



Standard Specification for Silica Fume Used in Cementitious Mixtures¹

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1. Scope

1.1 This specification covers silica fume for use in concrete and other systems containing hydraulic cement.

1.2 In the cases of slurried or densified silica fume, perform the tests on the raw silica fume from which these products have been made.

1.3 The units stated in SI are to be regarded as the standard.

1.4 The following safety hazards caveat pertains only to the test methods portions, Sections 10 – 19, of this specification: *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.* Read the material safety data sheets for materials used.

1.5 The text of this standard references notes and footnotes that provide explanatory information. These notes and footnotes (excluding those in tables) shall not be considered as requirements of this standard.

2. Referenced Documents

2.1 ASTM Standards:²

- C109/C109M Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens)
- C114 Test Methods for Chemical Analysis of Hydraulic Cement
- C125 Terminology Relating to Concrete and Concrete Aggregates
- C135 Test Method for True Specific Gravity of Refractory Materials by Water Immersion
- C183 Practice for Sampling and the Amount of Testing of Hydraulic Cement

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² For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

- C185 Test Method for Air Content of Hydraulic Cement Mortar
- C219 Terminology Relating to Hydraulic Cement
- C311 Test Methods for Sampling and Testing Fly Ash or Natural Pozzolans for Use in Portland-Cement Concrete
- C430 Test Method for Fineness of Hydraulic Cement by the 45- μ m (No. 325) Sieve
- C441 Test Method for Effectiveness of Pozzolans or Ground Blast-Furnace Slag in Preventing Excessive Expansion of Concrete Due to the Alkali-Silica Reaction
- C494/C494M Specification for Chemical Admixtures for Concrete
- C604 Test Method for True Specific Gravity of Refractory Materials by Gas-Comparison Pycnometer
- C670 Practice for Preparing Precision and Bias Statements for Test Methods for Construction Materials
- C1005 Specification for Reference Masses and Devices for Determining Mass and Volume for Use in the Physical Testing of Hydraulic Cements
- C1012 Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution
- C1069 Test Method for Specific Surface Area of Alumina or Quartz by Nitrogen Adsorption
- C1157 Performance Specification for Hydraulic Cement
- C1437 Test Method for Flow of Hydraulic Cement Mortar

3. Terminology

3.1 Definitions:

3.1.1 *silica fume, n*—very fine pozzolanic material, composed mostly of amorphous silica produced by electric arc furnaces as a by-product of the production of elemental silicon or ferro-silicon alloys (also known as condensed silica fume and microsilica).

3.1.2 *silica fume, densified, n*—silica fume processed to increase bulk density to facilitate handling and shipping.

3.1.3 *silica fume, undensified, n*—silica fume in its raw, as produced or as collected, unprocessed form.

3.1.4 Other terms in this specification are defined in Terminologies C125 and C219.

4. Ordering Information

4.1 The purchaser shall specify any optional chemical or physical requirements.

5. Chemical Composition

5.1 Silica fume shall conform to the requirements for chemical composition prescribed in Table 1.

6. Physical Requirements

6.1 Silica fume shall conform to the physical requirements prescribed in Table 2. Optional physical requirements are given in Table 3.

7. Sampling

7.1 When the purchaser desires that the silica fume be sampled and tested to verify compliance with this specification, perform the sampling and testing in accordance with Practice C183, modified as described in 7.3.

NOTE 1—Exercise caution in the interpretation of Practice C183, since there is a difference between the continuous manufacture of hydraulic cement and the generation and collection of silica fume. To a great extent, storage is dictated by the design of the silica-fume collection system. The design of silica-fume collection systems may not have provided for sampling points and practices.

7.2 Practice C183, as modified, is not designed for manufacturing quality control and is not required for manufacturer's certification.

7.3 The following modification of Practice C183 is necessary to render it applicable to silica fume.

7.3.1 Replace the words “hydraulic cement” and “cement” with the words “silica fume” every time that they appear in the text.

7.3.2 All samples, whether grab or composite, shall have a mass of at least 1 kg.

7.3.3 When compliance verification tests of silica fume are required to be made at a laboratory other than that of the silica-fume manufacturer or marketer, coordinate the silica-fume sampling schedule, sample transportation time, and sample testing schedule among the purchaser, manufacturer, and testing laboratory so that the test results will be available when the decision to accept or reject the silica fume must be made.

