on NACA 2421 airfoil with various angles of attacks by comparing C_L and C_D with the literature values. The maximum lift coefficient of a thin aerofoil that stalls because of flow separation at the leading edge can be determined based on the position of the leading edge. Operational efficiency of the airfoil declines as the leading-edge radius rises, while the performance spectrum widens. Thus, in the case below 7° the lift generated is very low and after 14° the wing begins to stall as well and the critical angle of attack is reached. By lowering the radius of the leading edge, the effectiveness of the aerofoil rises, however, the range gets shorter. With a shrinkage in blending distance from the leading edge upward to a 7-degree angle of attack, the ratio of the lift-to-drag coefficient climbs. A bigger radius delays the occurrence of the vortex bursting over the aerofoil modelling and it is indicated by the impact of the leading-edge radius on the position of the secondary separating line.

The project's purpose is to modify the leading-edge radius of the NACA 2421 aerofoil to raise the lift and facilitate drag by comparing three different leading edges, which are circular, elliptical and cone. That is done to smoothen the layer of the NACA 2421 Asymmetrical aerofoil area to raise the lift and facilitate the drag. The level of effectiveness of the airfoil improved by reducing the leading-edge radius, however, the range considerably declined. Obviously, we are aware that a wind turbine's aerodynamic maneuverability is influenced by the airfoil's blade profile. With a decrease in blending distance

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from the leading edge up to a 7-degree angle of attack, the lift-to-drag coefficient ratio escalates (Birajdar & Kale, 2015). Airfoil performance can be affected by leading-edge erosion, aerodynamic effects were tested at varying levels of leading-edge erosion. The operational efficiency of the airfoil declines as the leading-edge radius expands, while the performance spectrum widens (Sareen et al., 2014). The impact of the leading-edge radius on the position of the secondary line of separation depicts a higher radius delay in the happening of the vortex bursting over the airfoil model. The regional vorticity vector's direction is influenced by changes in the leading edge shape (Verhaagen, 2010). Discussed the different properties of fluids and their effect in various Mach numbers. Explaining about delaying of the turbulence transition from the laminar transition in the boundary layer has many obvious advantages (Bonnet, 1998). The theory of the wing section, as well as a summary of airfoil data", AE Dover Publication, New York, has discussed the properties of different types of wing sections with several NACA series.

It explains about different contents that were very much needed to test and to form an airfoil that was used to build wing sections for different airplanes (Abbott et al., 1950). Post stall Flow Control on an airfoil by Local Unsteady Forcing" has discussed various methods to control the flow through an aerofoil section. High lift requirements depend on the upper surface shape and mentioned about the maximum lift that can be carried by the upper surface (Wu et al., 1998). Effective controlling of separation of flow on wind turbine blades can be accomplished by positioning the right microcylinders in close proximity which is in front of the leading edge of the blade under different stall situations, according to numerical results, without increasing the wind turbine's load. Additionally, the aerodynamic efficiency of a wind turbine at various speeds of wind depends on the diameter and positioning of the micro-cylinders. Numerical estimates show that the blade torque can be enhanced by up to 27.3% by positioning a micro-cylinder with the genuine diameter and place precisely in the frontal part of the blade's leading edge (Wang et al., 2018). Using the recommended "surface curvature blade design technique", blade forms are possible to be developed, which provides precise guidance and control. Advised curvature of blade design has been used to develop stack three-dimensional turbine blades, compressors and fan blades, solitary airfoils, and wind turbines (Hamakhan & Korakianitis, 2010).

Outcomes obtained from this research may be useful in deciding on a maintenance point of view used for running wind turbines with damaged blades in real-world wind farms. Further investigations are anticipated to concentrate on controlling the flow separation brought on by the airfoil's leading-edge shortcomings (Balaji et al., 2021; Ge et al., 2019; Rajendran et al., 2020). Balaji et al. by adjusting the

aero spike's width and the dual materials' additional component traits, it was possible to study the flow separation and re-attachment throughout a round disc (Balaji et al., 2017; Kumar et al., 2021; Pandiyarajan et al., 2021; Rangaraj et al., 2207).

Nanda et al. (2023) focused on the effect of uniformly varying width leading-edge slots to improve the aerodynamic performance of wind turbine blades using NACA4412 airfoil. It is observed that aerodynamics performance was downgraded on the wind turbine blade at the flow separation zone and slot inlet region. Further, the numerical results were compared with wind tunnel data. Belamadi et al. (2016) numerical analysis carried out to improve the aerodynamic performance of slotted airfoil for wind turbine blades. It is found that passive methods improve the aerodynamics performance of wind turbine blades over the specific range of angle of attack and also this configuration has a higher drag value than the baseline airfoil leading to degrade the airfoil efficiency. Further, it reveals the outstanding aerodynamic performance in higher angles of attack from 10° to 20°.

Hongpeng et al. (2020) numerical analysis of aerodynamics performance of wind turbines by modification of asymmetric trailing edge thickness. It is observed that implementing a slotted airfoil enhances the lift coefficient and minimizes the drag coefficient at a higher angle of attack also, symmetrically increasing the trailing edge thickness of the airfoil leads to improved aerodynamic forces. Hence, the drag coefficient was effectively minimised by three different methods. Gao et al. (2015) Numerical analysis performed on a large wind turbine to improve the aerodynamics performance by using flow separation control devices such as Vortex generators (VGs). The different parameters that were modified on the VG are trailing edge height, length and spacing between the pair of VGs. It is observed that the drag penalty is more sensitive than lift and the increase of VG length induces a negative impact on lift and drag. Further increases in VG spacing amidst a nearby pair of Vortex generators have a positive impact on the suppression of flow separations. Nia et al. (2023) investigated the passive control of the flow mechanism to enhance the aerodynamic performance of wind turbine blades using a slot and Vortex Generator (VG). It is found that jet induced at slot exit leads to increases in the aerodynamics coefficient such as Cl/Cd by 91% at the post-stall conditions. Further, the passive flow control over the wind turbine blade shows better performance than the slotted profile in terms of lift coefficient in various angles of attack.

Airfoil nomenclature is depicted in Fig. 1. The fundamentals of airfoil nomenclatures, and the following basic explanation is provided: leading edge: The term "leading edge" refers to the airfoil's front edge. The leading edge is the major edge of an airfoil section and the part of the airfoil

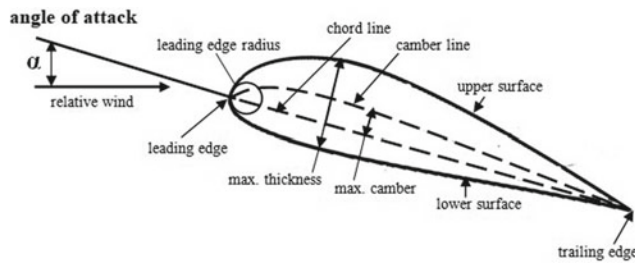


Fig. 1 Airfoil nomenclature

that first comes in contact with the incoming air. Mean Camber Line: The mean camber line is the location of the points that are halfway between the upper and lower surfaces. Camber: - The greatest distance between the chord line and mean camber. An airfoil typically has a camber built in to raise the maximum lift coefficient. Trailing edge: The term “trailing edge” refers to the area which is actually the backside portion of the airfoil. The line that is linked directly to the trailing edge from the area of the leading edge is called a chord.

2 Experimental Setup

The aerodynamics investigation of the force distributions over the three different leading edge airfoil blades is measured at various angles of attack such as 0° , 5° , 10° , 15° , -5° , -10° , -15° , respectively, at the low-speed wind tunnel, which is working in the subsonic range as shown in Fig. 2. The three-component force balance instrument was used to investigate the force on three different leading profiled airfoils taken over the model at 30 m/s velocity in the wind tunnel experimentally as illustrated in Figs. 3, 4 and 5. This section discusses all of the components of a wind tunnel. The major components of the experiment's structure are a NACA2421 airfoil prole blade, a multitube manometer along with a low-speed subsonic wind tunnel which is of suction type as well as a pitot static tube.

Figure 3 shows the elliptical leading-edge at 0° angles of attack. The velocity at which we have tested and undergone the experiment here is 30 m/s. The maximum velocity of the wind tunnel is 50 m/s. Figure 4 shows the Circular Leading-Edge at 5° Angle of Attack. The C_L and C_D are estimated by using the load cell arrangement of the wind tunnel. The Conical Leading Edge at 5° Angle of Attack is illustrated in Fig. 5. All the models are fabricated with respect to the size of the wind tunnel section 600 mm $\times$ 600 mm $\times$ 2000 mm, respectively.

3 Results and Discussion

The phenomenon of pressure distribution of NACA2421 airfoil profiled blades for various angles of attack with varied leading edge airfoil forms like circular, elliptical, and cone has been studied experimentally in the low subsonic wind tunnel establishment. The findings are presented. In Fig. 6, the graph is drawn between the Angle of attack and Standard values of C_L where Standard (C_L) is plotted along the y-axis whereas the Angle of attack is plotted along the x-axis. This graph gives the details of the coefficient of lift for different angles of attack ranging from 0° to 15° of Positive Angles of Attack and -5° to -15° of Negative Angles of Attack. The lift is maximum between 10° and 15° . The stalling takes place from 15° . Subsequently, in Fig. 7 the graph is drawn between the angle of attack and standard values of C_D where the “angle of attack” is plotted along x-axis and standard (C_D) is plotted along the y-axis. This graph gives the details of coefficient of drag for the different angle of attacks which ranges from 0° to 15° of Positive Angles of Attack and -5° to -15° of Negative Angles of Attack. The drag is maximum after 15° and above -15° . As the drag decreases with the decrease in the angle of attack until the positive side of Angles of Attack includes 0-degree Angles of Attack of the airfoil and vice versa along the negative direction.

In Fig. 8, the graph is drawn between the angle of attack and baseline aerofoil values of C_L/C_D . Angle of attack is plotted along the x-axis and the baseline airfoil (C_L/C_D) is plotted along the y-axis. This graph gives the details of C_L/C_D for the different angle of attacks ranging from 0° , 5° to 15° of Positive AOA and -5° to -15° of Negative Angle of attack. C_L/C_D is maximum between 5° and 10° , further decreasing as we increase the airfoil Angle of attack.

In Fig. 9, The graph is drawn between the angle of attack and elliptical radius leading edge airfoil C_L/C_D . Angle of attack is plotted along the x-axis and the elliptical leading-edge airfoil (C_L/C_D) is plotted along the y-axis. This graph gives the details of C_L/C_D for the different angles of attacks ranging from 0° , 5° to 15° of Positive AOA and -5° to -15° of Negative. From the graph, it was clear that C_L/C_D is maximum at $+10^\circ$ AOA of the airfoil and for the negative AOA the C_L/C_D is maximum at -5° of the elliptical leading-edge airfoil. In Fig. 10, the graph is drawn between the Angle of attack and the Circular radius leading edge airfoil C_L/C_D . Angle of attack is plotted along the x-axis and the Circular leading-edge airfoil (C_L/C_D) is plotted along the y-axis. This graph gives the details of C_L/C_D for different angles of attack ranging from 0° , 5° to 15° of Positive AOA

Fig. 2 Low-speed subsonic wind tunnel facility



Fig. 3 Elliptical leading-edge at 0° angle of attack



Fig. 4 Circular leading-edge at 5° angle of attack

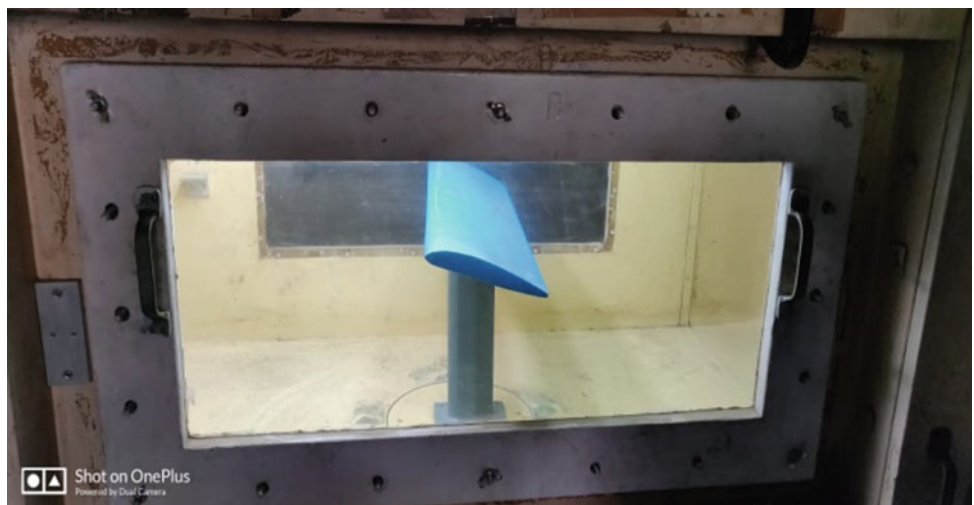


Fig. 5 Cone leading-edge at 5° angle of attack

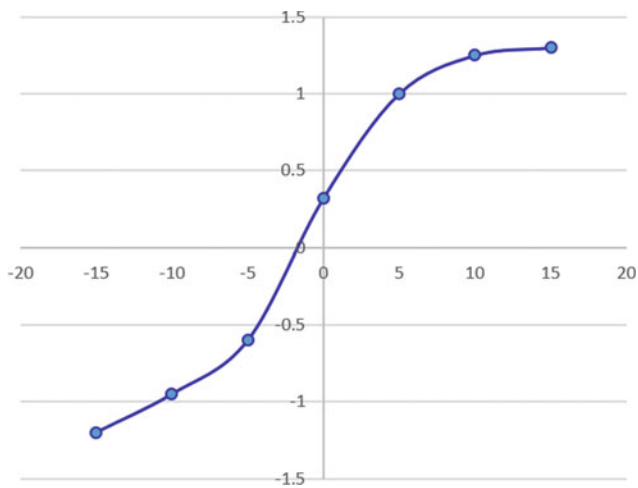
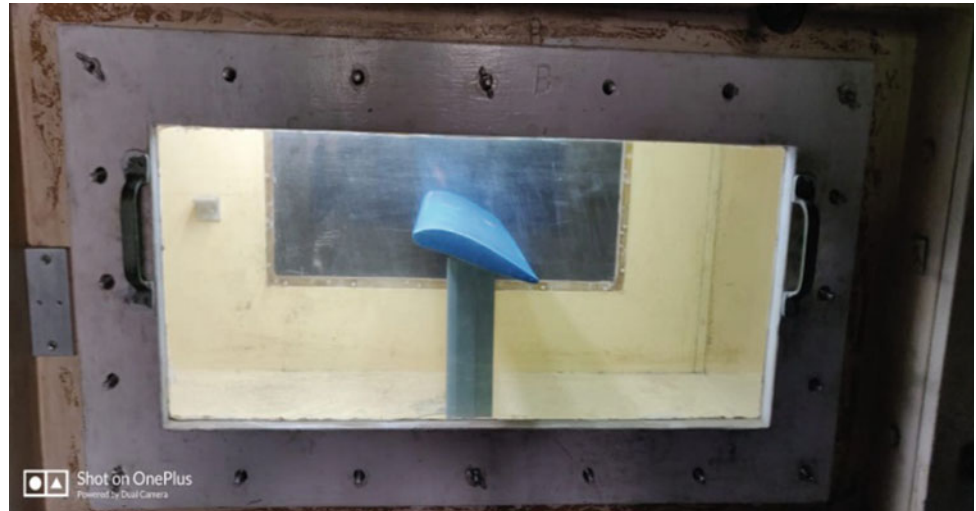


Fig. 6 AOA versus C_L for baseline airfoil

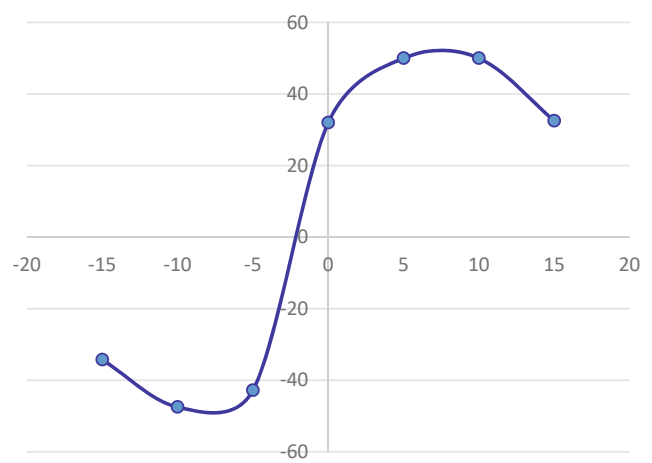


Fig. 8 AOA versus C_L/C_D for baseline airfoil

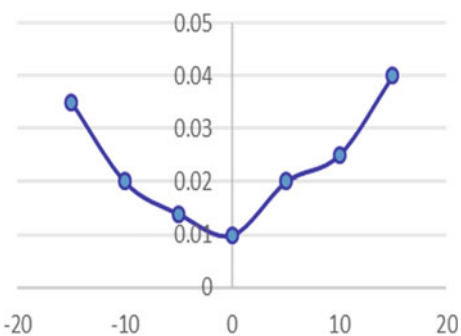


Fig. 7 AOA versus C_D for baseline airfoil

and -5° to -15° of Negative AOA. C_L/C_D is maximum at 10° with a value of 24.25 as this the performance of the aircraft will be good at the particular angle of attack of circular radius leading edge airfoil.

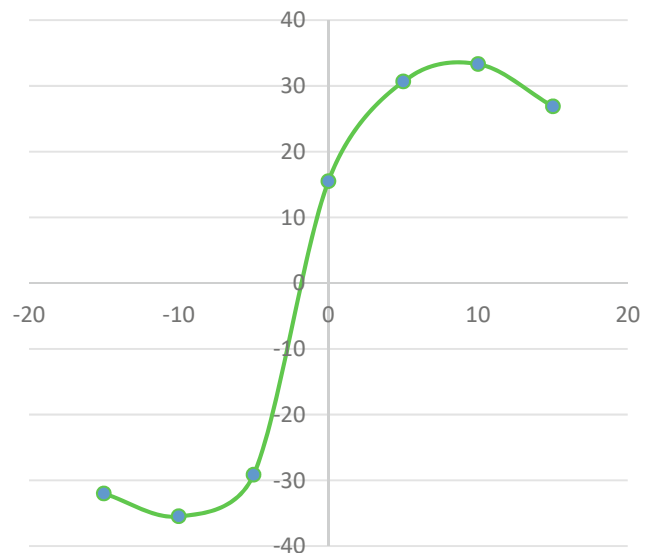


Fig. 9 AOA versus C_L/C_D for elliptical radius leading airfoil

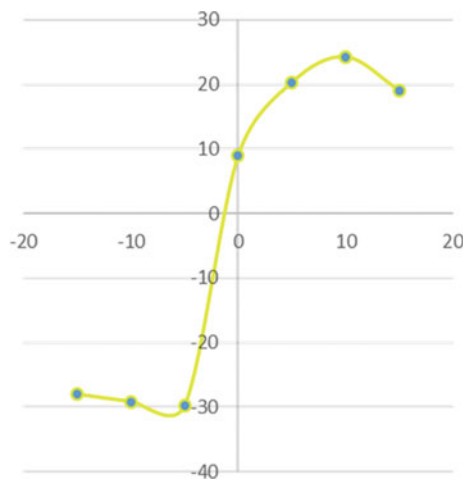


Fig. 10 AOA versus C_L/C_D for circular radius leading airfoil

In Fig. 11, the graph is drawn between Angle of attack and Cone radius leading edge airfoil C_L/C_D . Angle of attack is plotted along the x-axis and the conical radius leading edge airfoil C_L/C_D is plotted along y-axis. This graph gives the details of C_L/C_D for different angles of attacks ranging from 0° , 5° to 15° of Positive AOA and -5° to -15° of Negative AOA. C_L/C_D is maximum at 10° with a value of 20.61. At -15° C_L/C_D value is -27.86, and after 15° the value starts to decrease due to stalling as that of increase in the drag, flow separation takes place faster than elliptical and circular.

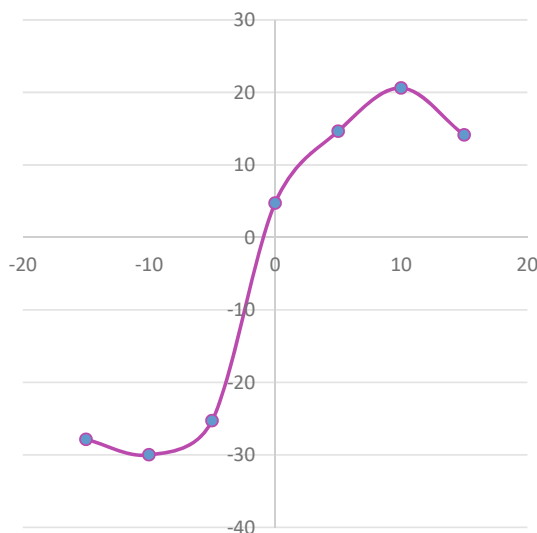


Fig. 11 A versus C_L/C_D for conical radius leading airfoil

4 Conclusion

Three different radius leading edge airfoils were tested at a freestream velocity of 30 m per second with different angles of attack in a low-speed wind tunnel. It is found that up to the stalling angle, lift increases simultaneously with increasing drag at all three different radius leading edge airfoils. The change in the leading edge will affect the generation of lift in the airfoil section. Based on the shapes of the leading edges of airfoil, the lift and drag vary with different leading-edge airfoils. These changes were observed from the graphs which are obtained from experimental analysis listed as follows.

- The percentage change of lift coefficient for baseline airfoil is 29% higher C_L than elliptical radius leading edge airfoil, followed by elliptical radius airfoil that is 25% higher C_L than circular radius leading edge airfoil, finally circular radius airfoil is 25.4% higher C_L than conical radius leading edge airfoil.
- The percentage changes of coefficient of drag for baseline airfoil is 30% lower C_D than elliptical radius airfoil, followed by elliptical radius airfoil that is 23% lower C_D than circular radius airfoil, finally circular radius airfoil is 4.08% lower C_D than Conical radius airfoil.
- The percentage change of C_L/C_D for baseline airfoil is 33.34% higher C_L/C_D than elliptical radius airfoil, followed by elliptical radius airfoil is 32.60% higher C_L/C_D than circular radius airfoil, and finally circular radius airfoil is 15.01% higher C_L/C_D than conical radius airfoil.
- After comparing the results with different leading edges airfoils, the baseline airfoil has a higher lift than the elliptical radius airfoil and elliptical radius airfoil has a higher lift than the circular radius airfoil and has a higher lift than the conical radius airfoil, at an angle of attack from 10° to 15° than stalling starts after 15° . Similarly, baseline airfoil has a superior lift-to-drag ratio, when compared to elliptical, circular, and conical radius airfoils.

