

Friction Materials

Curves of the coefficient of friction as a function of load and of the speed differential between the lining and facings and their mating surface are no longer available from many manufacturers. Perhaps this is a consequence of the ease with which trial lawyers in the United States can collect large financial rewards for weak liability claims based upon often trivial, or unavoidable (due to physical limits on manufacturing tolerances), differences between published data and a particular specimen of the manufactured product. Furthermore, differences between published and operational coefficients of friction are beyond the control of the manufacturer because comparison of laboratory and operational data have shown that temperature, humidity, contamination, and utilization cycles of the machinery using these linings and facings can cause significant changes in the effective coefficient of friction at any given moment. Consequently, the coefficients of friction mentioned are nominal, the following discussion is in generic terms, and all curves shown should be understood to represent only the general character of the material under laboratory conditions.

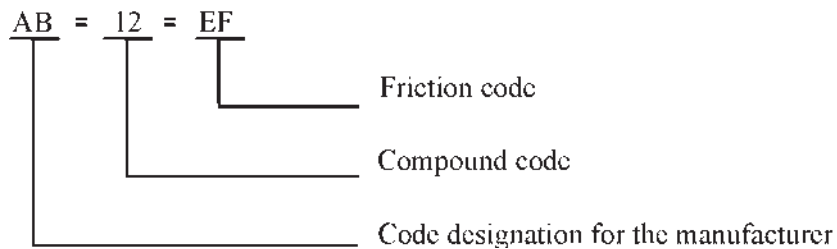
The value of laboratory data is twofold, even though the data should not be used for design purposes. First, the data provides a comparison of the performance of different lining materials under similar conditions, such as given by the SAE 661 standard. Second, comparison of the laboratory data with field data for a particular type of machine for several different linings may suggest an empirical relationship that yields an approximate means of predicting the field performance of other lining materials based upon their laboratory data. A history of the comparison of field and laboratory data

may, therefore serve as a starting point in the design of the prototype of a new machine of the same or similar type.

Field testing of a new machine by customers under the most adverse conditions is still necessary. Users often seem to devise abuses not envisioned by the design engineers.

I. FRICTION CODE

The usual range of the dynamic friction coefficients for those friction materials normally used in dry brake linings and pads is given in the Society of Automotive Engineers (SAE) coding standard SAE 866, which lists the code letters and friction coefficient ranges shown in Table 1 [1]. According to this code the first letter in the lining edge friction code indicates the normal friction coefficient and the second letter indicates the hot friction coefficient. Thus a lining material whose normal friction coefficient is 0.29 and whose hot friction coefficient is 0.40 would be coded as follows:



Temperatures for the normal and hot friction coefficients are defined in SAE J661, which also describes the measurement method to be used.

TABLE 1 Friction Identification System for Brake Linings and Brake Block for Motor Vehicles

Code letter	Friction coefficient
C	Not over 0.15
D	Over 0.15 but not over 0.25
E	Over 0.25 but not over 0.35
F	Over 0.35 but not over 0.45
G	Over 0.45 but not over 0.55
H	Over 0.55
Z	Unclassified

Static and dynamic coefficients of friction are usually different for most brake materials. If a brake is used to prevent shaft rotation during a particular operational phase, its stopping torque and heat dissipation are of secondary importance (i.e. a holding brake on a press); the static friction coefficient is the design parameter to be used. On the other hand, the pertinent design parameters are the dynamic friction coefficient and its change with temperature when a brake is designed for its stopping torque and heat dissipation when a rotating load is to be stopped or slowed.

Most manufacturers will provide custom compounds for the linings and facings within the general types that they manufacture if quantity requirements are met. In almost all applications it is suggested for all of these materials that the linings and facings run against either cast iron or steel with a surface finish of from 30 to 60 micro inches. Nonferrous metals are recommended only in special situations.

Effects of heating on the linings and facing discussed are expressed in terms of limiting temperatures or limiting power dissipated per unit area at the surface of the brake lining or clutch facing. Time is usually omitted, even though the surface temperature is determined by the power per unit area per unit time. This is because it is assumed that the power dissipation occurs over just a few seconds. More precise estimates, and only that, of the heat generated by the power dissipated in particular cases maybe had by using one of several heat transfer programs from suppliers of engineering software. It is for these reasons that prototype evaluation is always recommended.

II. WEAR

Hundreds of equations for wear may be found in the literature. These equations may depend a variety of factors, including the materials involved, the temperature, and the environment under consideration, i.e., the liquid or gas present, the formation of surface films, and so on [2]. Two of the relations that pertain to the following discussion are the specific wear rate and the wear rate.