7.3.4 The section entitled “Sampling” is modified as follows:

7.3.4.1 Take two grab samples or two composite samples for the first 100 Mg of silica fume. Take a grab sample or a composite sample for each subsequent 100 Mg of silica fume, but not less than two samples shall be taken in any sampling program.

7.3.4.2 *From Bulk Storage at Points of Discharge*—Withdraw silica fume from the discharge openings in a steady stream until sampling is completed. In sampling bulk storage at points of discharge, while the silica fume is flowing through the openings, take samples at such intervals so that, at a minimum, the sampling requirements of 7.3.4.1 are met.

TABLE 1 Chemical Requirements

SiO ₂ , min, %	85.0
Moisture content, max, %	3.0
Loss on ignition, max, %	6.0

TABLE 2 Physical Requirements

Oversize:	
Percent retained on 45- μ m (No. 325), max, % ^A	10
Percent retained on 45- μ m (No. 325), max variation from average, percentage points ^B	5
Accelerated pozzolanic strength activity index: ^C	
With portland cement at 7 days, min percent of control	105
Specific surface, min, m ² /g	15

^A Exercise care to avoid retaining agglomerations of extremely fine material.

^B The average shall consist of the ten preceding tests or all of the preceding tests if the number is less than ten.

^C Accelerated pozzolanic strength activity index is not to be considered a measure of the compressive strength of concrete containing the silica fume. This is a measure of the reactivity of a given silica fume with a given cement and may vary with the source of both the silica fume and the cement.

TABLE 3 Optional Physical Requirements^A

Uniformity requirements:	
When air-entraining concrete is specified, the quantity of air-entraining agent required to produce air content of 18.0 vol % of mortar shall not vary from the average established by the ten preceding tests or by all preceding tests if less than ten, by more than, %	20
Reactivity with cement alkalies: ^B	
Reduction of mortar expansion at 14 days, min, %	80
Sulfate resistance expansion, ^C	
(moderate resistance) 6 months, max, %	0.10
(high resistance) 6 months, max, %	0.05
(very high resistance) 1 year, max, %	0.05

^A Will be made only at the request of the purchaser.

^B The indicated tests for reactivity with cement alkalies shall not be requested unless the material is to be used with an aggregate that is regarded as deleteriously reactive with alkalies in hydraulic cement. The test for reduction of mortar expansion may be made using any high-alkali cement in accordance with Test Methods C311, if the cement to be used in the work is not known or is not available at the time of the test. The test for mortar expansion should be performed by each of the high-alkali cements to be used in the work.

^C Only one limit shall be specified.

7.3.5 The section entitled “Amount of Testing” is modified by deleting the first paragraph, “General.”

8. Frequency of Tests

8.1 Except for the tests listed in 8.2, make all chemical determinations and physical tests on composite samples representing no more than 400 Mg each. Prepare each composite sample by combining portions from the samples representing each 100 Mg, so that each 100 Mg is represented equally.

8.2 Test for specific surface, density, and accelerated pozzolanic strength activity index using composite samples that represent 3200 Mg or 3 months of production, whichever gives the highest frequency. Prepare each composite sample by combining portions from the samples representing each 400 Mg or 1 month, whichever gives the highest frequency, so that each sample is represented equally.

9. Preparation of Sample

9.1 Prepare composite samples for tests, as required in Section 8, by arranging all test samples in groups, with each group representing the number of megagrams required by the test or tests for which the composite sample is intended. From each of the samples in a group, take equal portions, sufficient in amount to form a composite sample large enough to permit making the required physical or chemical determinations.

9.2 Prior to testing, mix grab samples and composite samples thoroughly. A clean and dry laboratory concrete drum mixer provides adequate mixing for this purpose. Take care to limit the volume of silica fume in the drum mixer to the range of 10 to 50 % of the drum's total capacity. If necessary, secure a sheet of polyethylene film on the drum with an elastic tiedown to keep the material in the drum. Limit the mixing action to 5 ± 1 min.