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Effect of Pressure Distribution of NREL S809 Airfoil with Vortex Generator

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Abstract

The wind tunnel experiment was carried out to investigate the effect of a vortex generator on the aerodynamics characteristics of the NREL 2809 airfoil, which was used to design the wind turbine and wings. The main objective of the research is to investigate the coefficient of pressure distributions over the NREL S809 profiled airfoil blade at a freestream velocity of 12 and 20 m/s using low-speed subsonic wind tunnel. There are two configurations of vortex generators such as the Triangular vortex generator and Rectangular vortex generator named (TVG and RVG). The vortex generator has been placed over the wing in a spanwise direction at location x/c of 0.3. The pressure distribution over the NREL S809 airfoils being investigated experimentally undergoing different conditions of operation and various AOA varies from 0° to 25° with an interval of 5° . The set of Triangular and Rectangular Vortex Generator (RVG) was arranged individually over the S809 airfoil with uniform pitch and 15° tilted with respect to streamline flow. Hence, the coefficient of pressure is estimated for both vortex generator and the result are plotted and discussed. It is found that pressure distribution is minimal at a lower angle of attack and the rectangular vortex leads to a huge variation of pressure variation compared to the Triangular vortex generator.

Keywords

Vortex generator • S809 airfoil • Turbine blade • Triangular VG • Rectangular VG

1 Introduction

Generally, wind turbine and aircraft wing, the bent small structural model called Vortex Generators (VG) placed over the surface of the wing are frequently utilized to adjust the flow over certain areas of the blades and lead to modifying the pressure variations. Numerous researchers have used vortex generators for a long time and consider them to be very important. Filho et al. (2013) carried out experimental analysis using some of the NACA 63 series airfoils which are often used during the creation of the propellers of wind turbines—will be examined for their effects on the aerodynamic properties. At a Reynolds number of 320,000, an experimental investigation was carried out to determine force, moments, and pressure distribution across the airfoils in both scenarios—that is, with and without the vortex generators. The NACA 63 series specially the (215 and 415) had improved maximal coefficients of lift, while the one which is NACA 63-215 also had improved lift-to-drag ratios at AOA near to stall. Lin et al. (2002) investigated the passive control of low separation of the boundary layer utilizing a sizable vortex generator which has significant low profiles. The width of the mentioned generators varies between 10 and 50% of the boundary layer region. For some airfoils, higher lift and/or decreased drag result in significant performance benefits. Aircraft interior noise reduction and inlet flow distortion are two examples of performance improvements for non-airfoil applications. Such potential devices can create stream-wise eddies as well vortices that have the required strength to conquer the separation happening using the strategy of tiny near-wall protuberances with considerably smaller device heights.

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Sørensen et al. (2014) have undergone computational fluid dynamic techniques capable of dealing with a geometrically resolved VG on an airfoil segment. Following a description of the technique, it is used to examine two distinct airfoils, the FFAW3-301 and FFA-W3-360, at 3,000,000 Reynolds number. In order to compare the computations' predictions of drag as well lift which works as a function of AOA with actual Subsonic wind tunnel calculations from the Laminar Wind Tunnel. In its wide range of applications, it primarily helps to qualitatively assess various setups related to the Vortex generators with regard to the chord-wise location. Hansen et al. (2016) have studied a vortex generator in their research. They conducted their experiment inside a subsonic wind tunnel facility. When used on a thick airfoil, the influence on overall performance results in a higher lift-to-drag ratio than with conventional vortex generators. Therefore, it is advantageous to use a 25% thicker airfoil instead of traditional thin-plated VGs in terms of aerodynamics. It is clear that simply substituting aerodynamic VGs for conventional ones has boosted efficiency as indicated by maximum Cl/Cd by about 4%. Viswam and Sankar (2015) has performed computational simulations and discovered that adding vortex generators across the blades results in the development of superior lift and power. As a result, the wind turbine blade's ability to collect more energy from the atmospheric wind and function efficiently at lower velocities has risen. Placing VG on the separation point can enhance lift, which in turn increases blade efficiency to a lesser extent. Further improvement can be attained by changing the VG's shape and AOA. At the separating point, the VG is positioned. Rectangular-type VG has been employed. It is positioned at the airfoil section's greater camber length.

Manolesos and Voutsinas (2015) have done simulations and tests that have aided in understanding how passive vortex generators can be used to postpone or compress separation over an airfoil designed mainly for propellers of wind turbines, which are the blades in a quick and efficient manner. The Stall Cell type suffers three-dimensional separation. Considering some cases like three counter-rotating vortex generators, which form the shape of a triangle with a usual and ordinary flow, studies including visualization of flow and stereo particulate image velocimetry as well as Pressure have been addressed. Somewhere near about 37.2 VG heights downstream, a significant amount of turbulent interaction that took place between the underlying flow as well as the dual vortices is seen. Elevated normal levels of stress between the dual vortices are the result of the VG vortices' wandering motion. Haipeng et al. (Wang et al., 2016) carried out research using a computational analysis, the aerodynamic effectiveness of the airfoil S809 including as well as by excluding the vortex generators was examined. The generators which led to the formation of the vortex were

used for governing the flow stream inside the S809 airfoil's boundary layer with momentum transfer and vortex trajectory were dealt with. Furthermore, it has been demonstrated that these generators have the potential to significantly enhance the S809 airfoil's aerodynamic efficiency while reducing the boundary layer's thickness. The stall occurrence is postponed. The S809 airfoil performs more aerodynamically and with greater control of flow separation when using double vortex generator setups.

Li et al. (2019) have completed their research to find out how the height of the Vortex Generators impacted the regulation flow stream in the viscous region. Through wind tunnel tests and computational techniques, the attributes related to the vortex of a given profile as well as other aerodynamic aspects for vortex generators of an airfoil were investigated. Some values of H are 0.1, 0.5, and 1.0. The results demonstrate that in the height range of the VG, the vortex intensity is inversely correlated with the fluid's average kinetic energy. Furthermore, using three VGs in a wind tunnel, the impact of various heights related to the aerodynamic efficiency of the wing was investigated. Zhu et al. (2021) in order to increase the aerodynamic strength, explored passive vortex generators, which are frequently utilised on airfoils and turbines. Instead of rotational blades, flat plates and airfoils are used in the majority of VG experiments. This research compares the blades of the NREL Phase 6 flow and NREL S809 airfoil flow. A total of around 34–36 rectangular vortex generators are mounted in intervals of 25–50% of the blade's span, which is approximately 20%. According to the research, rotational factors cause a significant difference between blade flow with VGs and airfoil flow.

Balaji et al. (2022) conducted experiments within a subsonic wind tunnel facility and used a multitube manometer to evaluate the aerodynamic properties of the cambered airfoil model NACA5520 with a range of velocities and AOA. They look at the distribution of the pressure across the mentioned NACA5520 airfoil over various x/s locations and speeds of 5–20 m/s, it also includes 10 and 15 m/s. A pitot-static tube as well as a manometer having 30 ports have been considered for pressure calculation over the cambered airfoil at various AOA. Velte et al. (2010) carried out experiments examining the impact of VGs over flow stream characteristics close to stall have been carried out on a DU 91-W2-250 profile which has been specially constructed LM Glass fiber wind tunnel facility using SPIV. The goal was to look at how vortex generators on the airfoil affected the flow structures and separation-controlling behaviour. The research reveals key areas of induced vortices, including vortice oscillations principally in the spanwise direction and pulsations of axial velocity throughout the vortex cores. Sedaghat et al. (2014) using traditional HAWT, where the rotor velocity is held static and the velocity of the blade tip

fluctuates continually, continued their investigation. This significantly lowers the power generated by the wind turbine, especially at high wind speeds where the tip speed ratio is low. In order to provide the best blades for continuously changing speed HAWT or Horizontal Axis Wind Turbine, a closely packed momentum related to the blade element is developed in response to the increase of variable speed generators.

Zhu et al. (2019) evaluated the performance of the passive vortex generators in subsonic wind turbines to postpone the static stall. However, knowledge of dynamic stall control via passive VGs is still limited. It has been discovered that VGs significantly increase the maximum lift coefficient by approximately 38–40% and postpone the arrival of dynamic stalls. Therefore, it results in a beneficial reduction of the coefficients of lift as well as pitching moment and hysteresis intensities by 57 and 39%, respectively. These results imply that passive VGs hold great potential for preventing the stall from occurring dynamically in the wind turbine airfoils. Martínez-Filgueira et al. (2017) carried out their research employing vortex generators to prevent or postpone the separation of flows. The VG is typically determined using the same height as the thickness of the boundary layer. The residual drag associated with these types of passive flow control actuators can be reduced by the low-profile VGs. A prediction model has also been created to explain how the vortex size which is present at the backward region of the passive flow stream control vanes changes over time. Balaji et al. (2017) results showed that the taper ratio had a significant effect on the characteristics of wake downstream of the circular cylinder at higher taper ratios. Fouatih et al. (2016) experimentally investigated the flow separation over the NACA4415 airfoil with a vortex generator with various parameters such as thickness and height of VG, location, orientation angle with respect to the freestream direction and VG orientation along spanwise spacing. It observed that VG at 50 %c provides significant aerodynamic performance. Zhen et al. (2011) both the experimental and numerical investigations of Aludra UAV performance by using passive vortex generators to improve the aerodynamics performance of airfoil. Vortex generators placed various chord-wise locations on the NACA4415 airfoil and significant results were obtained nearer to the flow separations.

Cunha et al. (2014) Comparative study of experimental and numerical investigation of vortex generators to optimize the flow characteristic over the NACA0015 symmetrical airfoil at different flow conditions. It is observed that the height of the vortex generator substantially improves the aerodynamics performance of the NACA0015 airfoil by 22% and also it is found that optimized VG enhances the maximum lift coefficient to 14% and sequentially reduces the drag to 14%. Further, the Reynolds number effect also performed effectively. Di Ilio et al. (2018) Conducted a

numerical study of NACA0012 airfoil at a low Reynolds number using hybrid lattice Boltzmann methods. The performance of the symmetrical airfoil was analysed in very low Reynolds numbers at various angles of attack. It is observed that vortex shedding initiated at 8° and tends to stall at 26° and also it is found that highly complicated flow behaviour was accurately predicted by HLBT methods.

Kozmar (2011) did the experimental study of a Counihan truncated vortex generator investigated on a part-depth Atmospheric boundary layer wind tunnel. Three redesigned vortex generators with roughness effect simulated in the ABL wind tunnel with different terrain conditions such as rural, suburban and urban terrains set up. Finally, experimental validation of the Counihan vortex generator was successfully analysed using part depth ABL with various terrain conditions. Ockfen and Matveev (2009) numerical investigation of aerodynamics characteristic of NACA4412 airfoil section using flaps in extreme ground effect were analysed with different flow conditions. It is found that flap efficiency was minimized and separation rearranged in the upstream location due to the ground effect on high lift airfoil. Gibertini et al. (2015) experimentally and numerically investigated the vortex generator over the helicopter blade to reduce the drag effects. It is observed that the significant location over the helicopter blade to position the vortex generator plays a major role in this investigation and found that drag rises when the VG pitch angle increases. Further, it is observed that the co-rotation of the blade with two symmetrical arrays of VG was not more efficient than the counter-rotation of the blade with one array of VG. Henceforth, the blade using VG reduces 5% of drag compared to the base blade.

Current research is to investigate the effect of the distribution of pressure on NREL S809 airfoil with two different geometrical shapes of the vortex generator such triangular vortex generator named TVG and the Rectangular vortex generator named RVG. The low-speed wind tunnel facility is operated with freestream conditions of 12 and 20 m/s to investigate the effect of pressure coefficient over the airfoil with various angle attacks such as 0–25 with an interval of 5 as shown in Fig. 1. The experimental work carried out on the NREL S809 airfoil with a vortex generator uniformly arranged over the surface of the wing is shown in Fig. 2 and the schematic illustration of TVG and RVG is shown in Fig. 3.

2 Experimental Methods

Figure 4 shows that a low-speed wind tunnel facility is used to conduct the experiment to measure the distribution of pressure on the NREL S809 airfoil at $x/s = 0.5$. The mid-span of the wing, where, 26 port pressure is uniformly

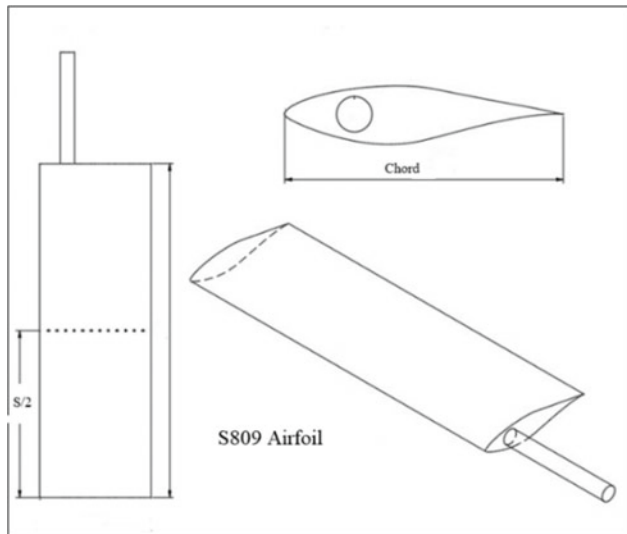


Fig. 1 Illustration of S809 Blade with tapping at $x/s = 0.5$

placed in the upper surface and lower surface of the wing and reading has been taken at two different freestream velocities such as 12 and 20 m/s and various angle of attack varies from 0° to 25° with an interval of 5° . The various instruments used to complete the experiments are low-speed wind tunnel, a multitube manometer set with manometric liquid of alcohol, a pitot-static tube, and a fabricated NREL S809 airfoil blade with a Triangular vortex generator (TVG) and Rectangular Vortex Generator (RVG).

The experiment is carried out in the suction type low-speed wind tunnel with test section dimensions of $(0.6 \text{ m} \times 0.6 \text{ m} \times 1.2 \text{ m})$ corresponding to width, breadth and length as shown in Fig. 4. The maximum velocity that can be obtained in the tunnel is 45 m/s present condition with a turbulence intensity level lower than 5%. The pressure tapping on the NREL S809 airfoil model and the pitot-static port was connected to the multitude manometer to measure the static pressure for various angles of attack and freestream velocities. The pressure coefficient is calculated using equation (i) as a non-dimensional number used to express the aerodynamics behaviour of the wing at different conditions as well as used for other applications and hydrodynamics.

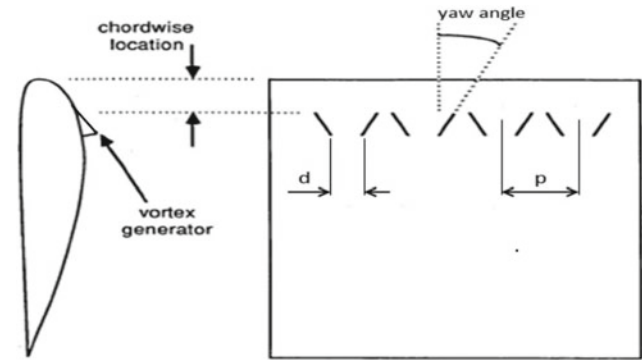


Fig. 2 Positioning of VG over the blade

The experimental model is fabricated using teak wood and pressure ports are uniformly arranged on upper surface and lower of the wing and also pressure effect is investigated with different geometries of vortex generators such as Triangular vortex Generator (TVG) and Rectangular Vortex Generator (RVG). The two different geometrical shapes of the vortex generator are positioned over the blade uniformly with a gap of d and pitching of P as given in Figs. 2 and 3. The VG is fabricated with a strip of steel sheet as per the dimension and placed over the NREL S809 airfoil at a location of $x/c = 0.25$. The vortex generator is produced with uniform dimensions of b and h for both types as shown in Fig. 3.

$$\text{Pressure coefficient, } C_p = \frac{P_s - P_\infty}{P_o - P_\infty} \quad (1)$$

The National Renewable Energy Laboratory S809 airfoil blade is fixed using separate holding fixtures in the middle of the test section in the wind tunnel. All the pressure taps are named over the flexible rubber tube that is fixed to the multitube manometer, and the NREL S809 blade in the test section has a different AOA. For measuring the static pressure and stagnation pressure, which is computed by Bernoulli's Equations, a pitot-static tube has been installed inside the test section (Fig. 5).

The calibration of the wind tunnel has been conducted by varying the speed of the rotor in the driving unit by different operating conditions of RPM. The model has been fabricated

Fig. 3 Schematic diagram of TVG and RVG

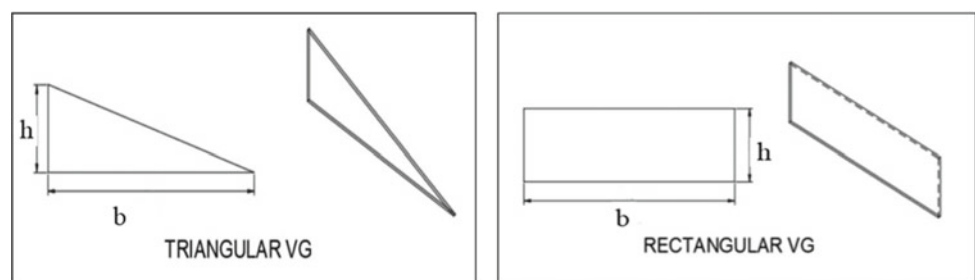


Fig. 4 Suction-type wind tunnel
—low-speed type



Fig. 5 Fabrication of NRELS809 airfoil with vortex generator and pressure port



and keeps the blockage ratio less than 5% with respect to the wind tunnel test section size. This analysis is more significant for aircraft wing designing and turbine blades and applications elsewhere.

3 Discussion of Results

3.1 The Distribution of Pressure Over the NREL S809 with TVG and RVG at 12 m/s

The analysis is carried out in the low-speed tunnel to investigate the pressure variation of the NREL S809 blade for various angles of attack and both present and absent of Triangular and Rectangular vortex generators (TVG and RVG) at freestream velocity of 12 m/s as given in Fig. 6a–f. In Fig. 6a–f, the coefficient of pressure (C_p) variations over the airfoil region ranges from 0° to 25° with a 5° increment.

The coefficient of pressure trend will be skewed downward at the TVGs' installation sites since the pressure taps are on the pressure side of the TVGs and at $x/s = 0.5$. The

Coefficient of pressure (C_p) trends of the airfoil over TVGs are identical at 0° and 10° AOA, and there are no differences in vortex generator heights, as shown in Fig. 6a, c. As the angle of attack increases, the airfoil blade separation position moves closer to the TVG installation location. When the AOA exceeds 15° , this design aids the Triangular Vortex Generator (TVG) in separating the flow from the surface. As a result, the reverse pressure gradient for the airfoil rises as the AOA increases. The negative pressure variations rise when the AOA increases from 5° to 15° , as seen in Fig. 6b–d. Figure 6e, f illustrates that the pressure coefficient drops as the angle of attack rises.

3.2 Distribution of Pressure Over the NREL S809 with TVG and RVG at 20 m/s

Evaluate the pressure distribution across the NREL S809 airfoil profiled wing at various AOA with baseline wing and with a triangular and rectangular vortex generator (TVG and RVG), experimental analysis is performed on the low-speed

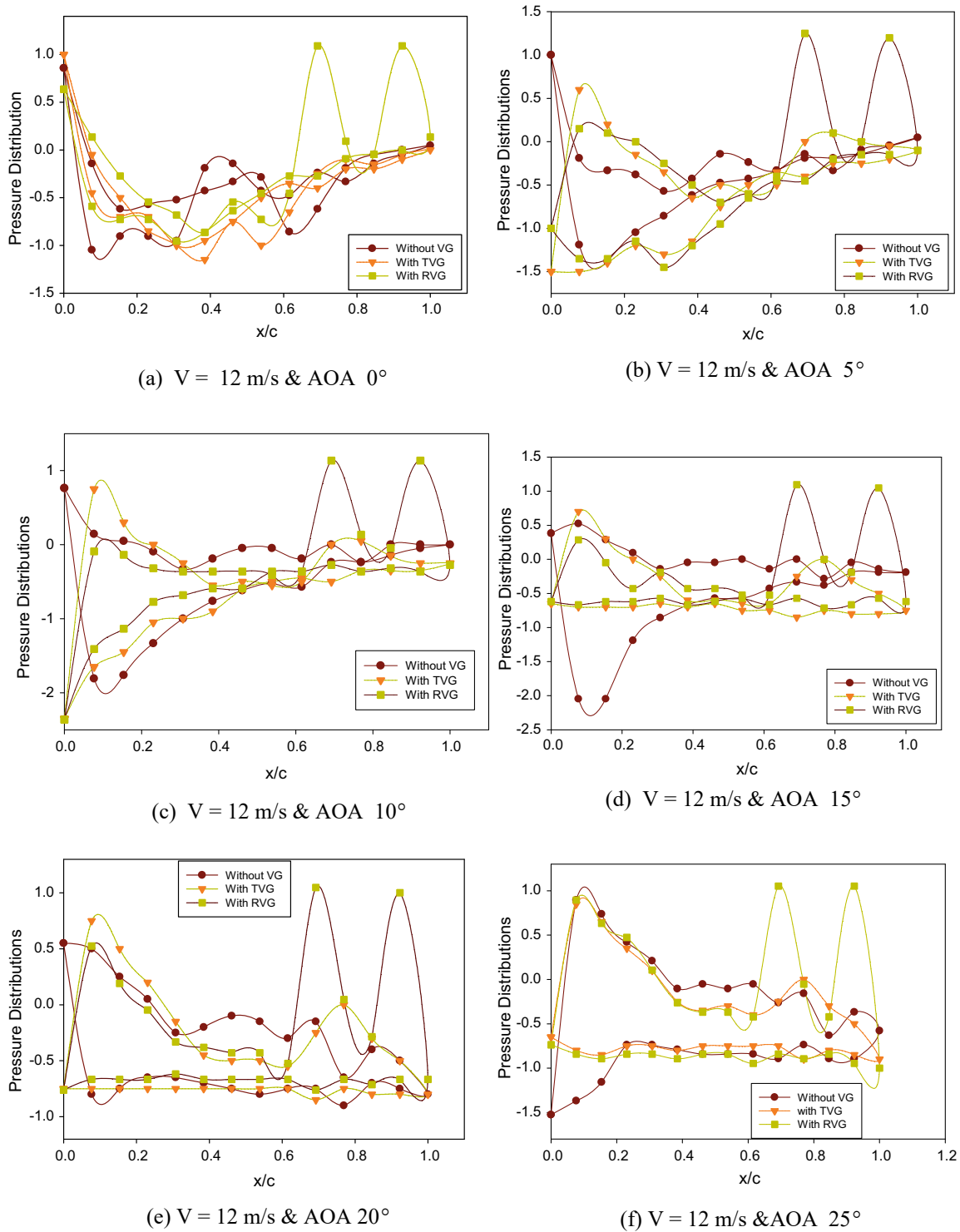


Fig. 6 The distribution of pressure on NREL S809 airfoil at 12 m/s for various AOA with and without VG

tunnel facility as illustrated in Fig. 7a–f. The coefficient of pressure (C_p) variations over the airfoil regime range from 0° to 25° with an interval of 5° and a velocity of 20 m/s. The C_p trend will decline in the opposite direction at the TVGs and RVGs fixed surface because the pressure taps are at