The first of these, the specific wear rate, or wear coefficient, is a dimensional constant K that appears in the relation

$$\delta A = v = K\rho A d = K F d$$

From which v may be written as

$$v = K F d \tag{2-1}$$

In these relations, δ represents the thickness of the lining material removed, v is the volume material removed, K is a dimensional constant that is termed the specific wear rate or the wear coefficient, and p is the pressure

acting over the surface area A that is in contact with the lining material. Force F is given by integral of the pressure acting on the specimen integrated over the area A over which it acts. Upon rewriting equation (2-1) to evaluate K we have that

$$K = v/(Fd) \quad (2-2)$$

Hence the units of K are lt^2/m where l , t , and m denote length, time, and mass, respectively. As a practical matter, if v is millimeters cubed (mm^3), if force F is in newtons (N), and if the distance d is in meters (m), then the units of K become $\text{mm}^3 \text{N}^{-1} \text{m}^{-1}$, which explicitly shows the physical quantities involved, as in [Figure 3](#).

The second relation that may be used by brake and clutch lining manufacturers to describe wear is

$$\Gamma = vPt\Theta \quad (2-3)$$

in which Γ represents the wear rate, P is the power dissipated in the lining, and t is the time during which volume V was removed at temperature Θ . The units of Γ in equation (2-3) are those of the work (ml^2/t^2) required to remove a unit volume of material multiplied by the volume (l^3) removed.

Whenever the temperature is held constant during a test, the temperature variable Θ is suppressed. Since brake testing according to the SAE 661b standard is done at 200°F , the wear rate is often given by $\Gamma = vPt$ and presented in the form $v = \Gamma/(Pt)$. Again, to be practical the wear rate divided by the product horsepower hours (hp hr) may be given in cubic inches (in.^3), as in [Table 2](#) near the end of this chapter.

III. BRAKE FADE

Brake fade is a term that refers to the reduced effectiveness of many dry brakes as they become heated. A standard test described in SAE J661 outlines a procedure that uses controlled temperature drums and controlled brake lining pressure to stimulate brake fading as a basis of comparison of the brake fading characteristics of various lining materials. The equipment and temperatures are essentially identical to those used in estimating the coefficient of friction as a function of temperature. Only the presentation of the data is different, as shown in [Figure 1](#). The fade test mode of presentation of data provides another indication of the recovery capability of the various lining materials. As with the previous test data, the fade test results are limited to a comparison of different lining materials for the test conditions only.

Limitation of the application of these data to preliminary design is emphasized because the friction coefficient is dependent upon the pressure,