9.2.1 When a small sample size precludes the use of a concrete mixer, use a heavy plastic bag, of a capacity at least five times larger than the sample volume, to mix the sample thoroughly. After placing the sample in the bag, close the bag by tying the bag opening tightly, and mix the material by rolling the bag around for 5 ± 1 min.

9.3 Take material for specific tests from a thoroughly mixed sample by using a sampling device (sampling tube, scoop, etc.) of appropriate size to make a test specimen. Make this test specimen from at least six random subsamples.

TEST METHODS—CHEMICAL ANALYSIS

10. Silicon Dioxide and Total Alkalies

10.1 *Reference Method*—Use the reference method in Test Methods C114 for cements with insoluble residue greater than 1 %. Analysts performing sodium oxide and potassium oxide determinations shall observe the precautions outlined in the applicable section of Performance Specification C1157 (refer to the section on Test Methods). Most pozzolans dissolve completely in lithium borate fluxes.

11. Moisture Content and Loss on Ignition

11.1 Follow the applicable provisions of Test Methods C311.

TEST METHODS—PHYSICAL TESTS

12. Density

12.1 Determine density using either Test Method C135 as modified in 12.1.1 or Test Method C604.

12.1.1 Test Method C135 modified as follows:

12.2 *Equipment*:

12.2.1 *Two 500-mL Volumetric Flasks*, Class A.

12.2.2 *Balance*, with an accuracy of at least 0.01 g.

12.2.3 *Constant Temperature Bath*, capable of being regulated within ± 0.5 °C.

12.3 *Deionized Water*.

12.4 *Procedure*:

12.4.1 Determine the density of the material as received, unless otherwise specified, as follows. If density determination on an ignited sample is required, first ignite the sample as described in the test for loss on ignition in the applicable section given in Test Methods C114.

12.4.2 Determine the mass (W_f), of a 500-mL volumetric flask, to an accuracy of 0.01 g. Add 30 g of silica fume. Determine the mass of the flask and the contents (W_a) to the nearest 0.01 g. Add water to the flask to fill it one-half full, and shake it to ensure thorough wetting of the material. Fill to the

mark with water. Remove air bubbles by shaking the flask at 15-min intervals until the liquid is free of air or by applying a vacuum to the flask. After all of the air bubbles are removed, place the flask in a constant temperature bath at 23 ± 0.5 °C until the flask and its contents reach a constant temperature. Remove the flask from the water bath; immediately add or remove water, at the same temperature, to the flask to get the meniscus on the mark. Wipe dry the exterior of the flask and determine the mass of the flask and its contents (W_s).

12.4.3 Empty, clean, and determine the mass of the 500-mL volumetric flask, used above, filled to the mark with water (W_t) stabilized at 23 ± 0.5 °C.

12.5 *Calculation*:

$$D_{sf} = \frac{(W_a - W_f)}{500 \text{ mL} - [(W_s - W_a)/D_w]} \quad (1)$$

where:

D_{sf} = density of silica fume, Mg/m³,

W_f = mass of 500-mL volumetric flask, g,

W_a = mass of 500-mL volumetric flask plus approximately 30 g of silica fume, g,

W_s = mass of 500-mL volumetric flask plus silica fume plus water to the mark, g,

W_t = mass of 500-mL volumetric flask plus water to the mark, g, and

D_w = ($W_t - W_f$)/500-mL, Mg/m³.

12.6 Report the average of two density determinations and the test method used in determining the density.

13. Oversize, Amount Retained When Wet-Sieved on a 45-μm (No. 325) Sieve

13.1 Use Test Method C430. Calibrate the sieves in accordance with Test Method C430.

NOTE 2—Oversize is used to determine the amount of contaminating material retained on the 45-μm sieve. See Appendix X2.