$x/s = 0.5$ and on the pressure side of the TVGs and RVGs. The pressure coefficient trends with and without TVGs and RVGs are equal at an angle of attack of 0° and 25° , and there were no differences in VG heights, as shown in Fig. 7a–f. As the angle of attack increases, the airfoil blade's separation

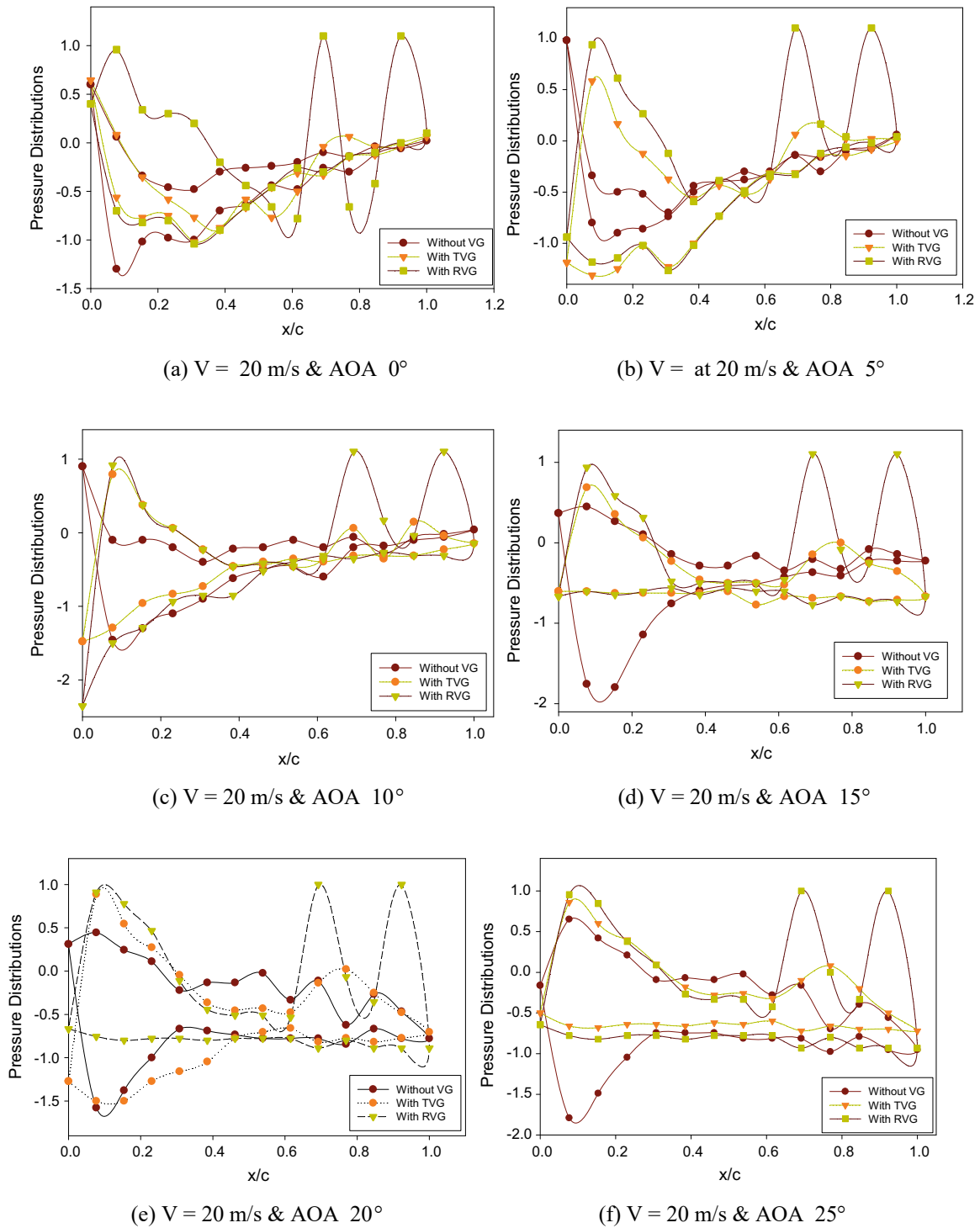


Fig. 7 Distribution of pressure on NREL S809 airfoil at 20 m/s for various AOAs with and without VG

position gets closer to where the TVGs and RVGs are installed. This design supports the TVGs in separating the flow while the AOA exceeds 15° . As a result, the reverse pressure gradient for the airfoil rises as the AOA increases.

The negative pressure coefficient rises while the angle of attack increases from 15° to 25° , as seen in Fig. 7b–d. Figure 7 illustrates how the pressure coefficient falls as the angle of attack rises (e and f).

4 Conclusion

The wind tunnel analysis has been carried out to examine the pressure variations of NREL S809 airfoil profile blade test on three distinct conditions such as baseline wing, with Triangular Vortex Generator (TVG) and Rectangular Vortex Generator (RVG) is tested in the low-speed tunnel different velocities. The experimental investigations reveal the finding listed below.

1. It has been observed that the aids of vortex generators can significantly enhance the pressure coefficient and improve the aerodynamic properties of the NREL S809 airfoil by delaying boundary layer separation.
2. With the aid of the Triangular Vortex Generator and Rectangular Vortex Generator, the pressure variation in the S809 airfoil at low angles of attack and speeds is minimal.
3. When compared to TVG and RVG, the pressure coefficient varies noticeably at high angles of attack. When using RVG instead of TVG, a dramatic difference in the pressure coefficient was seen in the airfoil.
4. Thus, it can be concluded that the use of a vortex generator allows for an experimental comparison of the pressure variations over a cambered airfoil using and excluding TVG and RVG while also improving the airfoil's performance characteristics.

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Experimental Study of Aerodynamics Performance of NACA4418 Airfoil with Fencing

G. Balaji, Chebrolu Sai Snehit, Alapati Bipin Sai Eswar, Debayan Singha, Mainak Mitra, S. Nagarajan, and G. Santhosh Kumar

Abstract

This study investigates the effects of the boundary layer fence on the aerodynamic effectiveness of the NACA4418 taper wing with a taper ratio of 0.8. Subsonic wind tunnel investigations were conducted to observe the influence of boundary layer covers on the aerodynamic performance of the wings of various freestream velocities such as 10–40 m/s with intervals of 10 m/s and different angles of attack varying from 0° to 40° with an interval of 10°. Two boundary layer fence configurations were tested in two different configurations: the first one is a single fence set at 50% of the span and the second configuration is two fences set at x/s of 0.3 and 0.6 on the wing span. The test setup also includes a three-component balance to measure lift and drag coefficients and low-speed subsonic wind tunnel with a testing section size of 600 mm0 600 mm × 1200 mm (B × W × L). It is found that the results by application of a boundary layer fence increase the coefficient of lift and lower the drag coefficient. These results suggest that boundary layer fencing is an effective technique for improving the aerodynamic performance of taper blades and may contribute to the development of more efficient and sustainable aircraft technologies.

Keywords

Fencing • NACA4418 • Airfoil • Cambered airfoil

1 Introduction

Maintaining the aircraft performance at a higher angle of attack remains a challenge in the aviation field. Avoiding the separation of airflow from the wing's upper surface is considered one of the key issues. Several passive and active flow control techniques have been developed to prevent and mitigate separation. Passive flow control includes geometric alterations to an object, such as boundary layer tripping, which aid in keeping the flow attached to higher angles of attack.

On the other hand, active flow control (AFC) manipulates the flow field around an object using energy or momentum. A boundary layer fence (BLF) integration is one of the passive flow control methods that could be used to increase the aerodynamic effectiveness and longitudinal static stabilization of wings. Hussain and Bons (2019) have conducted experiments on the performance of the NACA 643-618 laminar wing having a 30-degree leading edge sweep with active (slot on the wing) and BLF flow control techniques. The authors found that placing the boundary layer fence at 0.60 z/b increased the max cl by 10.2–19.3% and also delayed the onset of an unstable pitching moment. The AFC slot at the same location increased cl max by 10.6–23.4%. However, the results revealed that the AFC configuration experienced less separation inboard; this is because passive BLF presents a physical obstruction to the span-wise flow. Williams, et al. (2010) have conducted a numerical study and wind tunnel analysis on T-38 talon. Fences are placed at 0.825 semi span and the results were observed. During stall approaches, the fence decreased roll-off tendency and wing-rock magnitude. The wind tunnel investigations indicated that the fences decreased outward spanwise flow along the fence, and the findings supported the computer calculations.

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Democrat et al. (2020) have conducted experiments on NACA 0012 wing with a sweep of 45° . The fence is placed at 50, 60, 70 and 80%. The results revealed that the addition of a fence at 60, 70 and 80% showed improvements in the maximum lift coefficient and higher stall angles. The 50 and 60% locations showed a beneficial delay in the pitching moment shift, while the 70 and 80% locations showed a degraded performance in the pitching moment shift. However, the fence at 70% increased $c_{l\max}$ by 8.9%, so it is identified as the best fence configuration. Walker and Bons (2018) studied the impact of active and passive spanwise fences on the NACA 643–618 laminar wing with a sweep of 30° at the leading edge. The use of BLF helped in increasing the CL by approx. 15% and also improved the stall angle by 10%. Results show that both arrangements generate two vortices, which, in conjunction with the physical barrier, are accountable for regaining lift. Papadopoulos et al. (2022) conducted experiments to understand the passive flow control techniques namely wing fences and tubercles on a UAV Blended Wing Body (BWB). The work proved that both techniques can potentially improve the UAV's efficiency by reducing the c_d but the most promising method was proved to be a wing fence wrapped around from the tip of the suction side to the pressure side because they extended the stall angle to a higher value and also depleted the c_d value. Balaji et al. (2022a) it is found valuable insights into the aerodynamic behavior of airfoils and how changes in the angle of attack can affect the pressure distribution and lift characteristics of the airfoil.

Solfelt and Maple (2007) have conducted a CFD analysis on the impact of a Spanwise fence on a T-38 talon. The fence was fixed at 82.5% of the semi-span at full flapping conditions. The fence increases the $C_{L\max}$ by 7% and the slowdown of reaching $C_{L\max}$ from 12° to 13° Angle of Attack. This was accomplished by forming a pair of reverse-rotating vortices downstream of the BLF, which precluded the separation of flows at the tip area. This successfully delays flow separation throughout the rest of the wing, which results in the higher calculated lift. Scholar et al. (2016) in their work investigated aerodynamic attributes like lift, drag and stall, however, the study mainly focused on the behavior of lift. Computational studies were conducted on NACA 0012 Airfoil at higher angles of attacks including as well as excluding fences. The fence was exactly placed at half of the span and the double fences were fixed at 25% from their corresponding tips. The maximum CL of the base airfoil was 1.13, whereas it raised to 1.478 with one fence and to 1.477 when two fences were fixed. Approximately, a 30.7% increase in $c_{l\max}$ was noted. The stall angle of the base airfoil was 13° and it went up to 21° with the introduction of fences. Palmer and Gunasekaran (2019) tried fixing curved boundary fences and observed an increment in the aerodynamic efficiency. Aside from stall

propagation, it additionally affects the surface's spanwise velocity, having consequences in the wingtip vortices roll-up procedure and acting as a possible control surface. Force investigations were done on the curved BLFs and the results were evaluated to the traditional BLFs and baseline wing. Ultimately in all the cases, there is an increase in the aerodynamic efficiency. A morphing BLF might be a potential approach to boost the total aerodynamic effectiveness of the wing by utilizing the benefits provided by both linear BLFs and CBLFs.

Balaji et al. (2022b) simulate the aerodynamic properties of an airfoil with a leading edge tubercle at varied freestream velocities for low Reynolds numbers. For all velocities, pressure distribution differs dramatically close to the leading edge. Studies for various velocities and angles of attack are explored and supplied with pertinent facts. Alam et al. (2022) in their work proposed a replacement for the BLFs. They blocked spanwise flow by injection of the stream from fluidic actuators directly onto the boundary layer of the wing. The slot was fixed at 45% of the span of the primary wing and the effects of forces and pitching moments were noticed. Furthermore, a greater angle of attack (more than 12°), there is a major spanwise flow from the base to the wing tip, integrating the flow in spanwise directions to create shedding vortices at the tip.

Cerón-Muñoz et al. (2016) performed wind tunnel experiments to analyze the aerodynamics of the winglets, C-wing, fences and droop on a blended wing body. The droop was tested at a lower and higher angles of attacks, initially the slope of the c_l curve increased and then remained constant at higher angles of attack too, a notable improvement was the decrease in drag coefficient when compared to the baseline wing. The fences helped in reducing the angle of attack from the range of 4 – 12° . The C-wing configuration differs from the baseline till 80, when the CL is raised. In comparison to other methods, c-wing is showing maximum promising characteristics. Muheisen et al. (2023) conducted tests on the multi-cross-sectional HAWT blades. Some supercritical airfoils were employed and spread over the blade radius, also the NACA4412 HAWT blade with identical proportions was employed to evaluate the actions and total efficiency of all the blades. The use of fences resulted in a 16% improvement in overall power coefficient and good fluttering stability. The fence structure and placement decrease induced drag, increasing the coefficient of power by as much as 16% and allowing for exceptional flutter steadiness. The multi-cross-section blade elliptically modified the force balance along the blade diameter, reducing drag and increasing lift for exceptional efficiency and fluttering stability.

In this research, the experimental investigation is carried out for the aerodynamics performance of the NACA4418 profiled airfoil tapered wing is considered with and without

fencing at a subsonic speed wind tunnel. The fencing of the wing is located at two different locations of x/s ratios of the wing span. In first wing fencing is located at x/s of 0.5 as seen in Fig. 1 and another wing fencing is located at 0.3 and 0.6, respectively, as seen in Fig. 2. The main aim of the research is to investigate the aerodynamics performance of the NACA4418 profiled airfoil tapered wing and comparing the results with baseline wing of the same NACA4418 wing and the coefficient of lift and drag also need to be studied.

2 Experimental Setup

The experiment is conducted in the low-speed subsonic wind tunnel facility for the three different models such as baseline wing of the same NACA4418, boundary layer fencing located at 50% of the wing span, and fencing located at 30 and 60% of the wing span. The wing is made of teak wood as shown in Fig. The white cardboard with 5 mm thickness is used for boundary layer fencing over the wing as shown in Figs. 1 and 2. The three component force balance instruments are used for force measurement of all the configurations of the wing with and without fencing. The experimental model of the NACA4418 airfoil profiled wing with and without fencing is shown in Figs. 3 and 4.

The low-speed subsonic wind tunnel facility has a test section size of 600 mm $\times$ 600 mm $\times$ 1200 mm ($w \times b \times l$) and is located at Hindustan Institute of Technology and Science, Chennai being used for experiment study as shown in Fig. 5. This facility is a suction type open-circuit low-speed subsonic wind tunnel operating at a maximum freestream velocity of 50 m/s at the test section in turn velocity is slowed down by controlling the propeller revolving at the driving unit. The wind tunnel is calibrated with the help of a pitot static tube before conducting the experiments and the wind tunnel turbulence intensity is less than 2% and the blockage ratio is calculated as less than 5%.

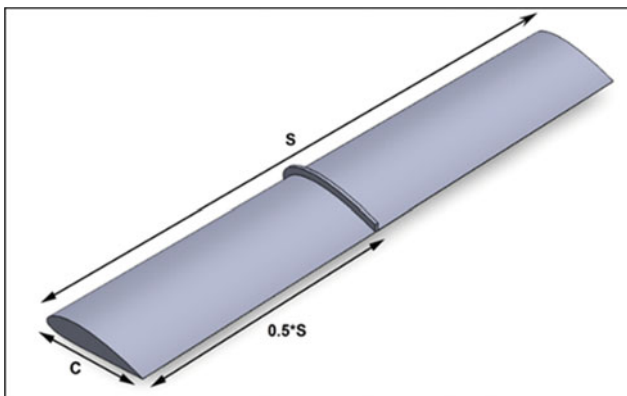


Fig. 1 Fencing at 50% of span locations

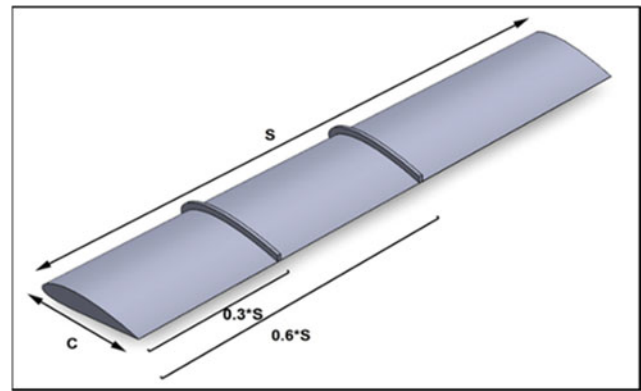


Fig. 2 Fencing at 30 and 60% of span locations



Fig. 3 NACA4418 wing one fencing

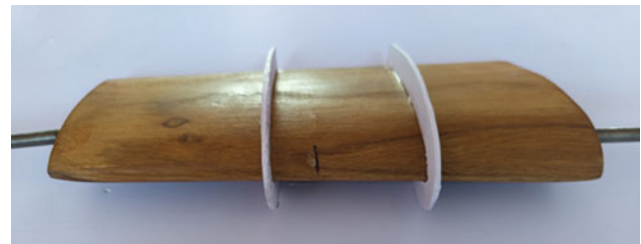


Fig. 4 NACA4418 wing with two fencing

3 Results and Discussion

The boundary layer fencing over the NACA4418 cambered airfoil profile 3D wing is investigated in the low-speed subsonic wind tunnel facility at different freestream velocities and various angles of attack as plotted and which is compared with the baseline model as shown in Figs. 6a–d, 7a–d and 8a–d. The lift coefficient is measured with three different configurations of NACA4418 profile wing such as baseline model, boundary layer fence located at x/s of 0.5, and fencing at x/s location of 0.2 and 0.6 plotted against various angles for different velocities such as 5–20 m/s with an interval of 5 m/s as seen in Figs. 6, 7 and 8a–d. It is observed that the baseline model gives a better lift coefficient than other configurations. The maximum lift coefficient of

Fig. 5 Low-speed suction-type subsonic wind tunnel facility



the baseline is found at 7.5 at 18° in a freestream of velocity of 10 m/s shown in Fig. 6b. Further, it is seen that the baseline lift coefficient slightly reduces with increasing freestream velocity. Hence, the fencing at x/s 0.3 & 0.6 configuration shows a linear variation in C_L than the x/s 0.5 configuration model. It is due to the later direction of flow across the wing excites the upstream flow and leads to an increase in the lift coefficient.

3.1 Effect of Lift Coefficient for Various Freestream Velocity and AOA

Figure 6a–d plotted for drag coefficient for various angles of attack. the drastic variation of drag coefficient was observed in all the freestream velocities. For the baseline, at freestream velocity of 5 m/s, the drag coefficient found at -2.5 at an angle of attack of 15° seen in Fig 6a and other cases baseline drag coefficient dominating fencing configurations of wing was observed. The fencing of the wing at x/s 0.5 has shown straight curves in all the velocity conditions and fencing with x/s locations of 0.3 and 0.6 is a little lower than baseline values.

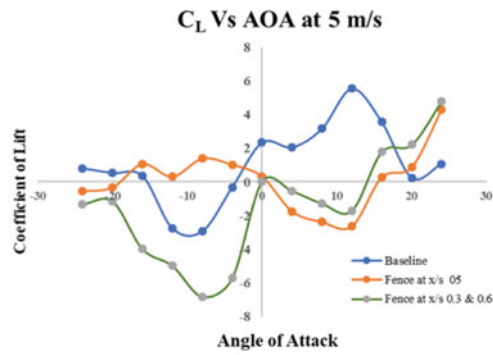
3.2 Effect of Drag Coefficient for Various Freestream Velocities and AOA

Figure 7a–d shows the drag coefficient of the cambered NACA4418 airfoil profile airfoil with a fence at two

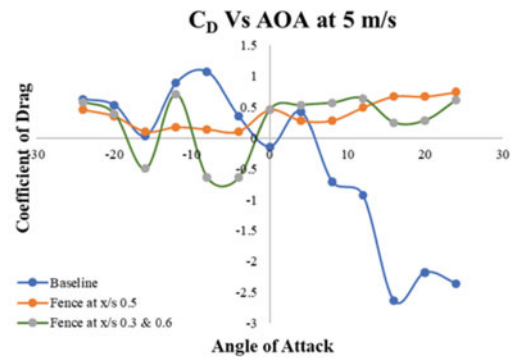
different locations at x/s 0.5 and x/s 0.3 & 0.6 for various angles of attack and freestream velocity. The distribution drag coefficient gradually varies by increasing freestream velocity and angle of attack and the baseline wing is compared with the fenced wing, which is provided at different locations. Further, it is found that the drag coefficient slightly varies for the fenced wing of both cases as shown in Fig. 7a–d. For the baseline, at freestream velocity of 5 m/s and 10 m/s, the drag coefficient was found at -2.7 at angle of attack of 16 and 3 at angle of attack of 24° as seen in Fig. 7a, b.

3.3 Effect of Lift and Drag Coefficient for Various Freestream Velocities and AOA

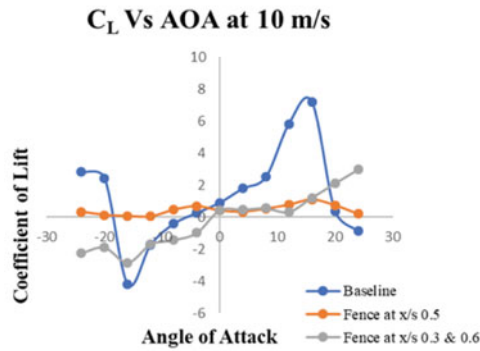
As Fig. 8a–d, the variations of C_L/C_D value are uniformly varying in positive and negative angle of attack for baseline and fenced wings for different freestream conditions. The coefficient value has been calculated for all the models such as the boundary layer fence located at x/s of 0.5, and the fencing located at x/s locations of 0.3 and 0.6 at velocities ranging from 5 to 20 m/s with steps of 5 m/s. It is observed that the baseline wing and fencing at x/s 0.3 & 0.6 are in good agreement and compared with the single fencing model and as freestream velocity of 10 m/s and 15 m/s at C_L/C_D value of 15 at 12° , value of -9 at 12° for baseline model and as freestream velocity of 5 m/s and 20 m/s at C_L/C_D value of 11 at 8° and -4 at -20° for two fencing model as shown in Fig. 8a–d. It found drastic variations of C_L/C_D value for freestream conditions and angle of attack.



