TEFLON BEARINGS IN BASE ISOLATION. I: TESTING

By Anoop Mokha,1 Michael Constantinou,2 Associate Member, ASCE, and Andrei Reinhorn,1 Member, ASCE

ABSTRACT: This paper describes the frictional properties of sheet type Teflon-steel interfaces in relation to their application in sliding bearings for base-isolated buildings and bridge structures. A series of laboratory experiments has been conducted on Teflon-steel interfaces to determine the effect of sliding velocity, sliding acceleration, bearing pressure, type of Teflon, and surface finish on the frictional characteristics of sliding bearings. It is found that sliding acceleration has insignificant effects on the recorded values of frictional force. However, sliding velocity and bearing pressure have important effects. Friction increases with increasing velocity up to a certain value of velocity beyond which it remains constant. Furthermore, friction drops with increasing pressure with a rate of reduction that is strongly dependent on velocity. It saturates at a value of pressure between 5,000 and 6,500 psi (34.5 and 44.9 N/mm²). Substantial differences between breakaway (or static) coefficient of friction and sliding (or kinetic) coefficient of friction are observed. In general, the breakaway value is two to four times larger than the sliding value.

INTRODUCTION

Teflon (TFE) sliding bearings have been used for the past several years to accommodate thermal movement and effects of prestressing, creep, and shrinkage in bridge applications. More recently, they have been proposed as part of seismic isolation systems (Kelly 1986). In total, six such systems have been proposed, of which two have reached the stage of implementation. These systems are the earthquake barrier system (Caspe and Reinhorn 1980), Alkisismos (Koromou 1985), the friction pendulum system (Zayas et al. 1987), Tasei or TASS (Nagashima et al. 1987), resilient friction base isolation system (R-FBI) (Mostaghel and Khodaverdian 1987), and Wabo-Eyfe earthquake protection system (Wabo-Eyfe 1981; Constantinou et al. 1988). These systems utilize Teflon-steel interfaces to support the weight of the structure and a mechanism to provide centering force capability and additional energy absorption capacity. A simple version of this mechanism may be in the form of cylindrical rubber springs that are attached to the basement and foundation slab of the structure and carry no vertical load. This simple mechanism has been used at the Technology Research Center of Taisei Corporation, Japan. This is a four-story building in Tokyo supported by eight TFE-elastomeric bearings, while eight Neoprene sprags provide centering force capability (Constantinou 1988). The Friction Pendulum System uses a

2Assoc. Prof., Dept. of Civ. Engrg., Univ. of Buffalo, State Univ. of New York, 212 Ketter Hall, Buffalo, NY.

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concave supporting surface that utilizes geometry and gravity to provide re-centering force. This approach has been used to seismically isolate a 50,000-gal emergency fire water tank in California.

There are two important advantages in sliding isolation systems with restoring force. First, the function of carrying the vertical load and the function of permanent horizontal stiffness at the isolation interface are separated. This results in a more stable system that eliminates the need for a fail-safe mechanism. Second, sliding systems with weak restoring force are insensitive to variations in the frequency content of ground excitation and tend to limit the intensity of the force imparted to the superstructure. This insensitivity to the frequency content of excitation is the most important advantage of sliding isolation systems.

The acceptance of sliding isolation systems by the engineering profession depends largely on the assessment of the characteristics of sliding bearings under conditions of interest in base isolation, on the experimental verification of the concept (shake table and/or monitoring of demonstration buildings), and on the development of standardized design procedures. The former is the subject of this paper.

The experimental program described in this paper has been designed for two specific objectives:

1. To create a data base of friction properties of Teflon sliding bearings for use in design of sliding isolated bridge and building structures.
2. To develop and calibrate mathematical models of the frictional behavior of these bearings.