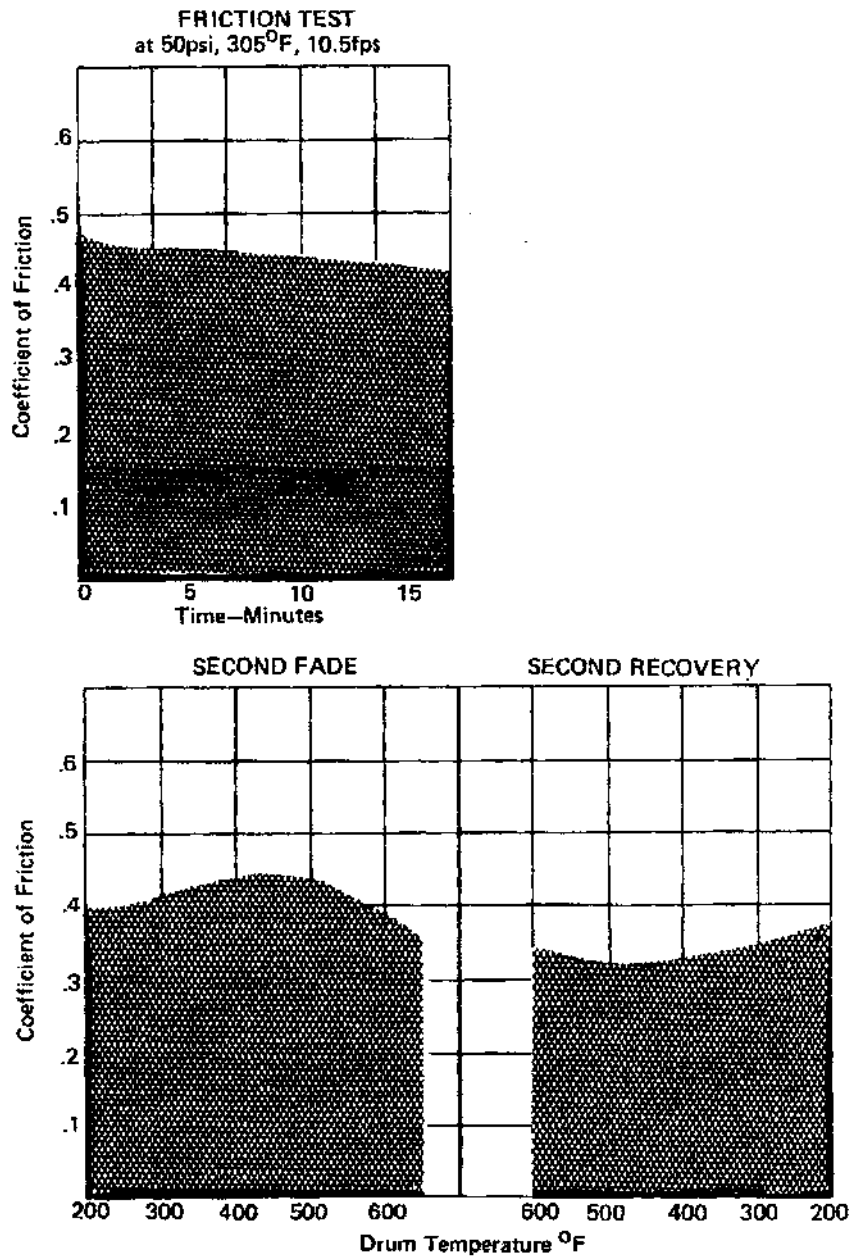


FIGURE 1 Display of brake lining fade test results. (Courtesy of Scan-Pac, Mequon, WI).

the temperature, and the relative velocities of the contracting surfaces, as noted earlier. Field tests are recommended before the production of any brake design because of the uncertainty usually associated with the variables involved in lining heating and in the cooling capability of the brake housing and any associated structure.

IV. FRICTION MATERIALS

Friction materials may be classified as either dry or wet. Wet friction lining materials are those that may operate in a fluid that is used for cooling because of the large amount of energy that must be dissipated during either braking or clutching. The fluids used are often motor oil or transmission fluids. Lining materials that cannot operate when immersed in a fluid are known as dry lining materials.

A. PTFE and TFE

At this time it appears that PTFE (polytetrafluoroethylene) and TFE (tetrafluoroethylene), both included under the trade name Teflon, are commonly used for brake linings [3]. PTFE exhibits a low coefficient of friction and is mechanically serviceable at about $\pm 260^{\circ}\text{C}$, is almost chemically inert, does not absorb water, and has good dimensional stability. Its weakness in shear stress is greatly improved by the addition of fillers, such as glass fibers. These fibers also increase its wear resistance and strength and increase its coefficient of friction by increasing its abrasiveness. The degree to which each of these properties is increased depends upon the amount, the physical dimensions, the orientation, and the nature of the material used as a filler [4].

Together these characteristics make PTFE brake pads useful for drag brakes in manufacturing processes, such as tape production, where the moving product must be held in tension during part of the manufacturing process. Likewise, PTFE clutch plates and linings that may be used whenever the transmitted torque should remain below a certain limit.

Laboratory measurements of the coefficients of friction at room temperature for several filled PTFE materials when subjected to loads of 1.415 Mpa, or 205 psi, and of 7.074 Mpa, or 1026 psi, are shown in [Figure 2](#). They indicate that the coefficients of friction for these PTFE specimens with various kinds and sizes of fillers are all fairly independent of sliding speed, especially at greater loads, when sliding against a mild steel surface with a roughness of s.c.a. $0.03\text{ }\mu\text{m}$ c.l.a. [4]

Nominal coefficients of friction given by a particular manufacturer may, as noted earlier, differ from those shown in Figure 2 because of the amount, size, orientation, and kind of filler material used. Their static coefficient of