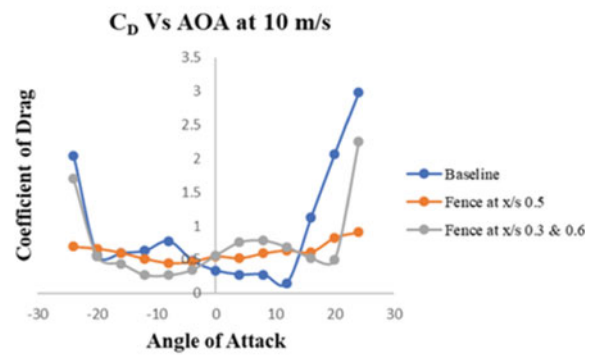
(a) Coefficient of lift at 5 m/s



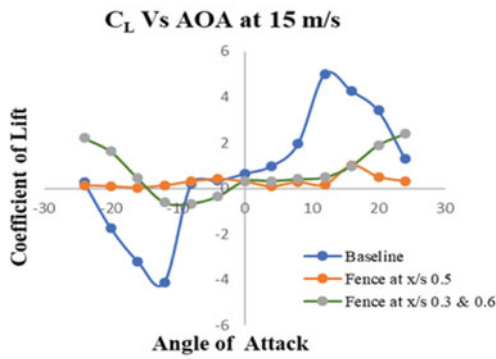
(a) Coefficient of drag at 5 m/s



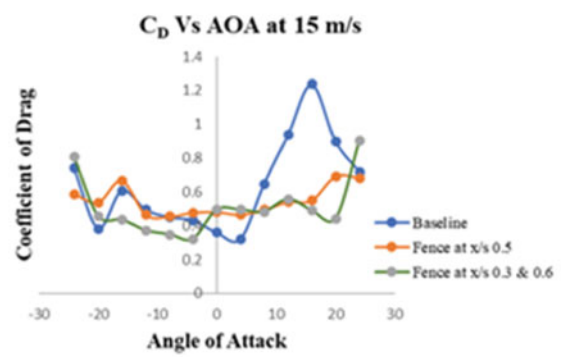
(b) Coefficient of lift at 10 m/s



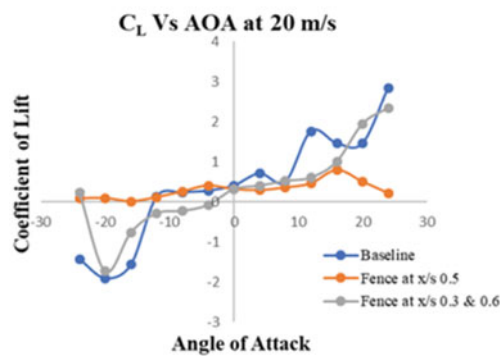
(b) Coefficient of drag at 10 m/s



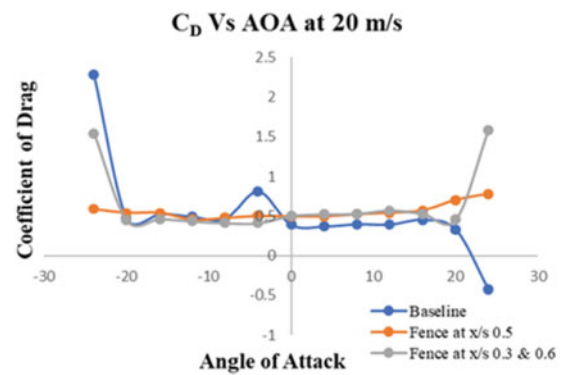
(c) Coefficient of lift at 15 m/s



(c) Coefficient of drag at 15 m/s



(d) Coefficient of lift at 20 m/s



(d) Coefficient of drag at 20 m/s

Fig. 6 Coefficient of lift at different freestream velocities and angle of attack

Fig. 7 Coefficient of drag at different freestream velocities and angle of attack

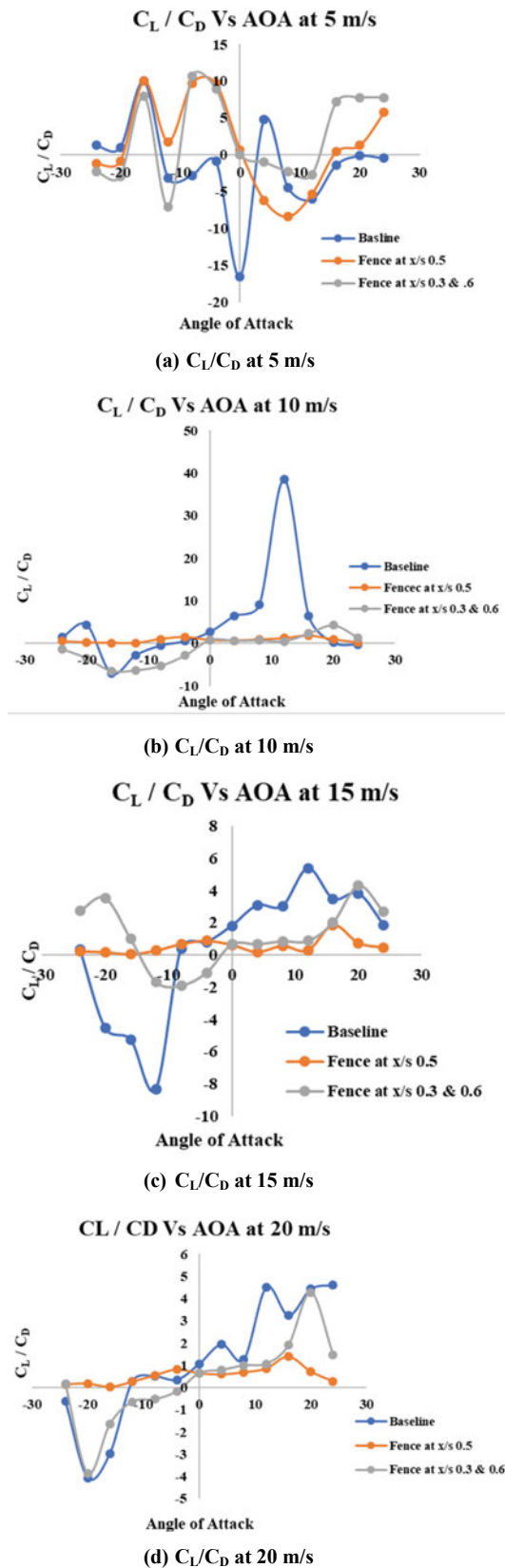


Fig. 8 C_L / C_D at different freestream velocities and angle of attack

4 Conclusion

Experimental work is carried out for baseline and boundary layer fencing wings for two different configurations at a low-speed wind tunnel facility. The following results are produced based on baseline and two different boundary layer fencing configurations were compared in this investigation. The fencing at x/s 0.3 & 0.6 configuration has moderate control of the stalling angle and maximum lift coefficient than the baseline wing. The baseline configurations have a maximum lift coefficient of 7.9 at AOA of 15 in freestream velocity of 10 m/s, for single fencing at x/s 0.5 has C_{Lmax} of 3.5 at 24° in 5 m/s and for two fencing at x/s 0.3 & 0.6 has C_{Lmax} of 4.2 at 24° in 5 m/s. With the help of fencing, it is reduced the drag coefficient by 20% compared to the baseline. It is observed that the number of fencing increases gives an effective result than single fencing and baseline configurations.

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Numerical Investigations of Aerodynamics Performance of Blunt Nose Cone with Aerodisk at Hypersonic Flow

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Abstract

The blunted nose cone with and without a sharp aerospike and an aerodisk of various diameters and lengths are investigated numerically in detail in the current study at a hypersonic Mach number of 10. The aerodisk diameter is described as d/D ratios such as 0.2, 0.4 and 0.6, and the length of the aerospike is represented as the L/D ratio of 1, 1.5 and 2. The main objective of the research is to examine the aerodynamic properties of blunt noses with and without aerodisks and aerospikes, as well as the influence of shock production over the model. The design of blunted nose cones with aerodisk was made up using CATIA and numerical investigation was performed on the ANSYS Fluent. The turbulence model of SST k - ω was considered for study. The current study revealed that shock patterns drastically varied nearer to the nose cone model at L/D ratio 2 and variation of drag reduction occurred due to the increase in d/D ratio and aerospike and also flow pattern over the model was clearly investigated.

Keywords

Aerodisk • Spike • ANSYS fluent • CFD • Blunt nose cone

1 Introduction

High speed vehicles that travel at hypersonic speeds such as spacecraft, launch vehicles, missiles, and re-entry vehicles, typically use a blunt nose body to reduce the heat. In hypersonic vehicles, as Mach numbers get larger, factors like viscous interactions, very high temperatures, formation of a thin shock layer and entropy layer became the highest priority. Excessive aerodynamic drag and aerodynamic heating transmit major obstacles for hypersonic vehicles. At supersonic and hypersonic speeds, the flow over a blunt body generates a bow shock wave that leads to massive surface pressure and severe aerodynamic drag. When in atmospheric flight, blunt bodies with high Mach numbers create a bow shock wave which raises the wave drag significantly and causes heating in the aerodynamic region by exerting a tremendous amount of pressure on the forward-facing area of the body. By creating an area of consistent low pressure in front of the body, which is dull and blunt, the dynamic pressure is reduced. Therefore, in order to reduce the aerodynamic drag and aerodynamic heating, the aerodisk attached with a spike is used which is a simple and useful method.

As bow shock plays an important role for hypersonic vehicles due to the blunt nose shape causing resistance for that reason aerodisk in the frontal area, so that bow shock converts into weak oblique shock. This oblique shock can be penetrated easily with a balance of every parameter. Now oblique shock coming near the body causes high heating issues which can be a high risk of damage to the vehicle. Aerodisk along with an appropriate length of aerospike attachment is there for heat dissipation around the atmosphere.

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Schnepf et al. (2015) simulated the wave drag reduction of the blunt slender body with the help of a self-alignment aerodisk and the complete missile configuration was qualitatively studied. Further observed that AD performance was interesting at much greater repetition rates and Mach numbers with available experimental data and taking into account the aerodisk's kinematics and structure when being shocked and separated, there is qualitatively good agreement. The distinct reduction of drag was achieved in comparison with the reference body without a self-alignment aerodisk. Wysocki et al. (2014) conducted the experimental study of wave drag reduction using self-aligning aerospike on slender body and research done in the transonic wind tunnel under dynamic as well as static environments. Self-aligning aerospikes have been found to reduce blunt-nosed slender bodies' overall drag by up to 25–30% for Mach numbers, which are present in the range of $M = 1.4$ and $M = 2.2$ and it is observed that it helps to fast pitching maneuver in the flow directions.

Deng et al. (2017) numerically investigated the spike effect on drag reduction for hypersonic lifting bodies. To find the optimal disc for reducing hypersonic drag, three alternative aerospike disc designs are studied. The twin flat-faced disc aerospike offers the best drag reduction, reducing pressure drag by 60.5% of the nose's portion at an angle of 8 degrees. Additionally, there is a large increase in drag as the flying angle of attack increases. The 1.6% advance in the pressure centre minimally affects the vehicle's vertical static stability. Hamid et al. (2022) worked on the two distinct geometries, such as two spherically blunted tangent aerodisks and two hemisphere aerodisks. These two geometries are simulated in OpenFOAM software. Understanding shock behaviour, aerodynamic drag, and thermal loading was the main objective of this study. The nose cone attached to the aerodisk has drag that is only 12% of the baseline case of the blunt nose cone, demonstrating that the effectiveness of the two-tangent gives aerodisks with spherically blunted ends in lowering drag. The separation region which is created by the aerodisk is the primary reason for the drag reduction.

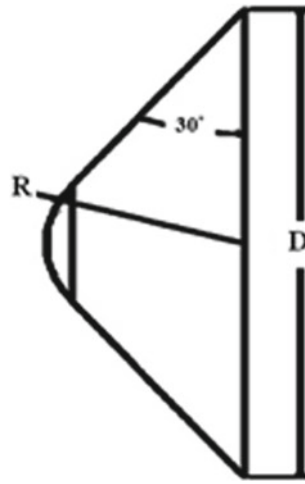
Elsamanoudy et al.'s (2013) After Reattachment Ring for Hypersonic Hemispherical Bodies and Drag Reduction Using Spiked-Aerodisks was studied, it is demonstrated that the reattachment ring, which is positioned exactly on the reattachment point, can be used to lessen the high pressure and aerodynamic heating created there. The simulation was performed using ANSYS Fluent. The reattachment ring, with dimensions of $0.1D$ in height and $0.025D$ in thickness, was a concept that the authors introduced. The ring's reattachment points experience the highest pressure and heating. It utilizes an unstructured mesh. The various models underwent rigorous testing at high Reynolds numbers Re of 4, 5, and 6, 106, as well as high Mach numbers 6, 8, and 10.

At a height of 25 km, the models are evaluated. Senthilkumar et al. (2021) A forward-facing spike was fixed to a hemispherical body generating a recirculation area that circles the area of stagnation of the dull and blunt body, significantly transforms the structure of the flow field and lowers the drag. Because of the geometry of the back-disk, the flow field immediately behind the Aerodisks is more complicated than the flow field directly in front of the conical spike. In order to understand and make most of the spike that is facing forward for more efficient drag reduction, the area of the reattachment point in the shear layer present on the body has to be moved in the backward region by choosing the spike that is similar to the perfect length with the proper arrangement of geometrical part of the nose.

Balaji et al. (2015) the improvement of Blunt Body's Aerodynamic Performance using Aero Disc, the author worked on the hemisphere aerodisk attached with a spike with different diameters of the aerodisk. They used different diameters like $0.1D$, $0.15D$ and $0.2D$, where D is blunt nose diameter. Overall spike to aerodisk length L/D ratio is 1. The spike effects on the Hypersonic lifting body have been examined for aerodynamics properties such as drag reduction, by numerical analysis and comparing the lifting body at 40 km altitude and Mach 8 when equipped with and without an Aerodisk. A numerical simulation of the flow over the vehicle with hemispheric disc aerospikes at various length-to-diameter ratios is performed. For an L/D ratio of 2.0, the hemispheric aerodisk aerospike and a flat conical aerodisk aerospike are compared in order to know about the flow field characteristics and techniques which are related to the reduction of drag. Effect of blunted aerodisk on the blunt nose that is actually aero-spiked cone at a superior velocity, they worked on the blunt nose cone, aerospike with different L/D ratios, hemispherical aerodisk and blunted aero disk. Kalimuthu et al. (2008) did some experimental research, and it was discovered that the Aerodisk is having more superiority and versatility in comparison to the aerospike. Additionally, it has been found that an Aerodisk with the right length, diameter, and nose configuration can lessen the drag on hypersonic vehicles (Balaji et al., 2022). The attachment of an aerodisk after fixing to the leading edge of the spike will help in the drag reduction mechanism. Thought must be given to the increased moment caused by the spike if it is at an angle of attack.

In the current research work, the consequences of aerospike and aerodisk over the blunted nose are investigated for a different hypersonic Mach number 10. The diameter of the hemispherical aerodisk changes for different d/D ratios such as 0.2, 0.3 and 0.4, where d is the diameter of the aerodisk, and D is the blunt body diameter. The aerodisk is positioned at different locations of the location of aerospike length described as an L/D ratio of 1, 1.5 and 2, where L is the length of aerospike. The blunt body's diameter serves as the

Fig. 1 Schematic diagram of blunt nose cone



foundation for the entire structure. The terms “blunted nose” and “blunted nose with aerospike and aerodisk placed in front of the nose cone” refer to two distinct nose cone configurations. The drag coefficients and lift coefficients are measured for different geometries of the nose cone model. This study demonstrates the influence of shock waves from the blunted nose and spiked contacts with aerodisk cones to understand the source of drag reduction and geometry as shown in Figs. 1 and 2.

2 CFD Methodology

In this research work, ANSYS Workbench is used to produce unstructured grids over the blunted nose and the blunted nose with aerospike and aerodisk. The entire surface of the nose cone is generated with an unstructured grid for both cases as shown in Figs. 3 and 4. The flow around the blunt nose cone body is attached to aerodisk which is

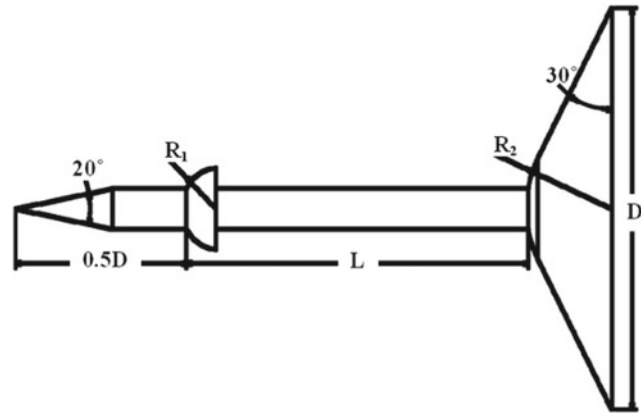


Fig. 2 Schematic diagram of blunt nose cone with aerospike and aerodisk

analysed by ANSYS Fluent. The computation of the flow field incorporates boundary conditions, such as the velocity inlet, velocity outlet, wall, and pressure far field conditions. The simulation of the blunt nose is carried out for various Mach numbers of 10.

The model of a hemispherical aerodisk is attached with a sharp spike and blunt body is designed in ANSYS Design Modeler. A CFD domain was created around the body and The CFD domain was given a name like inlet, outlet, symmetry, wall, and pressure far field. The meshing is generated over the model with an unstructured grid with a count of 150,000 cells. The Gauge pressure, Temperature and operating conditions are 26,425 Pa, 233 K and 0 Pa, respectively. For analysis of the CFD domain, the flow is considered as compressible, density-based solver used and also Turbulence model is considered as the SST k-omega model. The governing equations used for the turbulence model are described. The Shear Stress Transport k-omega model's transport equation variables are comparable to

Fig. 3 Meshing of the blunt nose cone

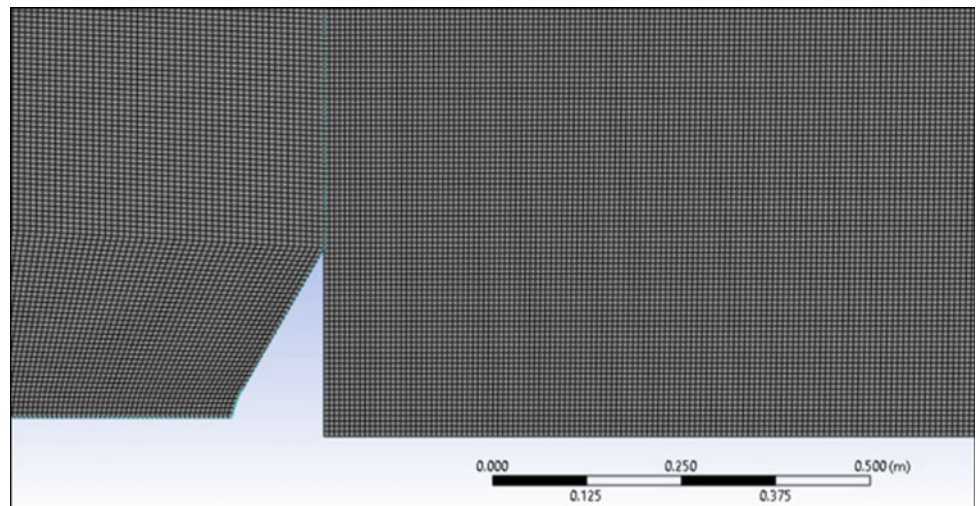
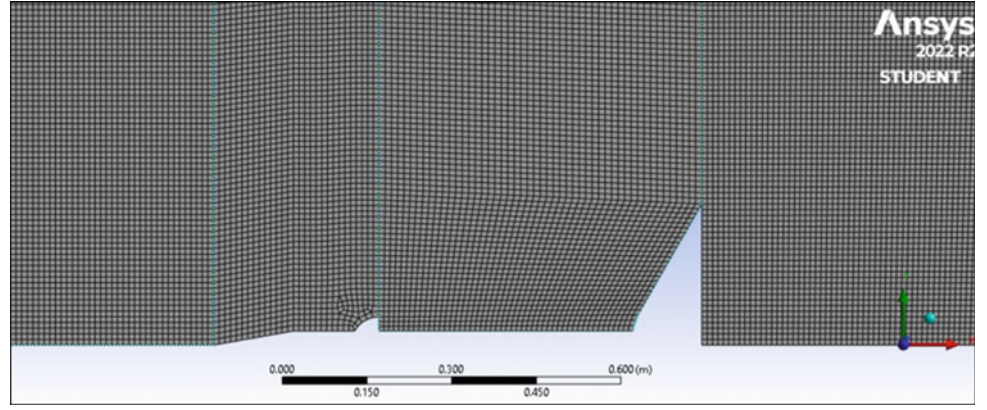


Fig. 4 Meshing of blunt nose cone with aerodisk and aerospike



turbulence's kinematic viscosity, with the exception of the viscous-affected region close to the wall. The transport equation related to the kinematic viscosity (ν) is given by

$$\begin{aligned} & \frac{\partial}{\partial t}(\rho\nu) + \frac{\partial}{\partial x_i}(\rho\nu x_i) \\ &= G_\nu + \frac{1}{\sigma_\nu} \left\{ \frac{\partial}{\partial x_i} \left[(\mu + \rho\nu) \frac{\partial \nu}{\partial x_j} \right] + C_{b2} \rho \left(\frac{\partial \nu}{\partial x_i} \right)^2 \right\} - Y_\nu + S_\nu \end{aligned} \quad (1)$$

where

G_ν is the generations of the turbulence viscosity, and σ_ν and C_{b2} are the constants, due to viscous damping and wall blocking, Y_ν is the degradation of the viscosity that is related to the eddy currents which is in close proximity to the wall zone. The viscosity of the molecular kinematics is. S is the user-defined source term represented in the Eq. (1).

3 Result and Discussion

Understanding the forebody's reattachment point requires knowledge of the shock contour plot. Understanding the amount of reattachment delay for varied aerodisk diameters and aerospike lengths is the goal of this study. The increase in aero disc diameter from the pressure coefficient plot is observed to cause a delay in shock reattachment on the forebody. Additionally, it has been discovered that shock reattachment has an impact on the forebody's pressure coefficient owing to the aerospike's diameter and aerospike length, and that the aero disk's diameter increases resulting

in a reduction in drag. On reattachment, the importance of such an aerodisk structure is implied. Additional combinations are also being included in this research.

3.1 Pressure of Contour of Blunt Nose Cone with and Without Aerospike and Aerodisk at Different Mach Numbers

This paper looked at different instances of disc spike performance in the region of the hypersonic lifting body aerodynamics. The computer simulation of flow which is hypersonic over a spiky lifting body at a Mach number of 10 with various L/D ratios and d/D ratio of the blunt nose conoid which is hovering at angles of attack 0 at various L/D ratios and d/D ratios. The pressure distribution over the blunt cone was examined for a Mach number of 10, represented with pressure contour, velocity contour, and velocity vector plots, giving insight into flow physics to analyze the behavior to find the drag reduction and shock pattern over the blunt nose cone with and without L/D ratio and d/D ratio shown in Figs. 5, 6, 7, 8, 9, 10, 11, 12 and 13.