More than 160 tests have been conducted on sheet type Teflon-steel interfaces at bearing pressure of 1,000, 2,000, 3,000, and 6,500 psi (6.9, 13.8, 20.7, and 45 N/mm²) and sliding velocity of 0.1–20 in./sec (0.25–50 cm/s). Unfilled and glass-filled Teflon (at 15% and 25% composition by weight) were tested against stainless steel polished to mirror finish. The effects of bearing pressure, sliding velocity, type of Teflon, and surface finish of stainless steel have been studied. Furthermore, in a limited number of tests the effects of the type of test, the acceleration at sliding interface, and the size of specimen have been studied.

It is observed that bearing pressure and sliding velocity have important effects on the recorded values of friction. The effects of the acceleration, the type of test, and the specimen size have been found to be minor or insignificant. A more detailed description of the employed experimental procedure, obtained results, modeling, and application of the results has been presented in the report by Mokha et al. (1988).

**Review of Domestic and Foreign Practice on Teflon Bearings**

Three types of bearings that utilize Teflon and that are commonly used in bridge applications are the pot, the disc, and the TFE-elastomeric bearings. All three types are utilized in sliding isolation systems (Mokha et al. 1988). The sliding plane in these bearings consists of Teflon (usually recessed in its backing steel plate) and highly polished stainless steel. The conditions at this interface (type of Teflon, roughness of stainless steel, bearing pressure, velocity, and acceleration of sliding, etc.) dictate the transmission of fric-
<table>
<thead>
<tr>
<th>Specification</th>
<th>Type of Teflon</th>
<th>Type of stainless steel</th>
<th>Maximum surface roughness (μin.)</th>
<th>Maximum bearing pressure (p/p N/mm²)</th>
<th>Minimum coefficient of friction</th>
</tr>
</thead>
<tbody>
<tr>
<td>AASHTO</td>
<td>Unfilled, filled, woven</td>
<td>ASTM A180 type 304</td>
<td>3.0 (0.075) RMS (με) plus lubrication</td>
<td>Not specified</td>
<td>0.04-0.12* Based on experiment</td>
</tr>
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<td></td>
<td>Unfilled glass filled at 15%</td>
<td>ASTM A180 type 304</td>
<td>10 (0.25) AA or CLA (με)</td>
<td>4,300-6,500</td>
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<td></td>
<td>Carbon filled at 25% (by weight)</td>
<td>ASTM A299 type 304</td>
<td>6 (0.15) SA or CLA (με)</td>
<td>4,300-6,500</td>
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<tr>
<td></td>
<td>Unfilled</td>
<td>DIN 4141, part 12</td>
<td></td>
<td></td>
<td>0.03-0.15* Based on experiment</td>
</tr>
</tbody>
</table>

*Depending on type of Teflon, lubrication, and pressure.

tional force to the superstructure. The design of sliding isolation systems that utilize such interfaces depends largely on our knowledge of the frictional properties of these interfaces. The writers anticipate that design specifications for Teflon bearings in base isolation applications will be largely based on existing specifications on the design of Teflon bearings in bridge applications. Various codes and specifications in the United States and abroad provide guidelines for the selection of materials for this interface and specify the conditions under which it should operate. Of course, these specifications apply for bridge applications in which motion is very slow. They reflect, however, our knowledge of the behavior of these interfaces. As such, we will first review various specifications for sliding Teflon bearings, and second, we will review the results of other experimental programs that are relevant to sliding Teflon bearings.

Specifications for sliding Teflon bearings and specified minimum friction coefficients in bridge applications are summarized in Table 1. The specifications reviewed are the American Association of State Highway and Transportation Officials (AASHTO) (AASHTO: Standard Specification 1983), Standard Specifications of the State of New York (Standard Specifications 1985); California Standard Special Provision (Sliding Bearings 1986); Ontario Highway Bridge Design Code (Ministry 1983); Ontario Provincial Standard Specification (OPSS) 1203 (OPSS: Material 1987); British Standards Institution (BS 5400 1983); and DIN 4141, Part 12, which is under development (Eggen et al. 1985).