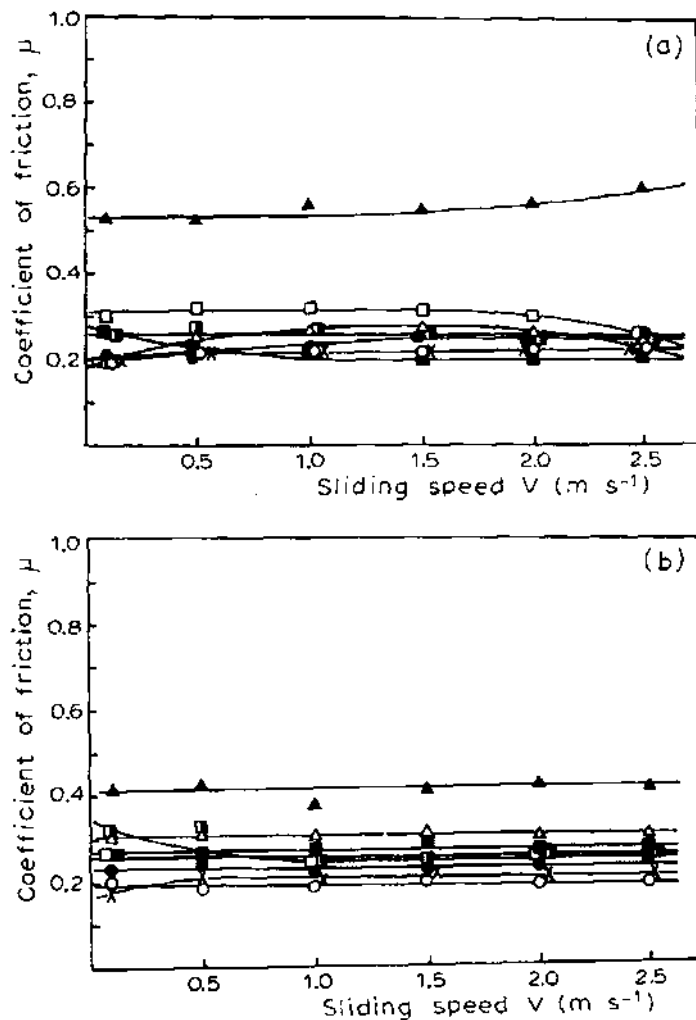


FIGURE 2 Coefficient of friction versus sliding speed at an average pressures of 1.415 Mpa, or 205 psi (a), and 7.074 Mpa, or 1,026 psi (b), for the fillers as indicated; Open triangle: TiO₂; filled triangle: ZrO₂; open square: glass; filled square: bronze; open circle: graphite; filled circle: MoS₂; X: unfilled, half-filled rectangle: Turcite (proprietary material, probably PTFE with bronze filler). (Courtesy Elsevier Science Publishers, New York.)

friction may from 0.089 to 0.108 and their dynamic coefficient may vary from 0.078 to 0.117 [3]. Under light loads of 1.0 Mpa (145 psi) and sliding speeds of 0.03 m/s (1.22 in./s) it has been reported that PTFE filled with bronze mesh displayed friction coefficients ranging from approximately 0.03 to 0.25 [5].

It may be of interest to note that unfilled Teflon has the property that its coefficient of friction, μ , is not given by $\mu = F_n/F_t$, but rather by $\mu = F_n^{0.85}/F_t$, where F_n denotes the force normal to the contact surface and F_t denotes the force tangential to the surface [6]. Fillers may modify this property by an amount that depends upon the kind, amount, or orientation of the filler.

Obviously, wear is also an important consideration in the selection of lining and facing materials because it determines the cost of the lining per hour of use in terms of main tenance time to replace the lining or facing in addition to the cost of the material itself, which is often the lesser of the two. Fortunately, experimental data, as shown in Figure 3, indicates that these fillers,

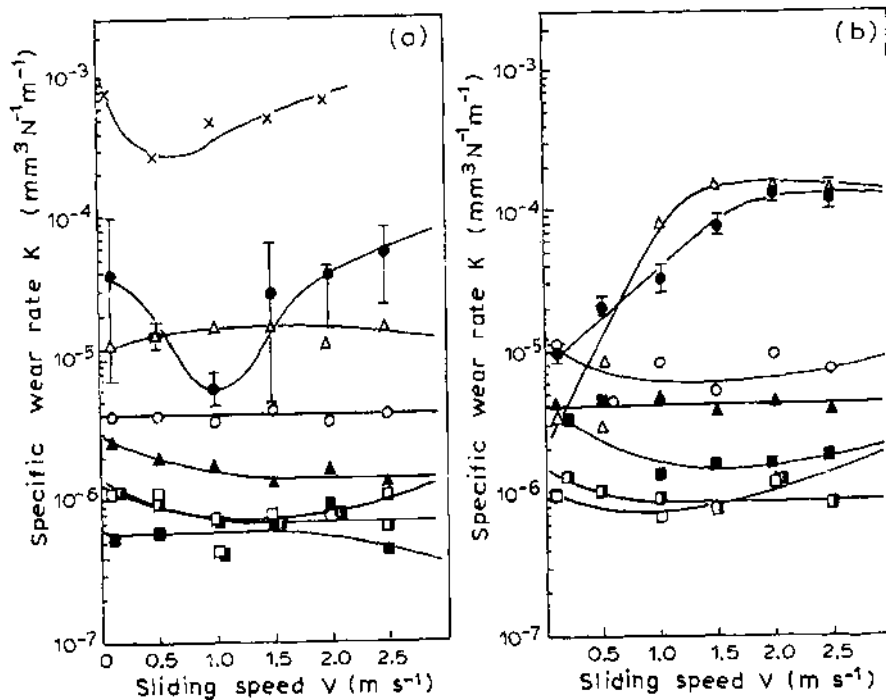


FIGURE 3 Specific wear of PTFE as a function of sliding speed for.

such as bronze, glass, and graphite, significantly add to the wear resistance of PTFE [3]. Glass appears to be the most commonly used.