14. Specific Surface

14.1 Determine the specific surface by the BET, nitrogen adsorption method, in accordance with Test Method C1069.

15. Air Entrainment of Mortar

15.1 Follow the applicable provisions of Test Methods C311, except use the following test mixture and equation for W_c :

	Test Mixture
Portland cement, g	300
Silica fume, g	30
20–30 Standard Ottawa sand, g	1170
Water, mL, sufficient to give a flow of 80 to 95 %	Y
Neutralized Vinsol resin solution, mL, sufficient to produce an air content of 18 ± 3 %	Z

$$W_c = \frac{300 + 1170 + 30 + (300 \times P \times 0.01)}{300/3.15 + 1170/2.65 + (30/D) + [(300 \times P \times 0.01)/1]} \quad (2)$$

Then calculate:

$$\text{Air content, volume \%} = 100[1 - (W_a/W_c)]W_a = W/400 \quad (3)$$

where:

W_a = actual mass per unit of volume of mortar as determined by Test Method C185, g/mL,

- W = mass of the specified 400 mL of mortar (see Test Method **C185**), g,
 W_c = theoretical mass per unit volume, calculated on an air-free basis and using the values for density and quantities of the materials in the mixture, g/mL,
 P = percent of mixing water plus Vinsol resin solution based on mass of cement, and
 D = density of silica fume used in the mixture, Mg/m³.

15.2 Determine the flow in accordance with the applicable provisions of Test Method **C109/C109M**.

16. Accelerated Pozzolanic Strength Activity Index with Portland Cement

16.1 Use the applicable section on strength activity index with portland cement of Test Methods **C311**, except change to reflect testing at constant flow range (100 to 115 %) and constant water to cementitious materials ratio. Mixtures not meeting flow range shall be discarded with new mixtures made following procedures below. High range water reducer is added directly to water in the bowl, then add cement and other ingredients and start mixing. Prepare test specimens from the batch proportions below, molding three cubes from both the control mix and the test mix.

16.1.1 Control Mixture:

- 16.1.1.1 500 g of portland cement,
- 16.1.1.2 1375 g of graded standard sand, and
- 16.1.1.3 242 mL of water for a flow of 100 to 115 %.

16.1.1.4 If flow is not within the required range add dry high range water reducing admixture, meeting Specification **C494/C494M** Type F to reach the target flow.

16.1.2 Test Mixture:

- 16.1.2.1 450 g of portland cement,
- 16.1.2.2 50 g of silica fume,
- 16.1.2.3 1375 g of graded standard sand, and
- 16.1.2.4 242 mL of water.

16.1.2.5 Use dry high-range water reducer, meeting Specification **C494/C494M** Type F, required to produce a flow of 100 to 115 %. Add the high-range water reducer directly to the mixing water in the mixing bowl. Then add the cement or the cement-silica fume mixture and start the mixing cycle.

16.1.3 Determine the flow in accordance with the applicable provisions of Test Method **C1437**.

16.1.4 *Storage of Specimens*—After 24 h of initial curing in the moist room (23 ± 2 °C and relative humidity of not less than 95 %), place the cubes in airtight glass containers and store at 65 ± 2°C for six days.

16.1.5 Determine the compressive strength, as specified in Test Method **C109/C109M**, of the three specimens of the control mixture and the three specimens of the test mixture at 7 days after molding.

17. Reactivity with Cement Alkalies

17.1 Determine the reduction of mortar expansion in accordance with Test Method **C441**, except that the amount of silica fume in the test mixture shall be 10 % by mass of cementitious material.

18. Sulfate Resistance

18.1 Determine sulfate resistance according to Test Method **C1012**, except that the amount of silica fume used in the test mixture is 10 % by mass of cementitious material.

19. Bulk Density

19.1 The bulk density of silica fume is defined as the mass of a unit volume of loose silica fume.

19.2 This test method covers determination of the bulk density of silica fume, as silica fume is transferred from one container to another with controlled minimum compaction. Its particular usefulness is in connection with identifying material form (as produced or densified), silo or truck storage capacity, material handling and transportation characteristics.

19.3 Equipment:

19.3.1 *Balance*, meeting Specification **C1005**, with a sensitivity of 0.1 g.

19.3.2 *Vibrating Table*³, Table top, electromagnetic vibrating table, with a controlled low-amplitude that does not exceed 1 mm linear vibration. Approximate deck size is 175 × 250 mm with a 5 kg capacity. The amplitude of the vibration shall be capable of being regulated to suit the characteristics of the material being handled.

19.3.3 *Stainless Steel Beaker*, of known volume, not less than 1 L calibrated to the nearest ±1 mL. Without a spout.