It is apparent in Table 1 that considerable differences exist between various specifications. The specified roughness of stainless steel exhibits a sub-
stantial variation, from 3 to 20 \( \mu \text{m} \) (0.076 to 0.5 \( \mu \text{m} \)) in the root mean square (RMS) or arithmetic average (AA) scale (also known as \( R_s \) or \( R_a \), respectively). Furthermore, the minimum coefficient of friction, specified in various codes, exhibits substantial variations. Consider, for example, the case of unfilled Teflon sliding against stainless steel without lubrication at pressure of about 3,500 psi (24 N/mm\(^2\)). AASHTO specifies a friction coefficient of 0.04 and British Standard (BS) 5400 specifies a coefficient of 0.07. The difference is substantial when considering that AASHTO specifies a roughness value that is about three times more than that of a threefold increase in roughness may result in a threefold, or more increase, in friction (Long 1974). This example should serve the purpose of illustrating the limitations of our understanding of the behavior of sliding Teflon bearings.

A number of experimental studies in the past have resulted in information on the frictional properties of Teflon bearings that are not reflected in the reviewed specifications. Taylor (1982) has conducted a comprehensive series of tests on unfilled and filled Teflon sliding against stainless steel. Bearing pressure was between 1,000 and 5,600 psi (6.9–40 N/mm\(^2\)) and maximum sliding velocity was less than 3 in./hr (7.6 cm/h). Friction coefficients were determined after running in the interfaces at maximum load, a process that requires a significant number of cycles. Other test programs have been conducted in United States, England, Germany, and South Africa, and have been reviewed by Campbell and Kong (1987). The maximum sliding velocity in these tests was 0.1 in./sec (0.25 cm/s). Clearly, these tests have been conducted at conditions of interest in bridge applications (nonseismic).

Tyler (1977) was the first to conduct tests on unfilled Teflon-steel interfaces under conditions of interest in base isolation. Pressure was 1,100–4,300 psi (7.6–30 N/mm\(^2\)) and peak sliding velocity was 2.5–15 in./sec (6.3–38 cm/s). At each pressure level, only two or three tests have been conducted at different velocities. More recently, Constantinou et al. (1987) have conducted small-scale shake table testing of a sliding model and obtained indirect measurements of friction coefficients. Both studies of Tyler and Constantinou et al., while useful in understanding the behavior of these interfaces under seismic conditions, have been limited to a small number of tests that precluded the development of mathematical models that could describe the behavior of Teflon-steel interfaces.

A considerable amount of data on friction of Teflon has been generated in the 1950s and have been collected in several publications of du Pont (du Pont 1981). A number of data have been at high velocities of sliding, and it has been common to refer to this data as representative of what might be the behavior of Teflon-steel interfaces under conditions to be encountered in base isolation applications. Unfortunately, this is not the case. First, these tests have been conducted on Teflon sliding against Teflon, which is the usual condition in repetitive sliding, e.g., mechanical bearings. Second, specimens have been very small with the contact area unknown (Flom and Portle 1955; Constantinou et al. 1987). Third, pressure at the interface was not reported, rather the load has been reported. Only one set of data has been as conditions of interest in structural applications (Thompson et al. 1955). However, velocity in these tests has been 0.1 in./sec (0.25 cm/s).

It is evident from the preceding review that comprehensive data on the frictional properties of Teflon sliding bearings is limited to velocities below
0.1 in./sec (0.25 cm/s). The design of sliding isolated structures requires experimental data at much faster velocities. The experimental program described in this paper addresses exactly this need.

**EXPERIMENTAL PROCEDURE**

**Materials**

The materials used were as follows:

1. Unfilled and glass-filled sheet type Teflon at compositions of 15% and 25% by weight. The material was virgin (not reprocessed) and in sheets of 1/8-in. (3.175-mm) thickness. It was cut into circular shapes of 10- and 5-in. (25.4- and 12.7-cm) diameter. Both surfaces were smooth (without re-estresses). One surface was chemically etched so that it accepts adhesives for bonding to steel.