B. Kevlar

Kevlar is the Du Pont trade name for an aramid (aromatic polyamide fiber) that has a tensile strength greater than some steels, i.e., some of these fibers have a modulus up to 27×10^6 psi (1.86×10^5 Mpa). Nevertheless they are flexible enough to be woven and processed as textiles, so Kevlar brake linings and clutch facings are available in either woven or nonwoven forms. They are used along with proprietary polymer binders in the manufacture of brake linings and clutch facings for both wet (oil bath) and dry clutch applications.

In dry brake and clutch applications, a flexible, nonwoven form can withstand dynamic pressure up to 3100 kPa (450 psi), are nonabrasive to iron, steel, and copper surfaces, and display a nominal coefficient of friction of 0.36 ± 0.1 , as stated by one manufacturer. This manufacturer also states that in a dry environment these brake linings show significant fade at 260°C (500°F) that becomes greater at 370°C (700°F) [7]. Hence, they may be used in those industrial, marine, and off-road applications where fade is not a limiting factor; applications can include agricultural, industrial, marine, and off-road equipment.

In wet applications this nonwoven form of facing material is said to withstand dynamic pressure up to 2760 kPa (400 psi) with a nominal coefficient of friction in the 0.10–0.15 range when dissipating 23–290 W/cm² (0.2–2.5 hp/in²) [7]. Ambient operating temperatures are replaced by power per unit area at the lining face in wet applications because the enveloping fluid bath cools the lining as it transfers the heat to cooling fins or to an oil cooler. Clutch facings and brake linings that contain no metal reinforcing wires or segments provide low wear on mating surfaces and eliminate the possibility of metal fragments in cooling system filters.

Kevlar has also been used in a proprietary solid form to obtain higher coefficients of friction in a woven material in which Kevlar fibers are mixed with other organic and inorganic fibers that enclose brass wire yarns to produce a lining that may be used as a direct replacement for older linings that contain asbestos [8]. Because of the brass wire and inorganic fibers, these linings may be more abrasive than those without these materials. This is, of course, a natural consequence of having higher friction coefficients on the orders of 0.40 dynamic and 0.42 static.

Representative second fade and second recovery curves of the friction coefficient vs. temperature of a representative of such linings are shown in [Figure 4](#), as determined according to the SAE J661 standard. Field perform-

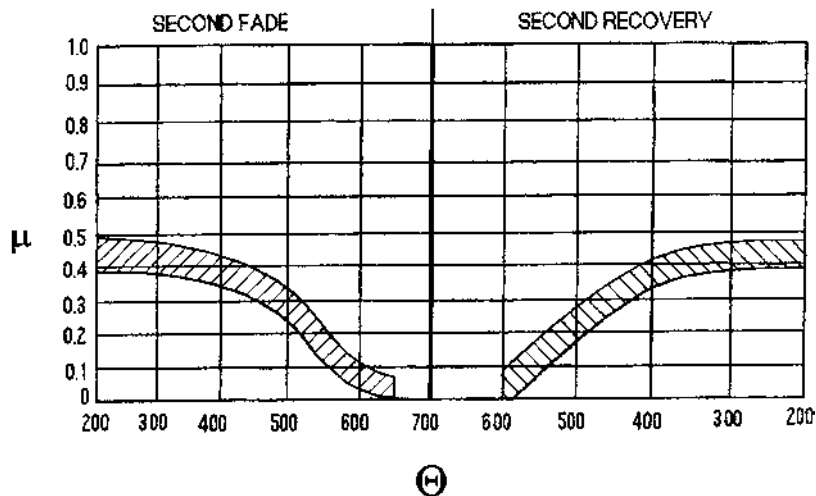


FIGURE 4 Second fade and second recovery vs. drum temperature (°F) for a proprietary lining containing Kevlar with a nominal coefficient of friction of 0.40. (Adapted from Reddaway Manufacturing Co., Inc., Newark, NJ.)

ance may be different from that shown in these graphs because of drum conditions, contamination, and other factors that depend upon the particular application.

The material whose may fall within the cross-hatched regions in Figure 4 may operate at a pressure no greater that 1379 kPa (200 psi) and a temperature no greater than 260°C (500°F) when in either a wet (oil) or a dry environment. This lining material may be used for band brakes and band clutches that work against steel or cast iron surfaces, as recommended by the manufacturer [8].

C. Mineral Enhanced

Mineral-based linings and facings are generally in the form of castings that can provide nominal friction coefficients ranging from 0.1 to 0.61. These friction materials may operate either dry or wet (oil) and find applications from tension control in manufacturing processes through overhead cranes, hoists, and industrial brakes and clutches and in farm and garden tractors.