19.4 Procedure:

19.4.1 Determine the mass of the clean dry beaker to the nearest 1 g.

19.4.2 Fill the beaker with silica fume and compact by use of the vibrating table at a mid-range setting for 15 s, adding material as needed.

19.4.3 Screed or strike off the measure, with a straight edge or spatula, to produce a flat, even surface, that is level with rim or edge of the beaker. Wipe off any excess silica fume that may adhere to the sides.

19.4.4 Place the filled measure on the balance and determine the mass of the silica fume to the nearest 1 g.

19.5 Calculation:

19.5.1 Divide the net mass of the silica fume in grams by the volume of the container in milliliters. Multiply by 1000 to express the density in kilograms per cubic meter. To convert the value in kilograms per cubic meter to pounds per cubic foot, divide by 16.01846.

20. Report

20.1 Report the following information:

- 20.1.1 SiO₂ content, %,
- 20.1.2 Moisture content, %,
- 20.1.3 Loss on ignition, %,
- 20.1.4 Oversize, % retained,

³ The sole source of supply of the vibrating table known to the committee at this time is the Syntron Paper Jogger, Model J-1, manufactured by F.M.C. Corp., 57 Cooper Ave., Homer City, PA 15748. If you are aware of alternative suppliers, please provide this information to ASTM International Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee,¹ which you may attend.

- 20.1.5 Bulk density, kg/m^3 ,
- 20.1.6 Density, Mg/m^3 ,
- 20.1.7 Name of manufacturer and brand, if applicable,
- 20.1.8 Accelerated Pozzolanic Strength Activity Index,
- 20.1.9 Specific surface, m^2/g , and
- 20.1.10 Total alkalis, as equivalent Na_2O , %.

20.2 Report the following information when specifically requested by the purchaser:

- 20.2.1 The quantity of air-entraining agent compared to the 10 preceding tests, %,
- 20.2.2 Reduction of mortar expansion, %, and
- 20.2.3 Sulfate resistance expansion, %.

21. Precision and Bias

21.1 Precision:

21.1.1 Accelerated Pozzolanic Strength Activity Index Test:

21.1.1.1 *Single-Operator Precision*—The precision of this test will be evaluated using Practice C670.

21.1.1.2 *Multilaboratory Precision*—The precision of this test will be evaluated using Practice C670.

21.1.1.3 *Bias*—Since there is no accepted reference material suitable for determining the bias for the procedures for measuring the accelerated pozzolanic strength activity index and the density, no statement on bias is being made.

21.1.2 Density Test:

21.1.2.1 *Single-Operator Precision*—The single-operator standard deviation among single test results (a test result is defined in this specification as the average of two separate measurements) has been found to be 0.035 Mg/m^3 .⁴ Therefore, results of two properly conducted tests by the same operator should not differ by more than 0.099 Mg/m^3 on the same silica fume.

21.1.2.2 *Multilaboratory Precision*—The multilaboratory standard deviation among single test results (a test result is defined in this specification as the average of two separate measurements) has been found to be 0.047 Mg/m^3 .⁴ Therefore, results of two properly conducted tests in different laboratories on the same silica fume should not differ by more than 0.132 Mg/m^3 of their average.⁴

21.1.2.3 *Bias*—Since there is no accepted reference material suitable for determining the bias for the procedures for measuring the accelerated pozzolanic strength activity index and the density, no statement on bias is being made.

21.1.3 Bulk Density:

21.1.3.1 *Precision*—The precision of this test method is valid for both undensified and densified silica fume. Determi-

nation was made from an interlaboratory study using eight samples of silica fume. The bulk density of the various samples ranged from about 200 kg/m^3 to about 800 kg/m^3 . Ten laboratories participated in the study.

21.1.3.2 *Single-Operator Precision*—The single-operator standard deviation for the bulk density has been found to be 4.6 kg/m^3 .⁴ Therefore, results of two properly conducted tests by the same operator on the same sample of silica fume should not differ by more than 13 kg/m^3 .⁴

21.1.3.3 *Multilaboratory Precision*—The multilaboratory standard deviation among single test results has been found to be 14.8 kg/m^3 .⁴ The results of two properly conducted tests in different laboratories on the same sample of silica fume are not expected to differ by more than 42 kg/m^3 .⁴

21.1.3.4 *Bias*—Because there is no accepted reference material suitable for determining any bias that might be associated with this test method, no statement on bias is being made.