3.1.1 Pressure Contour at Different D/D Ratios, $L/D = 1$ and Mach Number, $M = 10$

By analyzing the flow evolution which was found in a close diameter circling the area of blunt nose cone with and without the aerodisk and also the aerospikes depicted in Fig. 5a–d explains this discrepancy. In Fig. 5a, the pressure contour is somewhat elevated upstream of the blunt nose cone and creates the shock pattern distant from the blunt

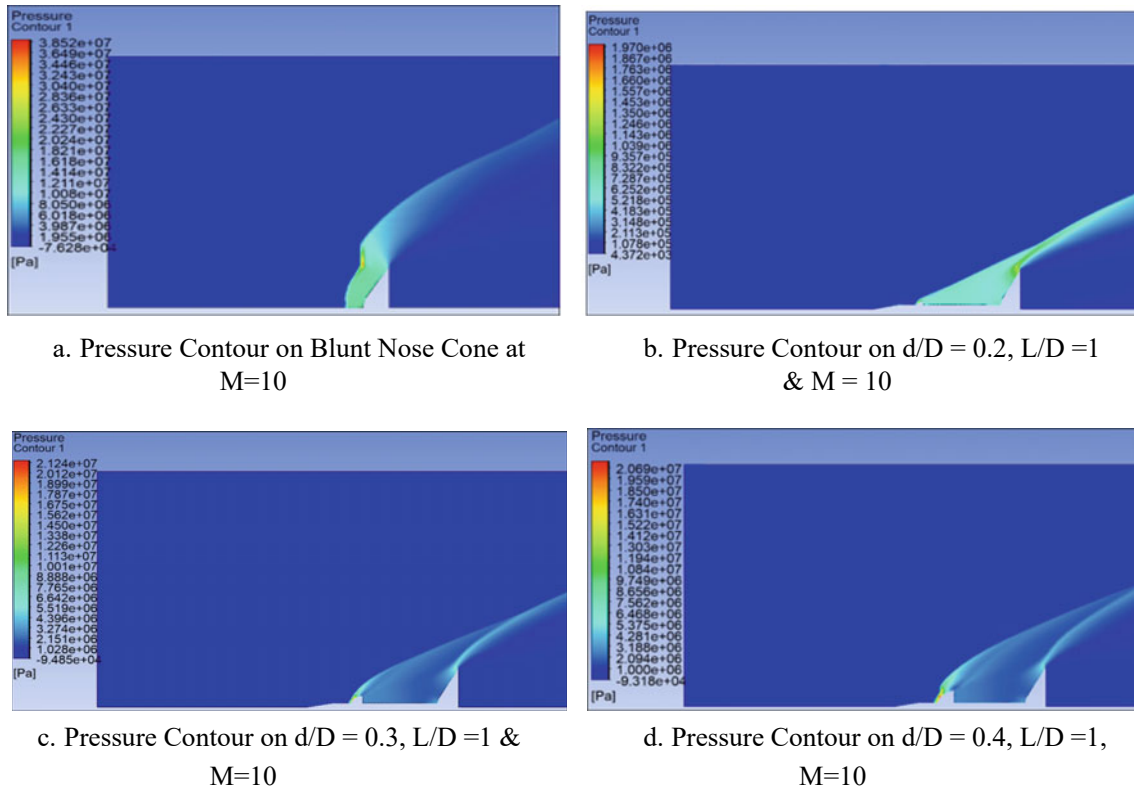


Fig. 5 Pressure distribution over the nose cone with and without aerospike and aerodisk at L/D ratio = 1

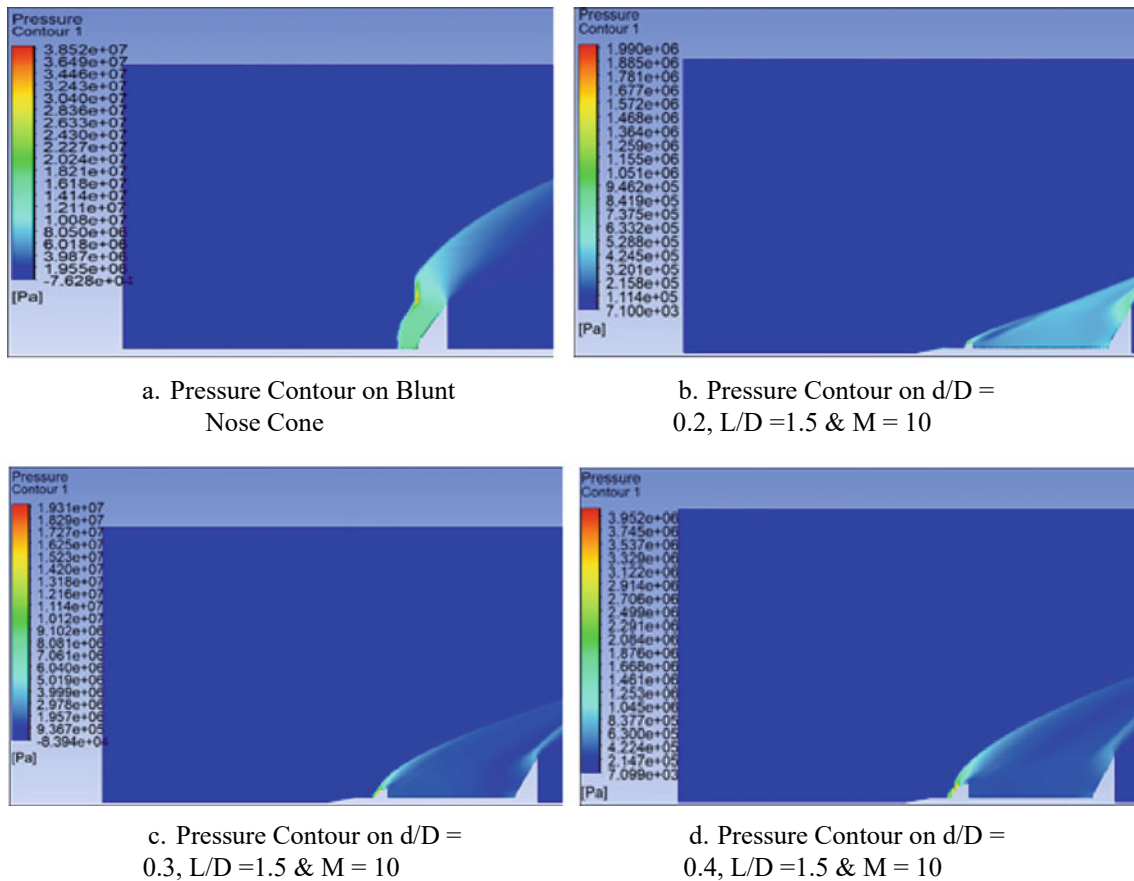


Fig. 6 Pressure distribution over the nose cone with and without aerospike and aerodisk at L/D ratio = 1.5

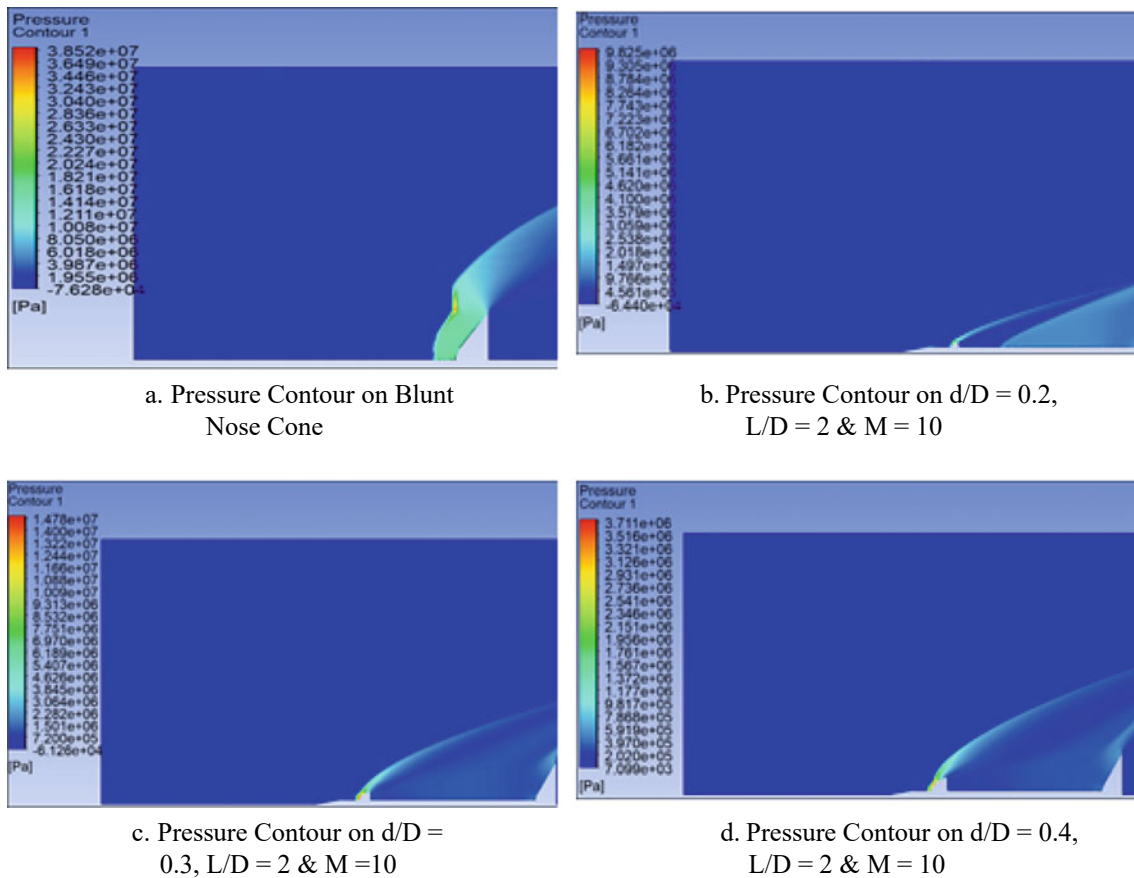


Fig. 7 Pressure distribution over the nose cone with and without aerospike and aerodisk at L/D ratio = 2

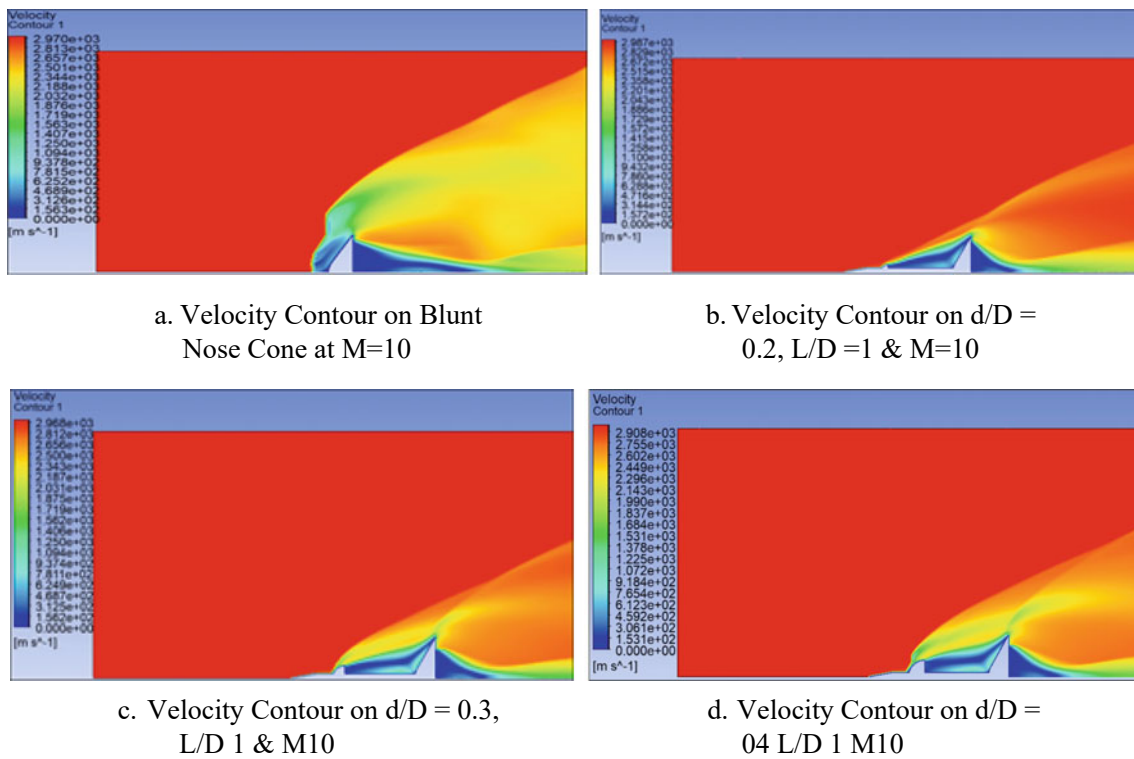


Fig. 8 Velocity distribution over the nose cone with and without aerospike and aerodisk at L/D ratio = 1

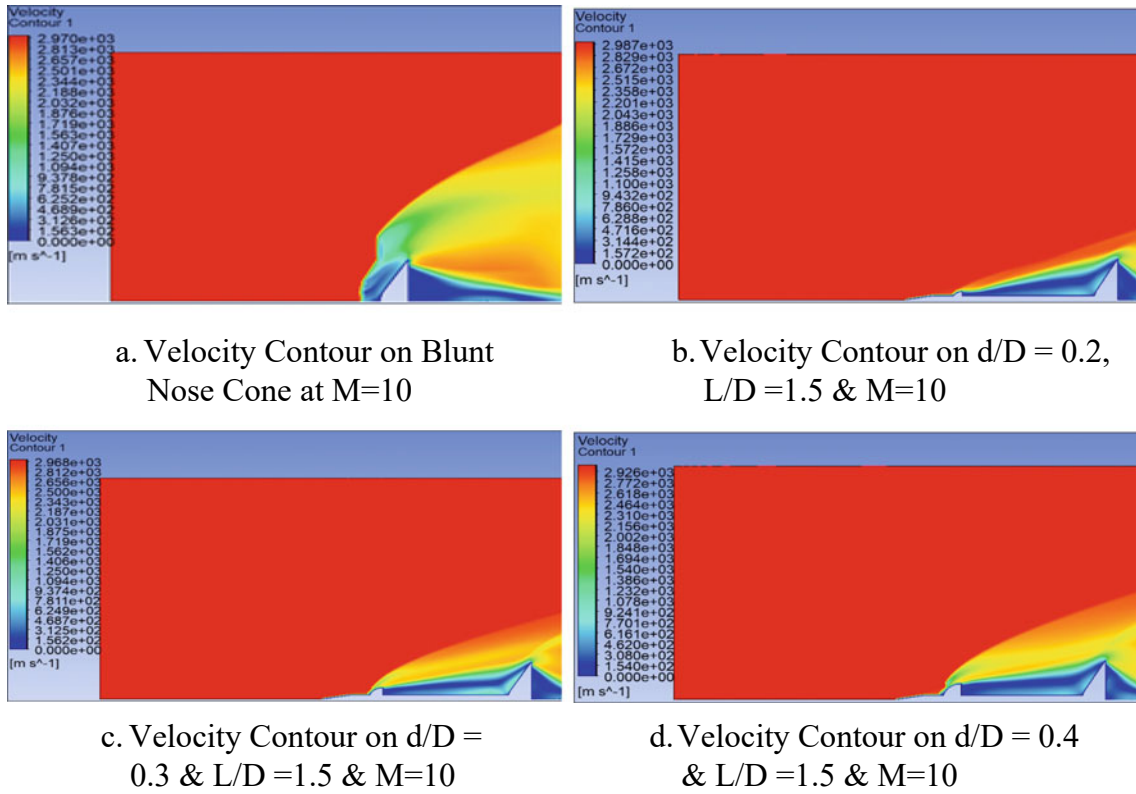


Fig. 9 Velocity distribution over the nose cone with and without aerospike and aerodisk at L/D ratio = 1.5

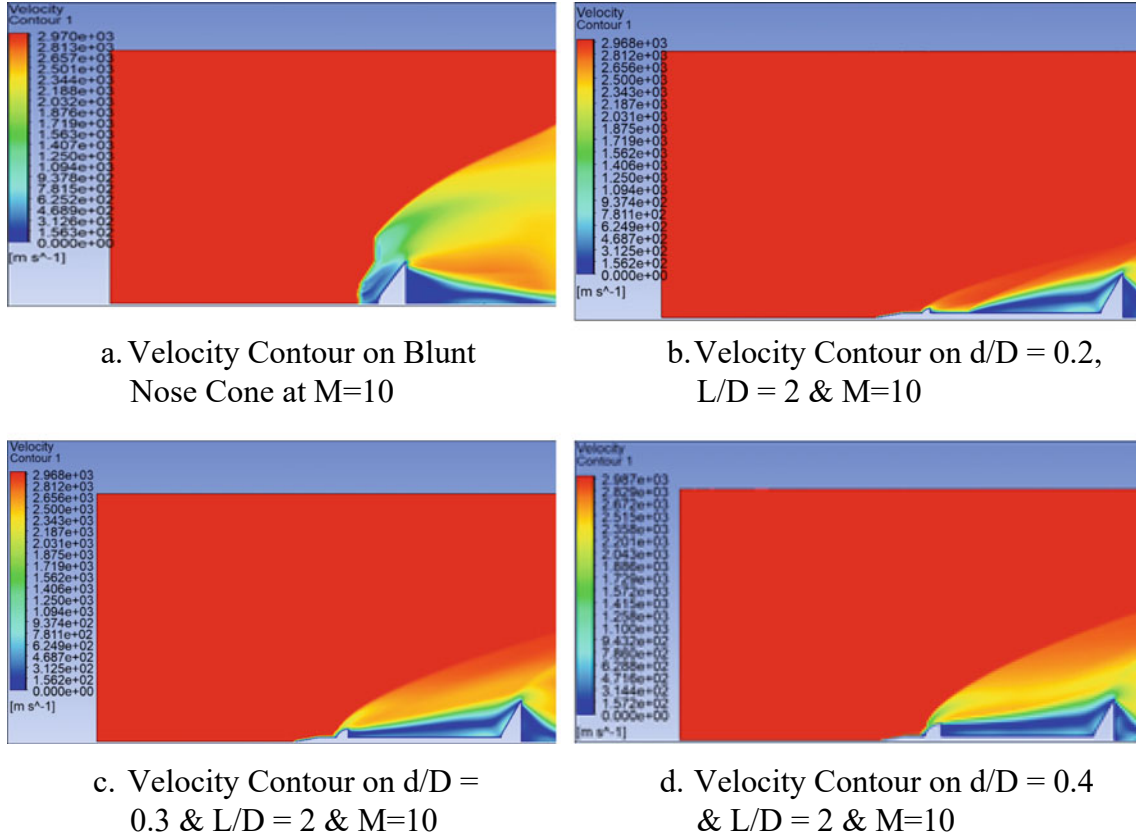


Fig. 10 Velocity distribution over the nose cone with and without aerospike and aerodisk at L/D ratio = 2

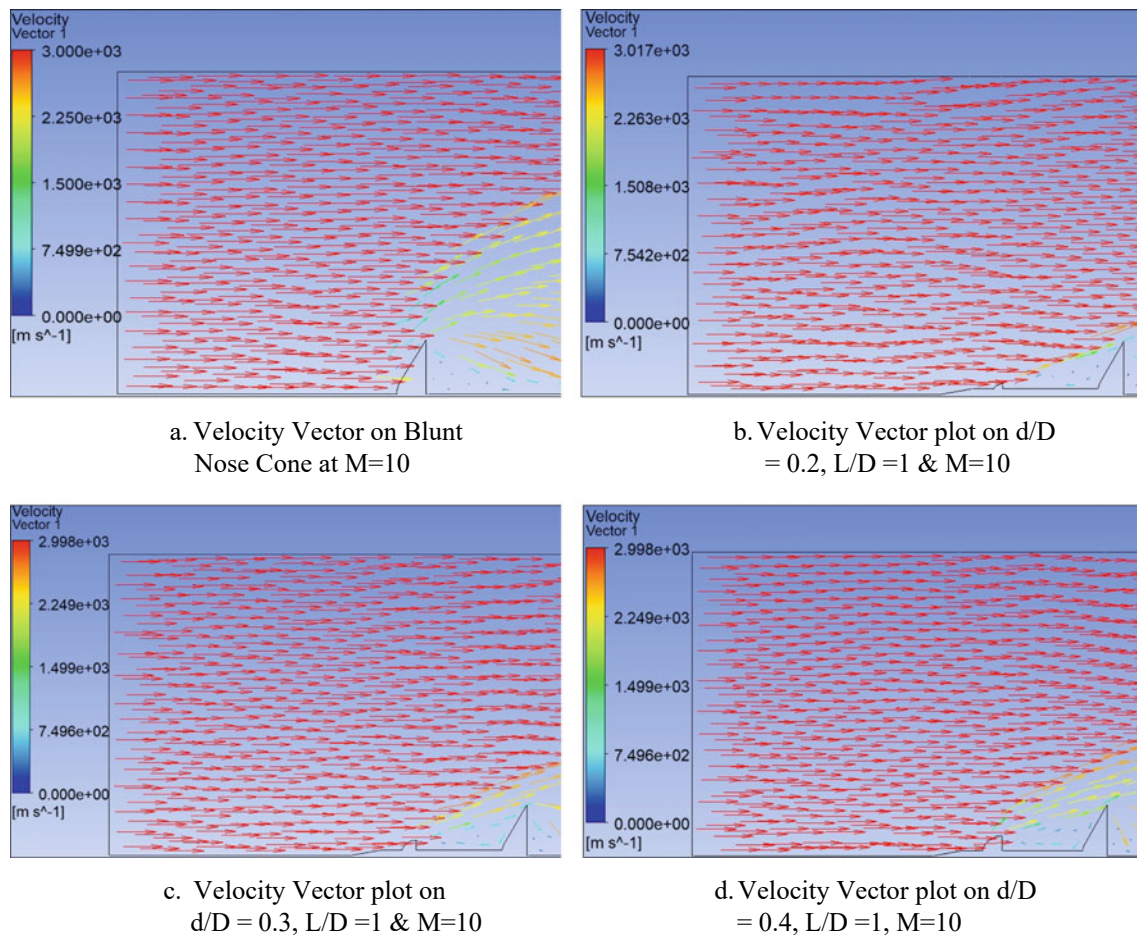


Fig. 11 Velocity Vector distribution over the nose cone with and without aerospike and aerodisk at L/D ratio = 1

nose cone's tip. The shock pattern that came into existence in the area of the nose cone that is blunted with aerodisk as well as aerospike has been demonstrated in Fig. 5b–d and the shock pattern intersects behind the nose cone. The strong shock pattern formation occurs at a d/D ratio of 0.2, 0.3 and 0.4 at the location of $L/D = 1$.

3.1.2 Pressure Contour at Different D/D , $L/D = 1.5$ and Mach Number, $M = 10$

Analysis and comprehension were done to find out why there is a difference, the flow field evolution of the blunt nose cone with the usage and also without the application of the aerodisk and aerospike shown in Fig. 6a–d is investigated. In Fig. 6a, the shock pattern is formed far from the blunt nose cone's tip by the pressure contour, which is slightly higher upstream of the blunt nose cone. Figure 6b–d depicts the shock pattern generation in the aerodisk and

aerospike-equipped blunt nose cone as well as the intersecting shock pattern that forms behind the nose cone. The powerful shock pattern develops for d/D ratios of 0.2, 0.3, and 0.4 when L/D is equal to 1.5.