Some or all of the following materials, and others, that are now necessary to produce a lining having a high friction coefficient may be embedded in the resin binders used [9].

Cyanamid	Barite	Wollastonite
Mica	Rubber dust	Collan
Glass fibers	Cellulose	Alumina
Vermiculite	Petroleum coke	Acrylic fibers
Graphite		

Because some of these materials have been classified as hazardous by one or both of the Occupational Safety and Health Administration (OSHA) or the American Conference of Governmental Industrial Hygienists (ACGIH) organizations, dust in the vicinity of their use and storage must be removed by vacuuming or by a dust suppressant according to the time schedules of one or both of OSHA and ACGIH.

Second fade and second recovery for such a material that has a nominal friction coefficient of 0.61, that may be subjected to a pressure of 350 psi (2.41 MPa), and that has a flash point above 600°C (1112°F) is shown in Figure 5. It has been used as a snubber for rail cars and is suitable for applications where high torque at low lining pressure is required. Test curves shown for this lining material hold for a test pressure of 1.034 MPa (1.50 psi) and a sliding speed of 6.1 m/s (20 ft/s).

D. Sintered

Proprietary sintered lining material, designated DM81, was available as an option on all Chevrolets, including Corvette, Corvair, and Chevy II brakes, in 1962 [10]. In normal driving they wore about twice as long as conventional linings of that time, with a larger ratio in favor of sintered linings for more severe service, as experienced by taxicabs.

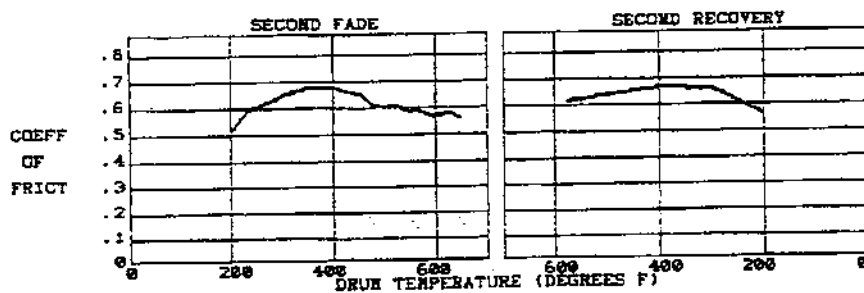


FIGURE 5 Second fade and second recovery vs. drum temperature (°F) for a mineral-enhanced lining (HF-61) with a nominal coefficient of friction of 0.61. (Courtesy Hibbing International Friction, New Castle, IN.)

Sintered metal friction material and carbon-carbon composites are widely used in brakes for large aircraft, such as long-range commercial jets, and in military aircraft. Their typical construction is shown in Figure 6. Brakes using sintered metal linings that press against steel plates are known as steel brakes, and those that press carbon lining material against carbon plates are known as carbon brakes in Figure 6. Stator plates are keyed to the brake housing, and rotor plates are keyed to the torque tube that rotates with the wheel to which it is attached.

Wear is greater in the lower-cost steel brake. The lining material in the steel brake is usually either a base of copper with additions of iron, graphite, and silicon as an abrasive and a high-temperature lubricant, such as molybdenum disulfide, or a base of iron with additions of copper and the other