22. Rejection and Retesting

22.1 The purchaser has the right to reject material that fails to conform to the requirements of this specification. Rejection shall be reported to the producer or supplier promptly and in writing. In case of dissatisfaction with the results of the tests, the producer or supplier is not prohibited from making a claim for retesting.

23. Certification

23.1 When specified in the purchase order or contract, the purchaser shall be furnished certification that samples have been tested as directed in this specification and the specified requirements have been met. When specified in the purchase order or contract, a report of the test results shall be furnished.

24. Packaging and Package Marking

24.1 When silica fume is delivered in packages, the name, and brand, if applicable, of the manufacturer or distributor and the mass of the silica fume contained therein shall be marked plainly on each package. Similar information shall be provided in the shipping invoices accompanying the shipment of packaged or bulk silica fume in dry or slurried forms. All packages shall be in good condition at the time of inspection.

25. Storage and Inspection

25.1 Silica fume shall be stored in such a manner as to permit easy access for the proper inspection and identification of each shipment. Facilities for inspection and sampling shall be provided at the point from which the material is to be shipped.

⁴ These measurements represent, respectively, the (1s) and (d2s) limits in accordance with Practice C670.

APPENDIXES**(Nonmandatory Information)****X1. SILICA CONTENT**

X1.1 Since the quantity of amorphous silica is one of the primary characteristics that determine the pozzolanic activity of silica fume, determination of the total silicon content is important. Gravimetric [“wet method”] determinations can be accomplished using sodium carbonate (Na_2CO_3) fusion as described in Test Methods **C114** and similar procedures. Instrumental methods successfully used for determination of total silicon in high silica materials include X-ray fluorescence spectrometry, inductively coupled plasma, optical emission spectrometry, and atomic absorption spectrophotometry. Silica Fume SRM® 2696 is available from the National Institute of Standards and Technology, for use in evaluating chemical and

instrumental methods of analysis of silica fume used in conjunction with product specifications. Because silica (SiO_2) is required in this specification to be at least 85 % by mass of the silica fume, additional silica reference materials, such as SRM® 1413 high alumina sand [82.77 %] and silica flour [99.9 %], may be suitable for use with instrumental methods of analysis. Analysts should note that the gravimetric method determines all chemical forms of silicon in the material as silica (SiO_2), whereas the instrumental test methods determine all chemical forms of silicon in the material as total silicon (Si), which is reported as SiO_2 . Typically, it is assumed that all or nearly all of the Si that is present in silica fume is SiO_2 .

X2. OVERSIZE

X2.1 The 45- μm (No. 325) sieve specification is to be used to determine the amount of foreign material present. Since silica fume is much finer than cement or fly ash, the particles will all pass through the sieve except for foreign material.

Extremely fine materials tend to form agglomerations; good judgment must be exercised to differentiate between easily dispersible agglomerates and foreign materials.

X3. PROBLEM OF MIXTURE PROPORTIONING FOR VARIOUS TEST MIXTURES

X3.1 Such test methods as accelerated pozzolanic strength activity index with portland cement, reactivity with cement alkalies, and sulfate resistance require mixtures where the silica fume being tested replaces a given amount of cement. For specification purposes, 10 % by mass replacement of cement by silica fume will be used rather than that which is stated in the present methods. Water-to-cementitious materials ratio will be replaced by a flow of between 100 and 115 %. As the percent replacement with silica fume increases, the mixture

becomes unworkable, and either more water is necessary or a water reducer is necessary to have a workable mixture. By limiting the mixtures to 10 % by mass replacement, the addition of water to a certain flow is a viable alternative, even though the addition of water reducer would probably produce a higher strength. Since this is a specification, the interest is in comparing material under similar conditions, rather than in maximum strength.

X4. SULFATE RESISTANCE

X4.1 Satisfactory reductions of expansion in laboratory mixtures have been obtained with silica fume replacement levels of 5 to 15 %. Each source of silica fume must be tested

with high- C_3A portland cement to establish appropriate replacement levels for adequate sulfate resistance.

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