3.1.3 Pressure Contour at Different D/D , $L/D = 2$ and Mach Number, $M = 10$

To analyze and for an understanding of the differences, the evolution of the flow field around the blunt nose cone with and without the aerodisk and aerospike depicted in Fig. 7a–d is compared. The shock pattern is formed away from the blunt nose cone's tip by a minor increase in the pressure contour at Fig. 7a upstream of the cone's blunt tip. The shock pattern is formed in the blunt nose cone with an aerodisk and aerospike, as shown in Fig. 7b–d, and intersects with the shock pattern behind the nose cone very far away. At the ratio of $L/D = 2$, the creation of a very

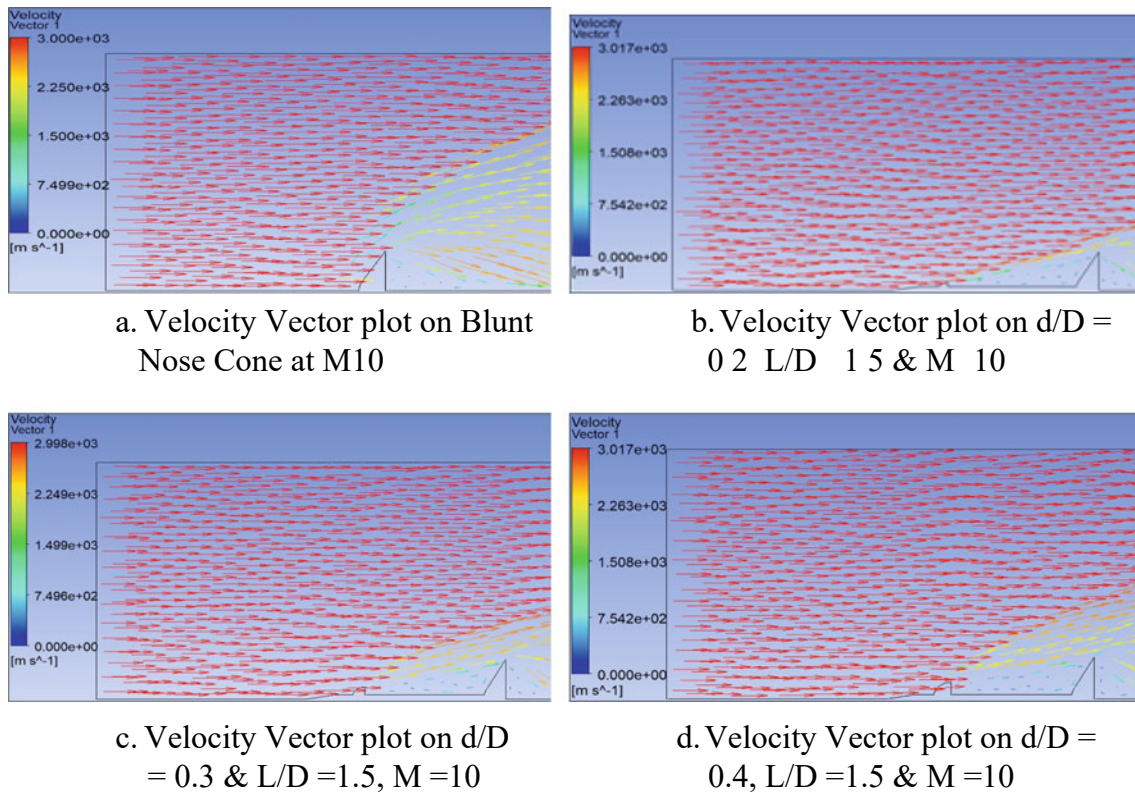


Fig. 12 Velocity Vector distribution over the nose cone with and without aerospoke and aerodisk at L/D ratio = 1.5

significant shock pattern takes place at d/D ratios of 0.2, 0.3, and 0.4. The strength of shock formation is slightly higher than other L/D ratios such as 1 and 1.5.

3.2 Velocity Contour of Blunt Nose Cone with and Without Aerospoke and Aerodisk at Mach Number 10

The velocity distribution over the blunt cone was investigated for Mach number of 10 represented with velocity contour gives flow physics to analyze the behavior to find shock pattern over the blunt nose cone with and without L/D ratio and d/D ratio as shown in Figs. 8, 9 and 10.

3.2.1 Velocity Contour at Different D/D , $L/D = 1$ and Mach Number, $M = 10$

For analysis and for a better understanding of the differences, the evolution of the flow field around the blunt nose cone with and without the aerodisk and aerospoke depicted in Fig. 8a–d is compared. The shock pattern is formed away from the blunt nose cone's tip by a minor increase in the velocity contour at Fig. 8a upstream of the cone's blunt tip. The shock pattern is formed in the blunt nose cone with an aerodisk and aerospoke, as shown in Fig. 8b–d, and an

intersect shock pattern is formed behind the nose cone very far away. At the ratio of $L/D = 2$, the creation of a very significant shock pattern takes place at d/D ratios of 0.2, 0.3, and 0.4. The strength of shock formation is slightly higher than other L/D ratios such as 1 and 1.5.

3.2.2 Velocity Contour at Different D/D , $L/D = 1.5$ and Mach Number, $M = 10$

Figure 9a–d illustrates the investigation of the velocity vector growth around the blunt nose cone with and without the aerodisk and aerospoke.

The shock pattern is formed away from the blunt nose cone's edge by a slight increase in the velocity contour at Fig. 9a upstream of the cone's blunt edge. The shock pattern is formed in the blunt nose cone with an aerodisk and aerospoke, as shown in Fig. 9b–d, and an intersect shock pattern is formed behind the nose cone very far away. At the ratio of $L/D = 2$, the formation of a significant shock pattern takes place at d/D ratios of 0.2, 0.3, and 0.4.

3.2.3 Velocity Contour at Different D/D , $L/D = 2$ and Mach Number, $M = 10$

The evolution of the flow field around the unsharpened and dull conoid of nose with the application as well as without the usage of the aerodisk and aerospoke shown in Fig. 8a–d

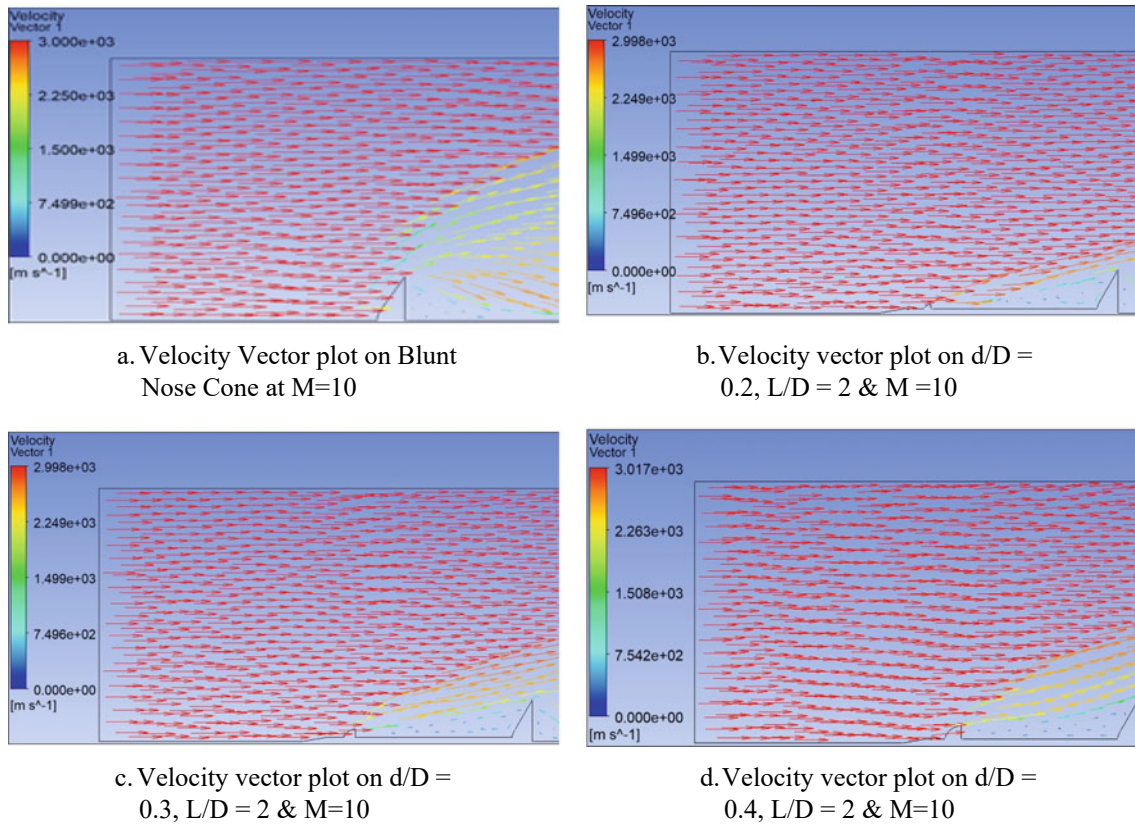


Fig. 13 Velocity vector distribution over the nose cone with and without aerospike and aerodisk at L/D ratio = 2

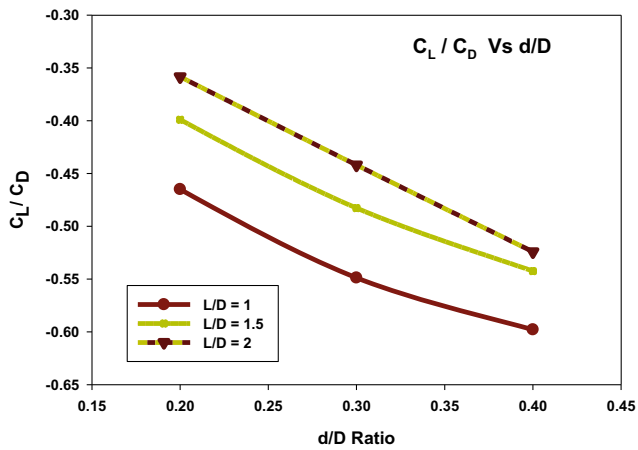


Fig. 14 C_L / C_D ratio versus d/D ratio

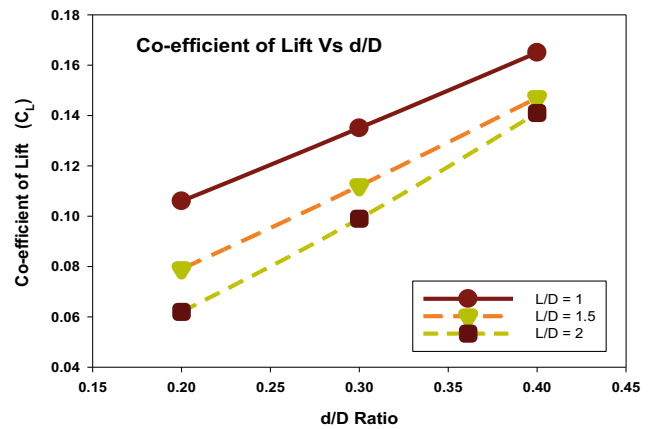


Fig. 15 C_L versus d/D ratio

is analyzed to understand the difference. The shock pattern is formed away from the blunt nose cone's tip by a minor increase in the velocity contour at Fig. 8a upstream of the cone's blunt tip. The shock pattern is formed in the blunt nose cone with an aerodisk and aerospike, as shown in

Fig. 8b–d, and an intersect shock pattern is formed behind the nose cone very far away. At the ratio of $L/D = 2$, the creation of a very significant shock pattern takes place at d/D ratios of 0.2, 0.3, and 0.4. The strength of shock formation is slightly higher than other L/D ratios such as 1 and 1.5.

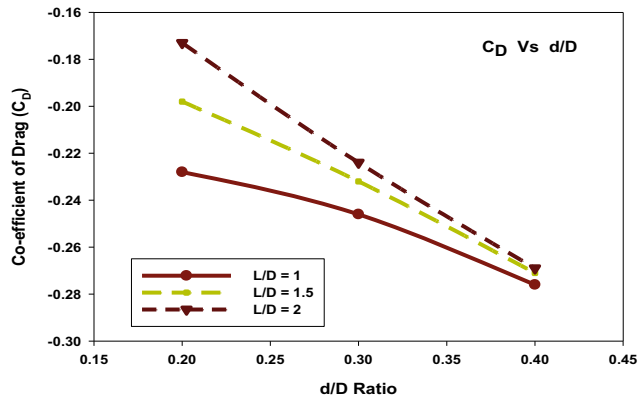


Fig. 16 CD versus d/D ratio

3.3 Velocity Vector Plot of Blunt Nose Cone with and Without Aerospire and Aerodisk at Different Mach Numbers

The distinct difference of flow features as well as velocity vector creations over the blunt nose cone with and without different L/D ratio and d/D ratio with Mach number of 10 is clearly shown in Figs. 11, 12 and 13.

3.3.1 Velocity Vector at Different D/D Ratios, L/D = 1 and Mach Number, M = 10

The streamlined flow over the blunt nose cone described by the velocity vector is shown in Fig. 5a and decelerated flow gets diverted and moves slightly away from the tip of the nose cone. But in the case of a blunt nose cone with aerodisk and aerospire, the flow accelerated behind the aerodisk is very closer to the aerospire by an increase in d/D as shown in Fig. 11b–d.

3.3.2 Velocity Vector at Different D/D, L/D = 1.5 and Mach Number, M = 10

The streamlined flow over the blunt nose cone described by the velocity vector is shown in Fig. 12a and the decelerating flow becomes sidetracked and drifts away from the nose cone's tip. But with a blunt nose cone equipped with an aerodisk and an aerospire, the flow accelerated behind the aerodisk very closer to the aerospire by an increase in d/D as shown in Fig. 12b–d.

3.3.3 Velocity Vector at Different D/D, L/D = 2 and Mach Number, M = 10

The streamlined flow over the blunt nose cone where described by the velocity vector is shown in Fig. 13a and decelerated flow gets diverted and moves slightly away from the tip of the nose cone. But in the case of blunt nose cone with aerodisk and aerospire, the flow accelerated behind the

aerodisk very high compared with other d/D [0.2 & 0.3] and closer to the aerospire very high d/D as shown in Fig. 13b–d.

3.4 Effect of Lift Co-efficient and Drag Co-efficient on Blunt Nose Cone with and Without Aerodisk and Aerospire with Mach Number of 10

The lift coefficient and drag coefficient play vital roles in the blunt nose cone and the research carried out provides us enough evidence that shows and proves the size of the aerodisk, and aerospire is having a significant impact involved in the decrease of drag. It is explored that aerospire and aerodisk diameter influences the pressure drag and lift during high-speed flow with Mach number 10 and it was clearly represented in Figs. 14 and 16. The coefficient of drag with different geometry of d/D = 0.2, 0.3 and 0.4 (d/D describes the ratio of aerodisk diameter to blunt nose diameter). It observed that the lift coefficient is not significant but accounted for in our study illustrated in Fig. 15 which shows that the lift coefficient is more effective in L/D = 1 increase with an increase in the aerodisk diameter than other L/D locations. In the case of the drag coefficient in Fig. 14, it is observed that drag reduction was influenced by an increase in aerodisk diameter at L/D = 1.

4 Conclusion

In this paper, the aerodisk assembly's sharp spike is intended to lessen the drag and aerodynamic heating. Mach number 10 free stream testing was conducted on the setup. The spiky aerodisk configuration outperformed two conventional configurations with a maximum drag reduction of 37.73%. The flow field around this arrangement demonstrated that it was better to separate the entering flow than the normal hemispherical aerodisk and the acute spike. As the length of the spike and diameter increases, the percentage of drag reduction increases. The peak heating value and static pressure on the blunt hemisphere surface both significantly dropped as a result of this idea being proposed. From the analysis, the reduction of drag does not work on the higher Mach speed. The shape hemi-spherical is likely more convenient than the blunt body for heat dissipation and drag reduction. In this research work, the results of the current study show that the shock pattern varies significantly closer to the nose cone model at L/D ratio 2 and that variations in drag reduction occur as a result of increasing d/D ratio and aerospire. Also, the flow pattern over the model was thoroughly examined.

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Analysis of Supercritical Hydrocarbon Fuel as a Coolant for Improved Thermal Performance of Scramjet

Athota Rathan Babu, Sravanthi Gudikandula, K. Sai Puravardhan, Surya Hevanth Nimmala, Premkumar Bet, and Sathvik Merugu

Abstract

Supercritical hydro-carbon fuel is engaged in concurrent cooling of corresponding combustors to recover heat. The working fluid preferred for the analysis is methane because of its heat transfer characteristics and it works significantly at higher Mach numbers. The aim is to develop the thermal performance and the convection heat transfer properties of a regenerative cooling system in scramjet engine. The model or replica of the cooling channel is a complicated task because of its factors, including the high wall temperature gradients, values of high Reynolds number (Re), and developing the three-dimensional geometry of passages. The working fluid is incorporated into the rectangular channels model with the required inlet mass, inlet temperature, and pressures.

Keywords

Supercritical fluids • Regenerative cooling • Reynolds number (Re) • Mach number • Methane

1 Introduction

Supercritical phenomena of fluids were discovered by Baron Charles Cagniard de la Tour in the late 1880s. Supercritical xenon, ethane, and carbon dioxide are examples of substances that combine gas and liquid properties, providing a variety of unique chemical possibilities. Due to the less viscous nature and more expansion in the variable phase, the supercritical fluid chromatography (SFC) method can theoretically be up to ten times faster than high-performance liquid chromatography (HPLC). SFC procession also particularly offers a thrice-to-five-fold reduction in analysis time compared to HPLC. The solvent strength of SFC depends on densities which are related to temperature and pressure, it has a higher rate of diffusion and has a lower viscosity than liquid. The astonishing properties of supercritical substances are because of their unique thermodynamic properties and exist between the properties of liquids and gas, these fluids allow constant extraction using economical and exceptionally non-toxic materials. Due to amorphous properties, they have been used for regenerative cooling effects as thermal protection of super-combustion stamping engines is a serious problem. Scramjet engines can reach temperatures of up to 2000 tu/ft-sec, thus regenerative cooling technology can provide better thermal protection than other methods for air-breathing hypersonic-jet flight, where it is gaining more attentiveness, scramjets are known as the most promising power source. The heat protection of combustion chambers will be a major issue when the flying Mach number increases due to the extremely warm environment. Active regenerative cooling technology, where the hydrocarbon fuel of a scramjet is employed as a coolant, is recommended as the most viable thermal protection solution. In the procedure of the cooling process, hydrocarbon fuel offers both physical and chemical heat sinks via endothermic reactions (also known as thermal cracking or pyrolysis).

Next-generation aircraft have been predicted to be hypersonic vehicles, which are built for both defense

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missions below or above the atmosphere and commercial usage. Scramjet is recognized as one of the most prominent air-breathing hypersonic propulsion systems, capable of driving a hypersonic vehicle alone or it is a key model of combined cycle engines. One of the technological hurdles in the construction of scramjets is heat protection for combustor walls. The total degrees/temperature of the gas mixture in the scramjet combustor will be greater than 2800 K in reaction, when the flight Mach number is over 5, and the corresponding heat flux density on the combustor walls will easily overlimit 10 MW/m², meaning that almost no material can withstand such a large heat load for an extended period of time. As a result, advanced cooling is used to preserve the scramjet combustor boundaries while also returning combustion heat dispersion back into the combustor for propulsion. However, at greater flying Mach numbers, regenerative cooling cannot match the high value for heat protection, particularly where the coolants are hydrocarbon fuels.

The X-43A, X-51A, and other hypersonic aircraft use regeneratively cooled engines with the help of implementing supercritical fluid as an essential cooling fluid. After a certain period of research, it is found that supercritical methane is best suited for the advanced cooling of the combustion chamber, as this paper gives information about the SFC (methane) the way it has been used, and the model that is demonstrated for producing extensive cooling effect from the advantageous properties of SFC methane (Fig. 1).

The major reason for not considering methane as fuel in every scramjet engine is that storing and utilizing it can be tricky and pose potential problems that may exacerbate the global warming issue we are currently facing. Thus, the reason the methane used in this analysis is not mixed with other toxic hydrocarbons leads to global warming, and less emerged methane used as supercritical fluid is pumped into the chamber and used for regenerative cooling.

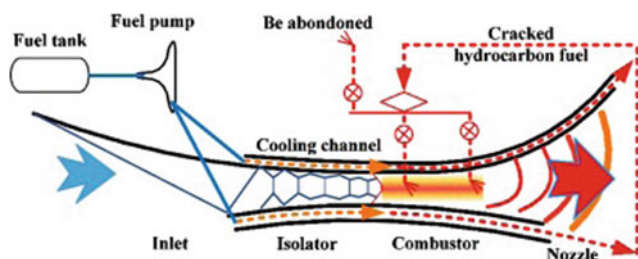


Fig. 1 Regenerative cooling method to a scramjet engine (Source Google)

2 Literature Survey

The heat exchanger equivalence of n-decane is in circumstances resembling a rejuvenated and cooled scramjet was examined through a sequence of mechanical heated tube experiments. In these experiments, the fuel was raised to high degrees in a 1.5 mm inmost diameter tube of 1Cr18Ni9Ti, where the fuel pressure is also changed by 4.0–4.3 MPa. The Reynolds number fluctuated between 800 and 70,000. Using least squares curve fitting method, the heat transfer equivalences of n-decane are laminar, transition, and turbulent flow areas were resolute by Zhang et al. (2013).

Sun et al. (2021) investigated the use of supercritical fluids, including hydrocarbons, H₂O, CO₂, and organic working mediums, as functioning fluids are refined by heat effectiveness in power cycles and energy conversions. The focus is on common problems such as heat transfer strengthening and degradation, especially for supercritical hydrocarbon fuels based on associated wall temperature and heat transfers. The review provides a comprehensive analysis of the heat behaviors of fluids in engineering applications. Supercritical (Li et al., 2021) fluids have expanded beyond power generation to include aerospace cooling and nuclear engineering. In the case of scramjet combustors, supercritical aviation kerosene is used for heat absorption during high Mach number flights, making it an active regeneration cooling technique in aerospace applications. The process involves compressing AV kerosene with a pump and flowing it into mediums across the combustor to remove heat developed in the combustion chamber. Chemical components, including nanoparticles, can be added to enhance heat transfer and prevent abnormal heat transfer occurrences.

Hua et al. (2010) explained the utilization of supercritical hydrocarbon fuel for cooling purposes in advanced aircraft that travel at high Mach numbers. In order to cope with the high temperatures in the engine, regenerative cooling is employed. Moreover, an advanced flexible cycle is determined through the utilization of a fuel-cooled scramjet. Nonetheless, the cooling channel can experience anisotropic turbulence and buoyancy-driven stratified flow, which will cause transient thermally activated flow oscillations in supercritical fluids. These oscillations can impact the invariability of fuel injections and in combustion process, making flow homogeneity crucial. The coolant of choice is N-decane, a pure hydrocarbon fuel in aerospace engineering. Its consequential temperature and pressure are taken at 617 K with 2.11 Mpa, respectively. The research employs

the large eddy simulation model to explore the effects of buoyancy-driven phenomena on thermal oscillations in anisotropic turbulent flow.