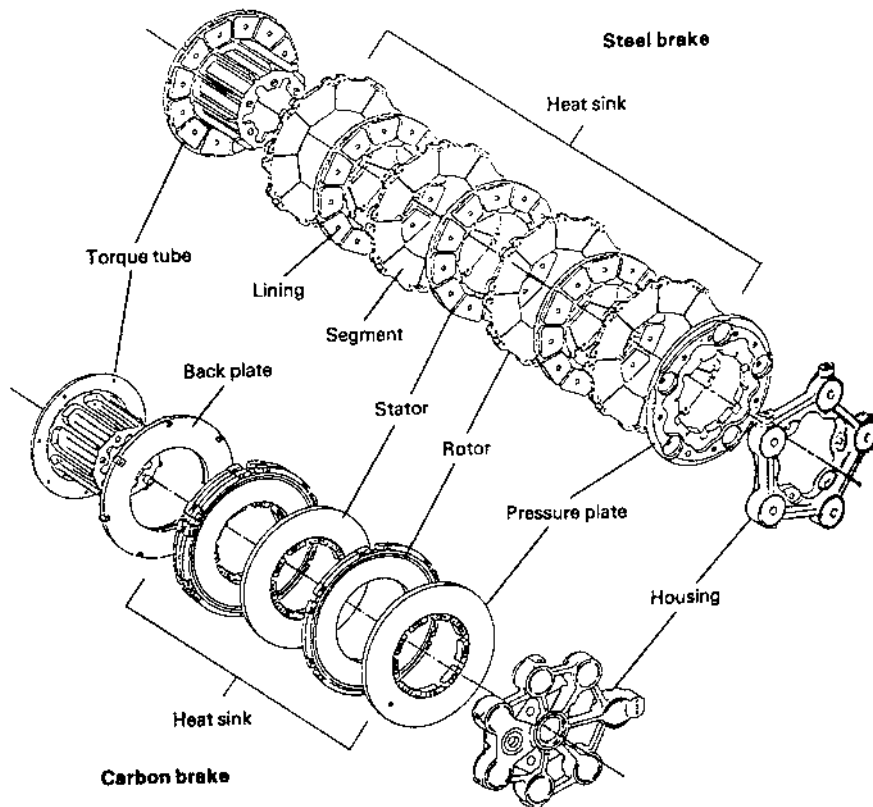


FIGURE 6 Construction of brakes having sintered linings working against steel plates (upper) and having carbon linings working against carbon plates (lower). (Courtesy ASM Handbook, ASM International, Materials Park, OH.)

additives just listed. The iron-based lining tends to provide a larger friction coefficient but may be more difficult to bond to its carrier plate.

Temperature dependence of the friction coefficient is indirectly indicated in Figure 7, where the energy per unit mass is the energy dissipated per unit mass for a series of alternate stator and rotor plates stacked along the axis of the brake [11].

E. Carbon–Carbon

Carbon–carbon brakes are made from manufactured carbon that is a composite of coke aggregate and carbon binders. It has been thermally stabilized to temperatures as high as 3000°C, and it has no melting point at atmospheric pressure. It sublimates at 3850°C. A useful characteristic for clutch and brake linings is that its strength increases with temperature up to anywhere from 2200°C to 2500°C. Beyond these temperatures it becomes viscoelastic and will, therefore, creep when stressed. Graphite crystals themselves are anisotropic because of their layered structure with their greater strength in the basal plane. In the basal plane a single crystal may have a tensile strength of approximately 1×10^5 MPa (14.5×10^6 psi), and graphite fibers have a tensile strength of the order of 2×10^4 MPa (2.9×10^4 psi).

So-called conventional graphites may have a tensile strength ranging from 6.5 to about 280 MPa (approximately 940 to about 40,600 psi) [12].

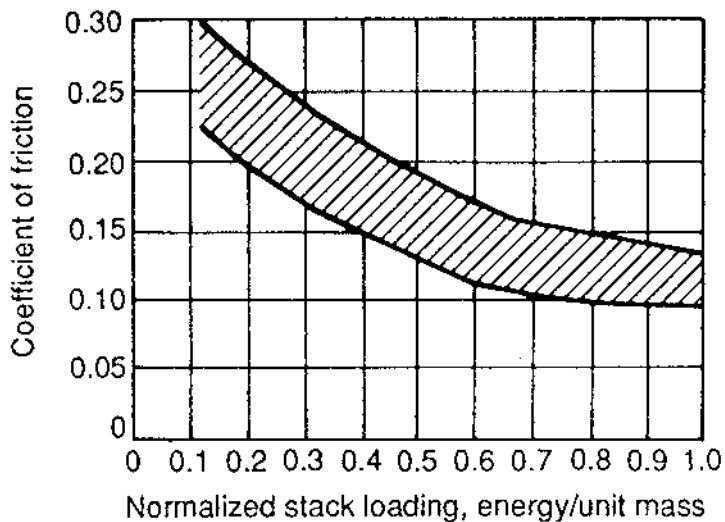


FIGURE 7 Typical range of friction coefficients for a steel brake based upon stack loading. (Courtesy *ASM Handbook*, ASM International, Materials Park, OH.)

Both carbon and graphite display porosity that varies with their grades. Blocking these pores with thermosetting resins that include phenolics, furans, and epoxies produces what is known as impervious graphite. Impervious graphite, graphite, and carbon resist corrosion by acids, alkalies, and many inorganic and organic compounds [12].

Carbon-carbon linings may display a range of friction coefficients, depending upon many factors, some of which remain proprietary with the lining manufacturers. Brake design, however, is known to have an effect in that μ increases with the number of rotors. Because carbons and graphites have an affinity for moisture, brakes that have been allowed to absorb moisture for several hours have a lower μ , sometimes known as *morning sickness*. The friction coefficient returns to its dry value because braking causes the moisture to evaporate [11].