2. Stainless steel plates of 12 × 26-in. (30.5 × 66 cm) dimensions and 0.063-in. (1.6-mm) thickness. The stainless steel conformed to American Society for Testing and Materials (ASTM) A-240, type 304 requirements. It was commercially polished to a No. 8 degree mirror finish. The direction of the predominant surface pattern (surface lay) was either parallel or perpendicular to the long dimension of each plate. Surface roughness measurements were obtained with a Surtronic 3P instrument with the cutoff length set at 0.8 mm and the traverse length set at 4.5 mm. Several measurements were obtained which systematically gave an Rₙ value of 0.03 μm in the parallel to lay direction and 0.04 μm in the perpendicular-to-lay direction. The stylus tip radius of the instrument was 5 μm, which may have resulted in an understimation of the Rₙ value by about 50% (*Surface Texture* 1985). As such, the actual Rₙ value in both directions is less than or equal to 0.07 μm. It satisfies the requirements of all specifications listed in Table 1.

**Testing Apparatus**

The testing apparatus is schematically shown in Fig. 1. A central steel plate of 1/2-in. (1.27-cm) thickness is faced with stainless steel plates and sandwiched between two Teflon sheets of 10-in. diameter. The Teflon sheets are recessed into a 1/16-in. (1.6-mm) recess in two heavy 2-in. (5-cm) thick steel plates. The Teflon-steel interface is surrounded by a massive arrangement that prevents any rigid body motion of the two heavy steel plates. The arrangement is compressed by either four or six pressurizing rods. The force is the rods is measured by load cells. This force can safely reach values of more than 60 kips (267.5 kN) in each rod. The arrangement is attached to the floor and a reaction concrete block, while the steel central plate is attached to a 110-kip (490-kN) actuator.

The instrumentation consists of four or six washer load cells for measuring the force in each pressurizing rod, the LVDT and load cell of the actuator, an accelerometer to measure the acceleration of the central steel plate, and a thermocouple that is embedded in the central steel plate. It is located 0.063 in. (1.6 mm) below the interface, which allows for reliable measurement of the temperature of the Teflon-steel interface.

An alternative version of the apparatus was used to test 5-in. (12.7-cm) diameter specimens at very high pressures. The 5-in. diameter specimens were recessed in two steel plates of 10-in. (25.4-cm) diameter, which in turn were placed in the 10-in. diameter recesses of the two heavy steel plates.
A particular characteristic of the test apparatus is the way by which the normal force is developed. Normal force may be maintained for prolonged periods of time, which is very important in evaluating any adhesion of the interfaces that may develop over time. At the conclusion of the tests reported herein, the arrangement has been prestressed at 160 kips (713 kN) of normal force and stored. It will be tested after several months to determine the effect of adhesion on the breakaway coefficient of friction.

**Specimen Preparation and Test Method**

The stainless-steel plate was attached to its backing plate by bolts at the two ends and along the short dimension of the plate. Bonding of the Teflon sheets within the recesses of the backing heavy steel plate was performed according to the following procedure. The steel plates were thoroughly cleaned,
degreased, and dried. The epoxy adhesive was prepared and uniformly applied on the steel surface. The Teflon sheets were attached to the two steel plates, and the whole arrangement was compressed by a hydraulic machine under the test normal load for about 14 hr (overnight). This resulted in a smooth surface without bubbles.

A set of about eight tests was conducted each day, all at the same normal load. The Teflon sheets were then removed, and fresh ones were attached and compressed overnight. This cycle was continued with only a few interruptions. In these interruptions, the interface was allowed to relax, unloaded, for about 24 hr before resuming testing.