Zhong et al. (2009) discussed about scramjet engines are a promising option for high-speed flight, but their high combustion temperatures present a challenge. Cooling systems are needed to prevent overheating, with endothermic hydrocarbons often used as coolants due to their efficiency in absorbing and dissipating heat. This coolant choice is necessary due to limited onboard fuel carrying capacity, as heat flux to mass flow rate ratios are greatest for fluids at normal pressures. For regenerative cooling, Li et al. (2023) discussed that in scramjet regenerative cooling channels, micro-rib is a useful technique for controlling heat transmission. The coolant qualities have a significant impact on cooling performance. Heat exchanger properties of a supercritical hydrogen flow are given by pocket-sized ribbed cooling channels and are investigated using illustrations of fluid wall limit layers and Fourier analysis studies of tiny-rib height. Due to an abnormally increased thermal boundary layer, the results show that microribs can't always efficiently diminish the boundary temperature of supercritical hydrogen. High temperatures boundary layer thickness can be up to 1/3 of channel height and substantially thicker than the velocity boundary layer with severe heat energy stratification. Heat transmission will be locally boosted only if fluid thermal expansions of supercritical hydrogen in the medium center are stimulated.

Experimental and numerical research by Bao et al. (2010) into the impact taken with a channel aspect ratio (AR) of a chemical revival process revealed like a small medium aspect ratio can also help that process by reducing the temperature differential. The size of each particular duct should kept as minute as possible, according to Pizzarelli et al.'s (2013) penetrative model for an incompressible fluid flowing in rectangular ducts with linked thermal conduction. To investigate an active cooling mechanism, Daniau et al. (2003) created a heat decomposition model for n-dodecane. Experimental evaluation of chemical or a compound heat sink offered by fuel pyrolysis and comparison of the findings with pertinent numerical data produced by internal MBDA-France software was conducted (Daniau & Sicard, 2005). A sensible agreement between experimental findings and simulations using chemically reactive n-dodecane, a fair degree of agreement was discovered. Preliminary and numerical studies of behavior with mild thermally cracked n-decane revealed that even at low conversion, chemical endothermic reactions were capable of absorbing large amounts of heat. By using two-dimensional numerical modeling, Xu et al. (2015a) investigated the impact of quadrilateral and triangular ribs in the thermal transmission of supercritical CH₄ in cooling

mediums of rocket engines. With chemically reactive n-dodecane, the data demonstrate that such ribs have extremely strong heat transfer enhancement performance and lower the wall temperature by over 200 K. Experimental and numerical studies of the behavior of mild thermally cracking n-decane revealed that chemical endothermic events provide heat absorption. The high-temperature behavior of transcritical n-Decane in small-ribbed cooling channels for scramjet engines is parametrically investigated by Li et al. (2018). Under supercritical pressures, the micro rib parameters have a non-monotonic effect on the boundary heat transfer of n-Decane, and the ideal microrib variables remain low due to abrupt variations in the thermophysical characteristics of the coolant in the near-critical zone. When compared to a smooth channel, the Nusselt number might be increased by more than twice with a micro rib array. Dimple is notable as an efficient heat transfer improvement technique due to its lower pressure drop penalty. The flow-stream properties and heat exchanger of dimpled mediums have taken on the subject of extensive research. Dimples have been shown to have 1.3–4.47 times the heat exchange layer of a smooth surface.

By using numerical simulations and tests, Ligrani et al. (2003) investigated the effects of dent shapes, the deepest part-to-diameters ratio, where the medium heights on flow circulate and heat exchange or transmission properties. According to Ligrani et al. (2001), dimples can occasionally produce vortex shedding pairs and the recombining of the shear layers, which greatly improves the heat exchanger while causing a small pressure drop. Additionally, Feng et al. attempted an augment the cooling capacity of scramjet engines by using dimples as emphasized heat transfer structures inside the regenerative cooling channels. In their investigation related to the thermal properties of jagged cooling tubes used as supercritical hydrocarbon fuels, Xu et al. (2015b) found that HTD can be significantly reduced when compared to circumstances in a smooth tube. Experimental research on the impact of coking sediments upon the stream flow and high-temperature transmission is examined, found that the spiral or circular centrifugal force will lessen pressure loss and thermal oxidation coking. Static Flow Instability (SFI) is a term used by Liu et al. (2012) to describe the hydrodynamic properties of supercritical fluid. SFI resembles the instability brought on by a disturbance and a catalyst for flow excursion. Experimental research by Yang et al. (2018) into the properties of supercritical cyclohexane flow led to the conclusion that OFI is considered as low point of the hydrodynamic multi-valued characteristic curve. Additionally, these are discovered at this point, when the fluid outlet degrees attained their pseudo-critical temperatures.

3 Methodology

Scramjet with a regenerative cooling system prevents overheating of the walls. The material for the complete model has been chosen as a steel alloy with the appropriate physical properties. The hydrocarbon methane with a liquid state enters into the channel as soon as the combustion takes place with an inlet temperature of 190 K (critical temperature) and operating pressure of 1 MPa. As the temperature rises with the combustion process, it gets treated beyond critical properties, which bring the methane to a supercritical state. This state of methane provides an immersive cooling effect to the walls.

The model has been designed using CATIA V5. Numerical simulations using ANSYS Fluent were performed to calculate detailed temperature, pressure, velocity contours, and heat transfer information by passing the fuel into the channels, it mixes with combustion and boosts the exhaust (Figs. 2 and 3).

3.1 Calculation

The dimensions of the cooling channel model are 1.5 m in length and 0.5 m in width, with specific outer and inner wall thickness. In this paper, the analysis focuses on a flow unit with four inlets that measure 0.025 m in length and 0.009 m in width, with a gap of 0.01 m between the channels. The cooling channel material is constructed from steel alloy, and methane is chosen as the coolant due to its exceptional properties demonstrated in rocket engines. The experimental process involves solving equations directly applied to the entire object, as the shape of the object is too complex or irregular to solve directly. To address this challenge, meshing is utilized to convert the irregular shapes into recognizable “elements”. By solving these individual equations, the solution for the complete geometry is attained. Finite element simulation applies a numerical grid to the fluid body

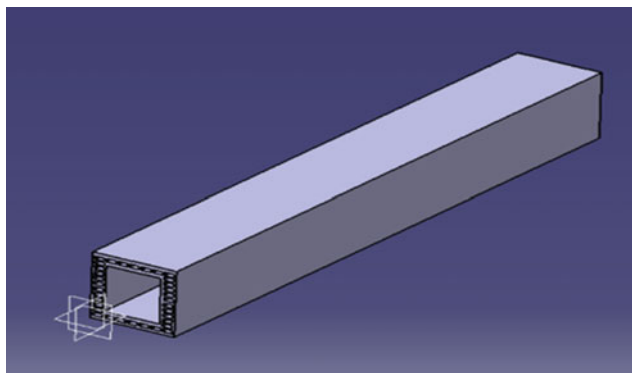


Fig. 2 CATIA design of the scramjet combustion chamber

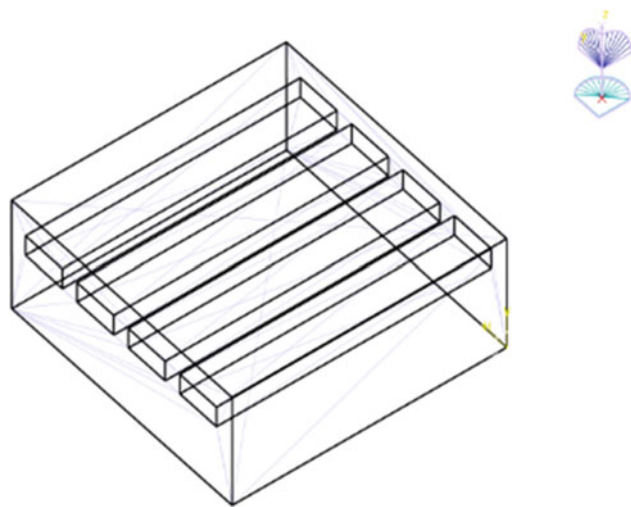


Fig. 3 Analysis model

and its boundary, demonstrating the ease and significance of meshing. The convergence and accuracy of a simulation are dependent on its mesh, and with appropriate settings, a structured coarse mesh with nodes at 1.0×10^5 and elements at 4.0×10^5 is generated for optimal simulation results (Fig. 4).

3.2 Simulation Conditions

The mass in-flow rate taken at 0.08–0.2 kg/s, varying pressure of 1 MPa, 2 MPa, and constant inlet temperature will be tested for the calculated area of length 1.5 m, and width 0.5 m. Using proper boundary and operating conditions is of great significance to the results, convergence point, and accuracy of the calculation. To the internal wall, heat flux of $1,000,000 \text{ W/m}^2$ without taking any radiation, outer wall, and other walls are considered as adiabatic with temperature 300 K, channel holds the temperature of methane.

3.3 Solving the Governing Equations

The governing equations are solved based on the physical conditions with a viscous model (k-epsilon, realizable and scalable wall functions). The equations are solved using a second-order upwind style and coupled algorithm (Table 1).

Supercritical fluids are medium with variable pressures and temperatures higher than those with the analytical point. Their popularity stems from their high specific heat, less viscous, and superior dispersing qualities. In heat exchange applications, fluid basically transitions joining the compacted and supercritical states (i.e., at a pressure higher than the analytic pressure but at a degree below the critical temperature). Fluid thermo-physical characteristics change

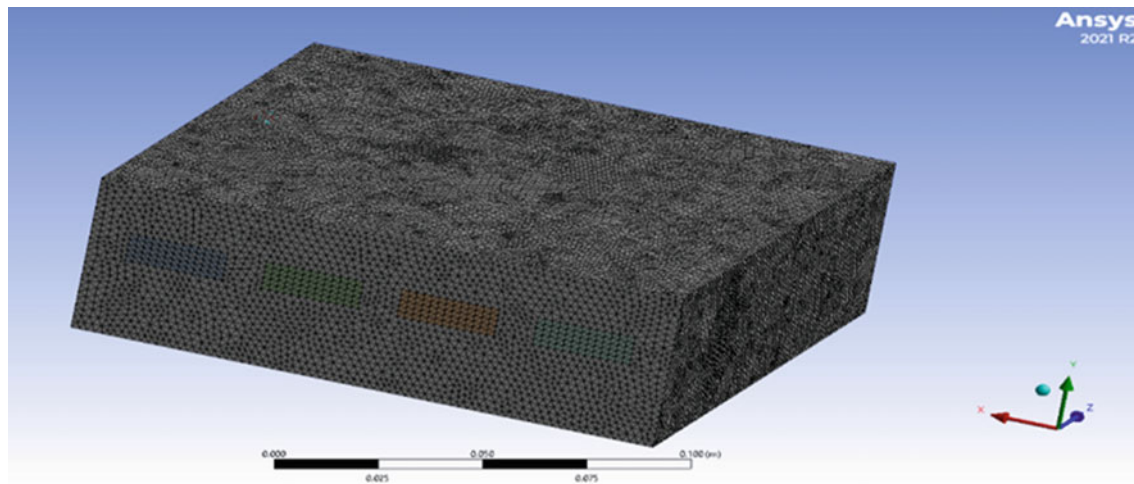


Fig. 4 Domain mesh

Table 1 Results of different mass flows—temperatures obtained

S. no	Mass flowrate (in kg/s)	Inlet temperature (k)	Inlet pressure (pa)	Average temperature (k)	Max temperature (k)
1	0.06			1354	3877
2	0.08	200	4 M	1018	3746
3	0.10			885	1344
4	0.3			433	1036
5	0.4			373	885
6	0.8			300	700
7	1			578	819
8	1.2			612	1022

substantially during this transition in the thermodynamical state. It has both better advantages and consequential implications for experimental applications.

4 Results and Conclusion

This paper proposes the numerical analysis of a regenerative cooling model with working fluid as supercritical methane (CH₄) in the scramjet engine to reduce weight and improve efficiency. The fluid is raised to supercritical temperatures to help with the cooling of the chamber, and the input of inlet pressure is provided using the appropriate formula with varying mass flow rates adopted to the geometry with the temperature being constant. When this fluid enters the channel, it gains heat by absorbing temperature inside the chamber thus the selected fluid exhibits supercritical properties and behaves as (SFC) methane. It was observed that enlarging the inlet mass flow scale results in a decrease in the maximum wall temperature. However, when the inlet mass

flow scale is below 0.08 kg/s, as growth in the degree or intensity of the wall is observed, this leads to inefficient cooling. Whereas, mass flow scaling of more than 0.6 kg/s is also observed to be behaving the same. It is predicted that the required effective cooling for the restoring/redeveloping cooling of the combustion chamber is equipped when the mass flow scale is kept between 0.06 and 0.6 kg/s. As a result, both the maximum temperature and average temperature are reduced with the best cooling performance (Figs. 5, 6 and 7).

Some standard papers published in the journals were briefly studied which were useful for the proposed design. The current development in our area of research was studied and existing problem-solving techniques used by researchers in our field and the efficiency of their methods were studied. Using solid works, and CATIA designing software the cylindrical rectangular cross-section was modeled with the help of boundary conditions and supercritical temperatures and pressures regenerative cooling is equipped in the combustion chamber.

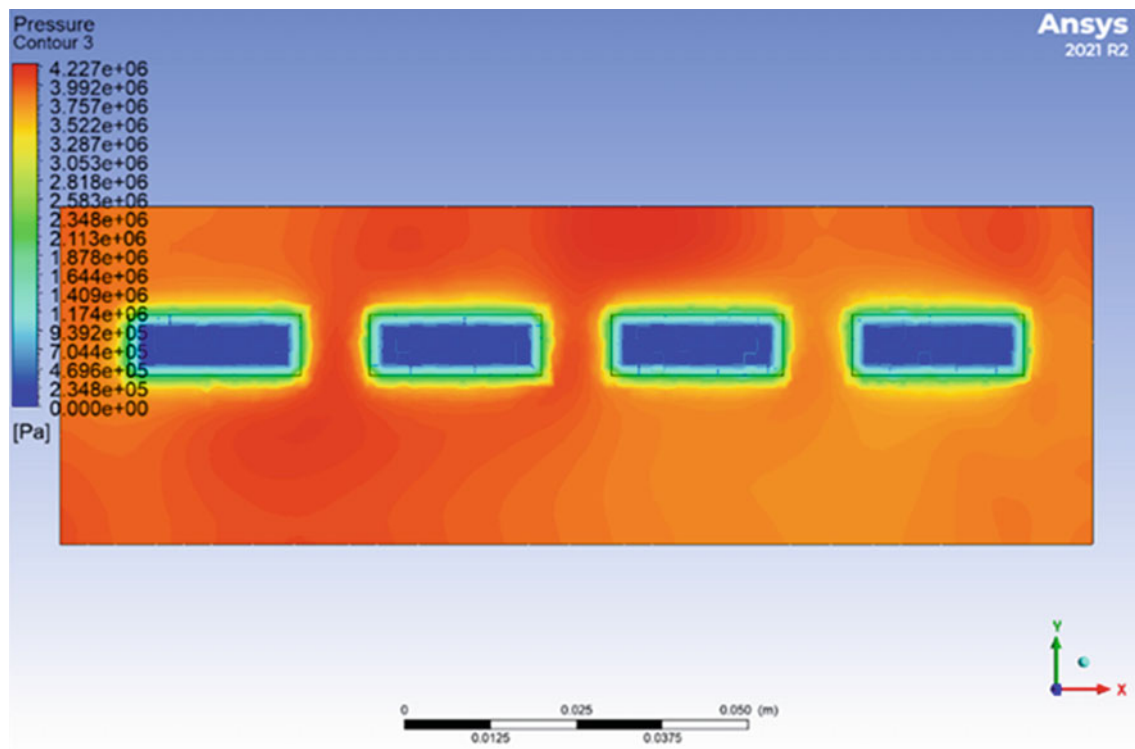


Fig. 5 Pressure contour at flow rate of 0.4 kg/s

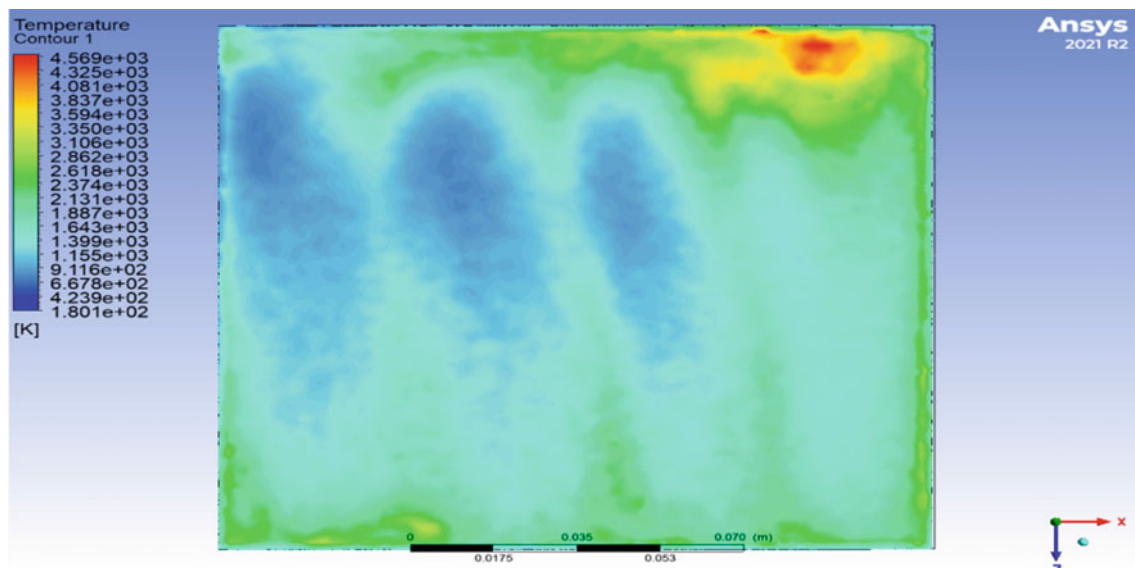


Fig. 6 Temperature distribution at a mass flow rate of 0.4 kg/s

5 Future Work

Supercritical pure/mixture fluids improve system performance by improving the mixture of current fluid temperature to the secondary fluid temperature at the time of heating/cooling operation. Meanwhile, given the

experimental use, an unbalanced heating technology such as circularly one-sided heated smooth or silt tubes and inclined tubes are to be grimly tested.

To increase the simulation's accuracy, the researchers focused heavily on RANS turbulence models, which, in normal circumstances, present a challenge to more established turbulence models. After studying different research

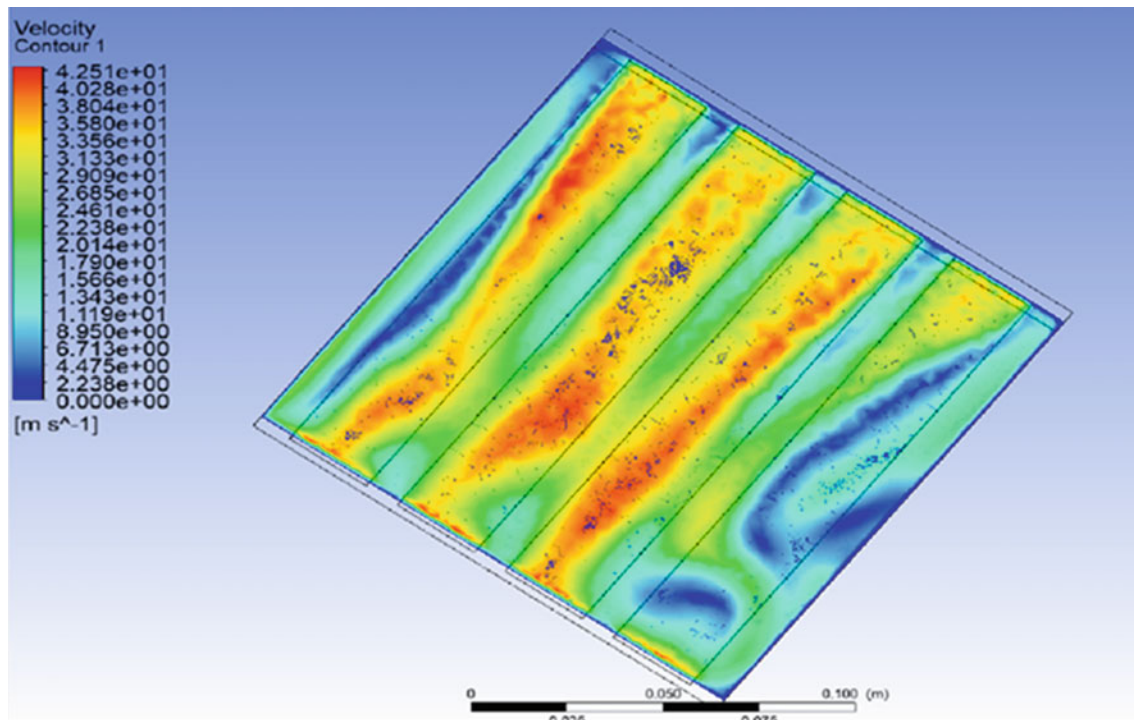


Fig. 7 Velocity distribution of regenerative cooling channel

papers, ideas about supercritical fluids and their properties were briefly understood and the application of supercritical fluids in different domains was also examined. A better understanding of the SFC in the aero sector is carefully studied.

By this, we can:

1. Analysis of the different parameters, and properties of the fluids not only on the mass flow, temperature, and pressure.
2. Also using different light-weighted manufacturing components for the combustion chamber.
3. Directly exposed to the SFC fluid rather than using the injected fuels for the mission purpose.
4. Used for heat absorption also including heat transfer (when the fluid is sent into the chamber the heat is absorbed by the fluid thus increasing pressure to a supercritical state thereby SFC heat absorption is performed).
5. Determine how accurate the numerical simulations are in calculating the heat exchange of supercritical fluids. Most present turbulence models are assessable where they can be exaggerated or underestimated with boundary, especially wall temperatures.
6. To avoid damage to heated channels under high temperatures, models that predict the commencement of heat exchanger stagnation are implemented.