The greatest wear on aircraft brakes occurs during a rejected takeoff (RTO) in which an aircraft taxis up to takeoff speed and then must brake to a stop. RTOs are scheduled several times during a manufacturer's ground test of prototype aircraft but rarely occur during the operation of properly maintained aircraft in service. An RTO is a spectacular display of smoke, burning rubber, and the roar of engines with the thrust reversers on. Break wear during an RTO is said to range anywhere from 100 to 1000 times greater than during a normal service stop. Wheels and brakes after an RTO are normally scrapped. Changes in μ during an RTO are shown in Figure 8, which

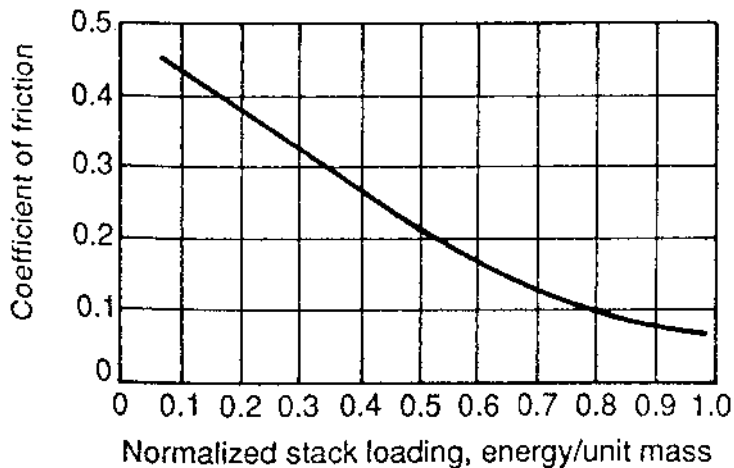


FIGURE 8 Variation of μ from taxiing on the left-hand side to RTO on the right-hand side. (Courtesy *ASM Handbook*, ASM International, Materials Park, OH.)

indicates a change in μ from approximately 0.45 to approximately 0.07, for a change of 84.4%. In contrast to this, [Figure 7](#) for steel brakes with sintered linings shows a change in μ from a midrange value of about 0.25 to a midrange value of about 0.14, for a change of 44%. However, carbon–carbon brakes are lighter than steel brakes and can be made from a single material [11].

F. Other Proprietary Materials

Friction materials produced by most manufacturers are proprietary to the extent that not all of their ingredients are disclosed. None of the ingredients may be listed for those lining materials that perform satisfactorily without components provided by others, such as Kevlar. Absence of asbestos always will be noted by U.S. suppliers.

Many manufacturers of entirely or partially proprietary linings provide data on the nominal friction coefficients, wear, and recommended temperature ranges of their products, although a few will supply data only to a manufacturing customer. This data may be in either tabular or graphical form. Typical tabular data for dry lining materials may be similar to that shown in Table 2, and typical data for wet (oil, transmission fluid) lining materials may be similar to that shown in [Table 3](#) for two different lining materials. The first of these, GL 483-110, is described as a layered Kevlar mat with embedded carbon particles that are highly wear resistant. This layered composition is bound together with a high strength, temperature resistant phenolics resin. The second, GL 383-114, is a non-asbestos, cellulose fiber composite friction paper that is saturated with a similar phenolics resin. (See [Fig. 1](#).)

Data in both tables were obtained from conditions that may differ from those experienced by the lining material in any particular application. Data in Table 3 especially may differ significantly from that found in any given application because of the profound effects of the finish and hardness of the mating surface along with the effects of the nature and temperature of the enveloping fluid upon the performance of the lining material.

TABLE 2 Proprietary Dry Clutch/Brake Lining Material

Product type	$P_{\max}$	μ_{dynamic} (normal)	μ_{hot}	μ_{static}	Wear rate (hp hr)	Comment
GL 121-120	150 psi	0.48	0.47	0.66	0.009 in. ³	Flexible
GL 134-142	450 psi	0.42	0.40	0.56	0.011 in. ³	Flexible
GL 181-142	33,000 psi	0.56	0.52	0.49	0.009 in. ³	Rigid

Source: Web site: Great Lakes Friction Products, Milwaukee, WI.

TABLE 3 Proprietary Wet Clutch/Brake Lining Material

$p_{\max}$ (psi)	1800	μ_{static}	0.11
Energy (hp/in. ²)	4.6	$F_{\max}^o$	600
μ_{dynamic}	0.12	F_{spike}^o	750

Source: Web site: Great Lakes Friction Products, Milwaukee, WI.

V. NOTATION

A	area (l^2)
d	distance (l)
F	force (ml/t^2)
K	specific wear (lt^2/m)
p	pressure (m/lt^2)
P	power (ml^2/t^3)
t	time (t)
Γ	wear rate (ml^2/t^2)
δ	thickness removed (l)
Θ	temperature (l)
v	volume removed (l^3)

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