A considerable number of accomplishments have been made in terms of the high temperature transport exploits of supercritical fluids, which has permitted recent advances. As a result, the following fresh insights will be addressed in the future:

1. Given the present RANS turbulence models' lack of accuracy, enhancing with the RANS turbulence model of agitation and altering turbulent variables such as the non-linear turbulent Prandtl number is examined. Large Eddy Simulation (LES), Direct Numerical Simulation (DNS), Lattice Boltzmann Method (LBM), Direct Simulation Monte Carlo (DSMC), and Molecular Dynamics Method (MDM) are examples of improvements in the processing methods of supercritical fluids.
2. The design and escalation of the assembled models are precisely to be carried out based on the techniques said to be heat exchange in order, which avoid the uneven high temperature transmission regimes and enhance the heat exchange. To boost heat carrier efficiency, all modern heat exchange augmentation approaches are to be in empirical engineering.
3. Microscopic mechanism research was desperately required for understanding of origins with anomalous high-temperature transport. Whereas heat transmission properties of supercritical assorted are also required. Additional chemical components, such as nano-particles,

can be added to avoid anomalous heat transfer and improve heat transfer.

4. Although conditions for operation fluctuate in actual processes, the dynamic where the total heat transfer coefficient effectuation of heat exchangers is probably connected with the overall systems of thermodynamic effectuation.
5. The development of empirical correlations and the design of SCO₂ heat exchangers should take into account all aspects that affect heat transfer after additional research on flow processes with heat transfer. By this most necessary to construct a relation that can encompass every SCO₂ cooling setting which is also indicated by the local heat transfer coefficient. Accurate heat transfer correlations can increase heat exchanger design accuracy, enhancing system efficiency.

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Experimental Investigation of Double Delta Wings with Different Angles of Attack at Subsonic Speeds

G. Balaji, A. Bharath Kumar, R. Divya, G. Boopathy, N. Seenu, and G. Santhosh Kumar

Abstract

The wind tunnel experimental study has been carried out on a double delta wing of different geometrical configurations such as $80^\circ/45^\circ$, $75^\circ/45^\circ$ and $70^\circ/45^\circ$ sweep angles given as Model I, Model II and Model III with various freestream velocities from 10 to 40 m/s with a step of 10 m/s in Hindustan Institute of Technology and Science, Chennai, Low Speed Wind tunnel (HITSLSWT). The experiment is conducted for the measurement of lift and drag forces using single component force balance. The investigation was done to look into the effects of changing the double delta wing's leading edge sweep angles. Three different models have been tested at various angles of attack ranging from 0° to $+16^\circ$ and 0° to -16° with 4° and four different freestream velocities based on the delta wing's chord. It is observed that the influence of variation of leading edge sweep angles affects the performance of aerodynamic characteristics of the model. The increase in angle in attack with increased velocity gives better aerodynamic performance. This paper provides good insight into the aerodynamic force measurement of double delta wing and the low-speed performance of the models.

Keywords

Double delta • Wing • AOA • Aerodynamics force • Subsonic speed • Wind tunnel test

1 Introduction

Moreover, the double delta wing configuration gives a low drag value at supersonic speed and to further improve the aerodynamics performance of the double delta wing thin or sharp leading edges are imposed on it. Due to differences in pressure around the wing, flow at the leading edge splits and flows spanwise over the upper surface. But, in this research work, the aerodynamics characteristic of the double delta wing has been investigated at a very low subsonic speed, and three different configurations as $80^\circ/45^\circ$ model, $75^\circ/45^\circ$ model and $70^\circ/45^\circ$ model were experimentally investigated. Saha and Majumdar (2013) Based upon the wing model's length of the root chord, experimental and numerical analysis was conducted to visualize the flow on the surface of a single beveled, sharp-edged and $76^\circ/40^\circ$ double delta wing at free stream Reynolds number of 2×10^5 with varying angles of attack. Comparing the experimental and CFD data of the flow visualization shown for the double delta wing leads to this conclusion.

Ashwin Kumar et al. (2018) performed the numerical and experimental study at a freestream velocity of 20 m/s on a double delta wing with a sweep of $81/45$. It has been noted that measuring the forces showed that the double delta wing's lift and drag increase while increasing the angles of attack. Additionally, studies done to acknowledge the impact on the leading-edge shape, showed that at low speeds, a blunt leading edge of a double delta wing obtains greater lift compared to a prominent leading edge delta wing. Further, at the leading edge, a delay occurs due to the principal separation, this causes a majority of the vortex to be postponed. The experiments and computations showed a fair amount of agreement.

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Al-Garni et al. (2008) conducted the experimental and numerical investigation of aerodynamics performance on 65 single delta and 64°/45° double at different pitch angles and side slip angles. When results are compared, it is seen that the predictions of the CFD are similar to the calculations done theoretically at angles with zero sideslip as well as showing good agreement between the various experimental experiments. et al. (2015) conducted a numerical study of different aerodynamic characteristics of single delta wing and double delta wing. It was observed that the new design, when applied to single delta wings and double delta wings, results in a reduction in drag for every angle of attack. Additionally, the ratio of lift and drag is improved and the overall efficiency of the single delta wing and double delta wing is improved by the suggested new design's drag reduction. Mahdavi and Reza (2021) conducted the experimental study over a cranked-delta wing for merging of the vortex at speeds in the subsonic range. The study came to the conclusion that if there is any increase in the angle of attack, the communication among both vortices gets increased, causing the vortex on the inner part to flow outward while the vortex on the outer part flows inward. Further, the vortices combine with one another at a high angle of attack, where the breakdown in the vortex migrates to the surface of the wing at a specific angle of attack and causes the suction peak to collapse and spread spanwise. The angle of attack at which vortex bursting passes onto the surface of the wing coincides with the earlier investigations about the aforementioned longitudinal uncertainty, according to surface pressure measurements.

Manshadi et al. (2016) did an experimental analysis of flow pressure and velocity distribution on the cranked double delta wing at Reynolds number 2×10^5 and the corresponding freestream velocity is 20 m/s on two different sweep angles of 55° and 30°. It was observed that with an increase in the angle of attack, the drop in pressure also increases, the vortices are widened, and the vortices along the wing are moved inside and far from the surface. Naimuddin et al. (2014) conducted the experimental investigation of a compound delta wing and observed that the vortices on the wing surface enlarge as the angle-of-attack increases and explode at higher angles of attack. Additionally, the outcomes might offer useful information for wing structural design and vortex bursting management. Hu et al. (2021) carried out the numerical and experimental study on characteristics of lift for a double delta wing at various numbers of reduced frequency. It was discovered that the hysteresis effect for the lift was amplified by raising the lowered frequency of pitching. The virtual camber effect caused due to pitching might dominate the field of motion as soon as the reduced frequency increases to a certain level, which could reduce the influence of the geometry of the wing for lift characteristics.

Bilakanti et al. (2013) conducted an Experimental study on a Double delta Wing Model for its flow characteristics with a Leading Edge rounded to 80°/45°. It is discovered that the flow of leeward vortex over a double delta wing with an 80°/45° rounded leading edge with deflection in the control surface and without deflection in the control surface has been studied for angle of attacks that ranges from 0° to 20° sideslip conditions are zero for Reynolds Number that ranges from 3.6 to 4.36 million at different range of transonic and subsonic speeds. Grismer and Nelson (1995) conducted the experiment on subsonic speed on a double delta wing for both without and with sideslip was carried out on a strake or wing platform, under static and dynamic conditions. Both static aerodynamics and dynamic aerodynamics of an 80°/60°/0.6 double-delta wing were explored for various angles of attack for both without and with sideslip using various factors such as flow visualization, force, and moment studies.

The effects of different Reynolds number over the 76/40° double delta wings were examined by Verhaagen (2002). It was noted that the Reynolds number seemed to have minimal impact on the flow over the wing. Strong Reynolds numbers showed significant effects on the interplay between the wing vortices and the strake on the wing panels for Reynolds numbers less than 105/m. At large Reynolds numbers, the interaction between these vortices is minimal for low angles and strong if the angle is higher than 10°.

In this research work, force measurement on the double delta with three different configurations such as 70°/45° model, 75°/45° model and 80°/45° model is investigated in the low-speed wind tunnel located at Hindustan Institute of Technology and Science, Chennai. The three configurations of double delta model are named Model I, Model II and Model III as shown in Fig. 1a–c investigated for different freestream velocity condition such as 10, 20, and 40 m/s. The three double delta model is inclined to different angles of attack that range from 0° to 16° in the positive scale and 0° to –16° in the negative scale with a step of 4°. The three-component force measurement is used to measure the lift force and drag force. The geometric diagrams of double delta wing configurations as seen in Fig. 1a–c.

2 Experimental Setup

The experiments were conducted out at Hindustan Institute of Technology and Science's low-speed wind tunnel that operates in a subsonic range (HITSLSWT), with test section dimensions as 600 mm × 600 mm × 1200 mm (Width × Height × Length) Subsonic Wind Tunnel at Low Speed. The Tunnel is capable of operating with a maximum freestream velocity of 50 m/s in the wind tunnel test section. The wind

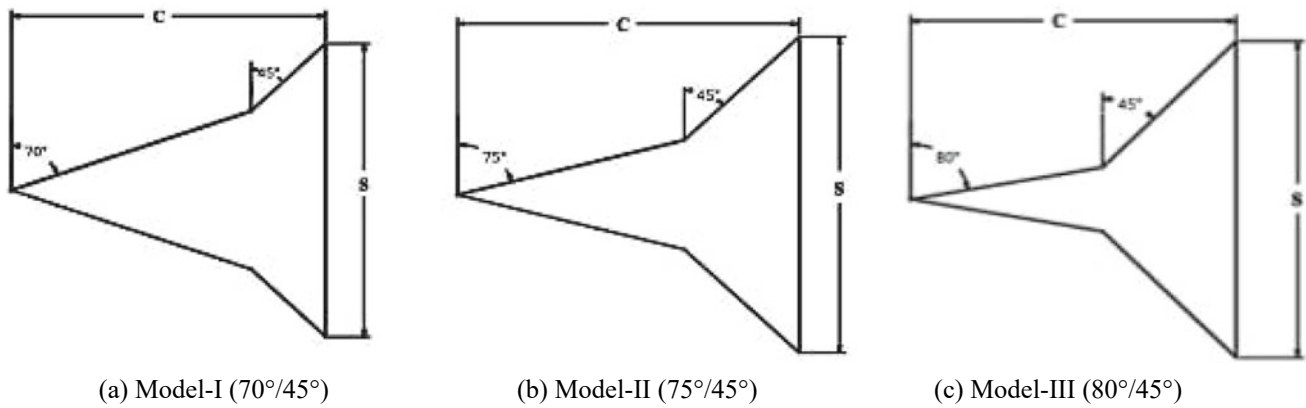


Fig. 1 The schematic diagram of three different double delta wings

tunnels were calibrated before conducting the experiment and calculated the turbulence to be less than 5% and the blockage ratio was less than 5%. The length of the wind tunnel test is 1200 mm which is split into two partitions to conduct the force measurement and pressure measurement. The wind tunnel operates in an open circuit continuous flow and experiments were carried out for various freestream velocities and corresponding Reynolds Number 2×10^4 and at a velocity of 10 m/s. A schematic illustration of a low-speed wind tunnel facility is seen in Fig. 2. The three different configurations of the double delta wing were tested at various angles of attack from 0° to 16° and 0° to -16° with a step of 4° . The experimental setup mainly consists of a suction-type low-speed subsonic wind tunnel, three-component force measurement and three different configurations of experimental models.

Experiments were conducted on three different configurations of double delta wing models with sweep angles $80^\circ/45^\circ$, $75^\circ/45^\circ$, $70^\circ/45^\circ$ having sharp leading edges and rectangular trailing edges. Three configurations of the experimental sharp edge double delta wing double delta model are named Model-I, Model-II, and Model-III as shown in Fig. 3a–c. The models were fabricated of teak wood. The leading edge is beveled with a single bevel at a 20° angle. The models were further smoothed, and polished and finishing was done. The models have been further polished, smoothed, and finished. A three-component balance was utilized to measure the lift force, drag force and pitching moment exerted on the three different configurations of double delta models. The three-component balance (WBAL-00103) was manufactured by the Sunshine product used for carrying out the experiments.

Fig. 2 Low-speed subsonic wind tunnel facility (HITSLSWT)



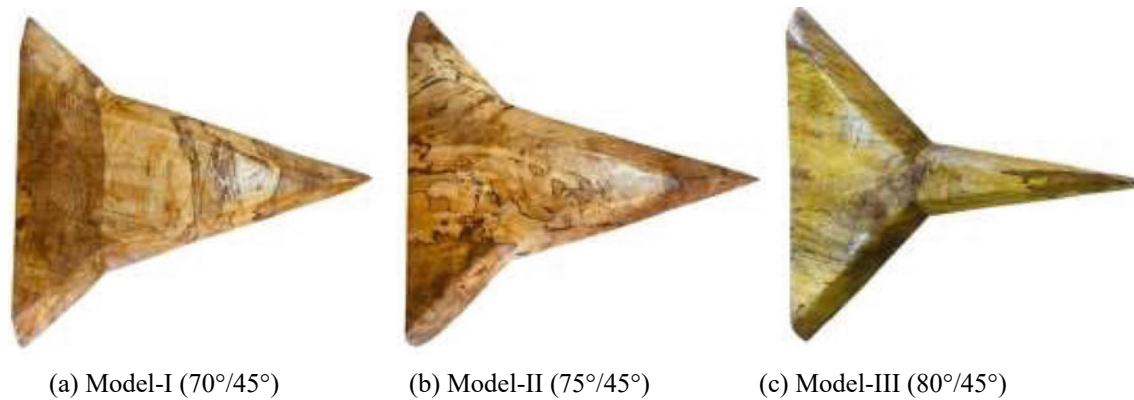


Fig. 3 Experimental model of different configurations of double delta wing

3 Result and Discussion

3.1 Effect of Lift Force on Various Configurations of Double Delta at Subsonic Speed

Figure 4a–c shows the force distribution of three different geometries of double delta wings at various angles of attacks and freestream velocity. This experiment is conducted for a limited angle of attack from 0° up to 16° . It is observed that lift forces increase with an increase in the angle of attack and free stream velocity depicted in Fig. 4a–c. In Fig. 4b, it observed that a maximum lift force of 6N occurs for the velocity of 40 m/s due to strake flow intersecting with wing flow leading to maximum lift force occurring in Model-II.

3.2 Effect of Drag Force on Various Configurations of Double Delta at Subsonic Speed

Figure 5a–c shows the drag force distribution of three different geometries of double delta wing for various angles of attack and freestream velocity. This experiment is conducted for a limited angle of attack from 0° up to 16° . It is observed that drag forces remain uniform for every angle of attack and show drag forces increase for the negative angles of attack depicted in Fig. 5a–c. The drag forces increase as the nose cone angle of the double delta wing increases as seen in Fig. 5a–c and the maximum drag force value of 22 N at 40 m/s observed the Model-III (b) due to strake flow and wind intersect with tip flow of the double delta wings lead to increase the drag force as shown in Fig. 5c.

3.3 Effect of Pitching Moment on Different Configurations of Double Delta at Subsonic Speed

Figure 6a–c shows the pitching moment distribution of three different geometries of double delta wing at various angles of attack and freestream velocity. Due to the three-component balance's operating range, this experiment is only conducted over a limited range of attack angles, from 0° to 16° . It is observed that the pitching moment is increased with an increase in all angles of attack and conversely the pitching moment magnitude decreases with an increase of the nose cone angle. The maximum pitching moment magnitude observed at the Model-I of 15 Nm in Fig. 6a. Also, it is observed that the maximum deviation of change pitching moment induced on the double delta wing due to strake flow vortices caused by nose cones.

4 Conclusion

An experimental investigation of different configurations of double delta wings was carried out in the low-speed wind tunnel. The main objective of this study was to investigate the lift force, drag force and pitching moment induced in different configurations of the double delta wings such as $70^\circ/45^\circ$, $75^\circ/45^\circ$ and $80^\circ/45^\circ$ corresponding to Model-I, II and III, respectively, for different freestream 10 m/s, 20 m/s, 30 m/s and 40 m/s and various angles of attack. It is observed that the force measurement indicates that with increasing the freestream velocity and angle of attack there is an increment in lift force and drag force on the sharp edge double delta wing. Also, various experiments were performed to understand various effects due to the sharp

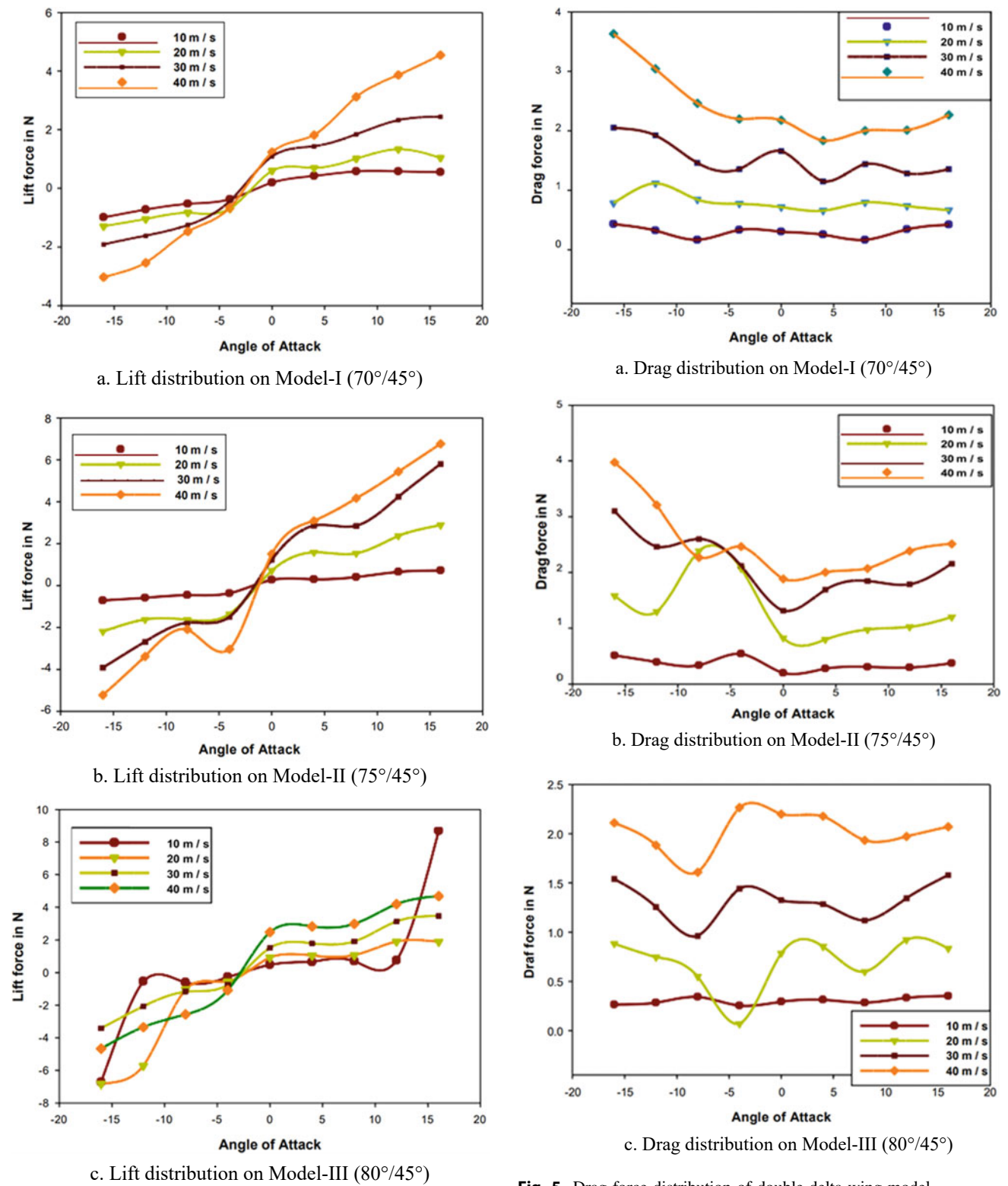
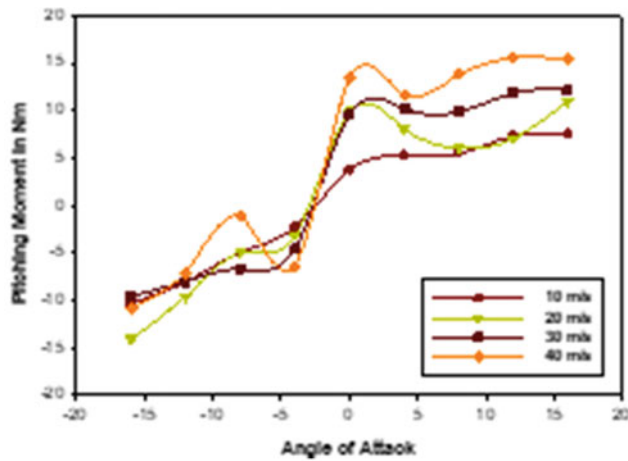
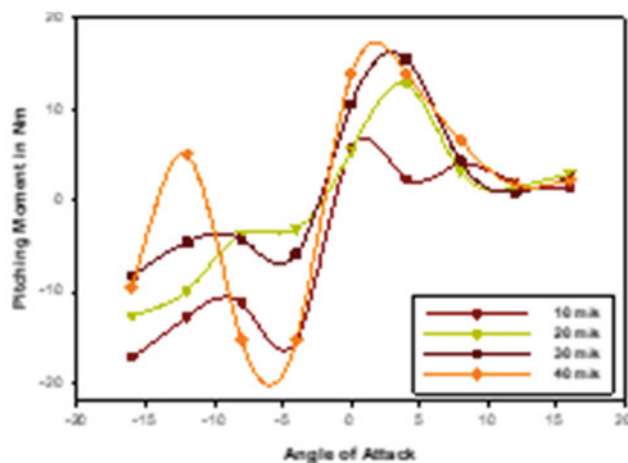
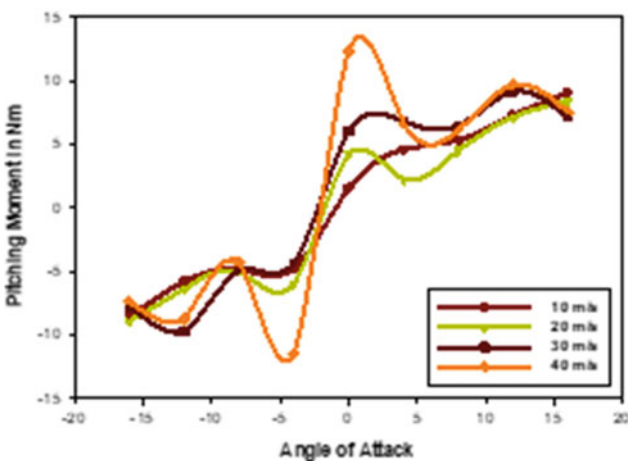


Fig. 4 Lift force distribution over the double delta wing model

Fig. 5 Drag force distribution of double delta wing model

leading-edge shapes for the three different configurations of double delta wings at low speeds. The pitching moment is drastically varying in the model-I as compared to other

models. Overall, the results of the comparison of lift force, drag force and pitching moments show good agreement with experiments.

(a) Pitching Moment distribution on Model-I ($70^\circ/45^\circ$)(b) Pitching Moment distribution on Model-II ($75^\circ/45^\circ$)(c) Pitching Moment distribution on Model-III ($80^\circ/45^\circ$)**Fig. 6** Pitching moment distribution of double delta wing model

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