The tests were conducted according to the following procedure. Motion of the central steel plate was imposed by the actuator, and recordings of the force needed to initiate and maintain this motion were made. This is the frictional force from two identical Teflon-steel interfaces. In most of the tests, the motion was sinusoidal with specified amplitude and frequency. Furthermore, a number of tests were conducted with constant velocity type of motion (sawtooth displacement). The two types of experiments produced almost identical results for the same peak velocity of sliding.

There was significant transfer of Teflon flakes to the stainless steel plates. The formation of a thin Teflon film on the stainless-steel plate results in substantial reduction of the frictional force transmitted through the interface (equivalent to running in the interface). Furthermore, it was observed that, in the case of glass filled Teflon, very fine steel particles were transferred from the stainless-steel plate to the Teflon surface. This resulted in a very smooth, like polished, surface. At the conclusion of each test, the stainless-steel plate and Teflon sheet were cleaned to maintain their original condition. The surface of glass-filled Teflon was refurbished with a sharp instrument. Furthermore, sufficient time was allowed between experiments for thorough cooling. Temperature, at the start of experiments, was between 70° and 90° F.

An important observation was made that has significant influence on the recorded frictional force: the frictional force record at low sliding velocity following a high-velocity test was higher than the original value recorded on a fresh interface. This behavior has been observed by other researchers (Plom and Porile 1955), and it is attributed to degradation of Teflon caused by frictional heating. Based on this observation, it was decided to use fresh Teflon for each set of tests. These tests were conducted at the same pressure and in increasing order of peak sliding velocity.

It should be noted that all tests have been conducted on clean interfaces that have been restored to their original condition. No lubrication has been used, despite the fact that bridge-design specifications allow, or recommend, the use of lubrication (Table 1). Lubrication significantly reduces friction. However, the stability of lubricants is a concern in base isolation applications.

**Results**

Tests were conducted at pressures of 1,000, 2,000, 3,000, and 6,500 psi (6.9, 13.8, 20.7, and 44.9 N/mm²) and peak sliding velocity of 0.1–20 in./sec (0.25–50.8 cm/s). The direction of sliding was either parallel or perpendicular to the lay. The tests on glass-filled Teflon were conducted only with the direction of sliding parallel to the lay. The tests at 1,000-, 2,000-,
and 3,000-psi (6.9-, 13.8-, 20.7-N/mm²) pressure were conducted with 10-in. (25.4-cm) diameter specimens, while the tests at 6,500-psi (44.9-N/mm²) pressure were conducted with 5-in. (12.7-cm) diameter specimens.

Representative frictional force-displacement loops are shown in Fig. 2 (force from two interfaces). Both tests (No. 80 and 81) were conducted on unfilled Teflon, at 2,000-psi (13.8-N/mm²) pressure and 2-in. (5-cm) amplitude. The first is a sinusoidal test while the second is a constant velocity test. Different
FIG. 3. Variation of Sliding Coefficient of Friction with Velocity and Pressure of Unfilled Teflon Sliding Parallel to Lay (1 in. = 2.54 cm, 1,000 psi = 6.9 N/mm²)

FIG. 4. Variation of Sliding Coefficient of Friction with Velocity and Pressure of Unfilled Teflon Sliding Perpendicular to Lay
FIG. 5. Variation of Sliding Coefficient of Friction with Velocity and Pressure of Glass-Filled Teflon at 15% by Weight, Sliding Parallel to Lay

FIG. 6. Variation of Sliding Coefficient of Friction with Velocity and Pressure of Glass-Filled Teflon at 25% by Weight, Sliding Parallel to Lay

frequencies were used in order to achieve the same peak velocity of 4 in./sec (10 cm/s). It is apparent that the two loops are almost identical.

The recorded frictional force was used to extract various frictional characteristics of interest. The frictional force at initiation of sliding upon di-
vision by the normal force results in the coefficient of breakaway friction \( \mu_b \). This value of the coefficient of friction is also known as static friction. The value of the coefficient of friction at peak velocity is the sliding coefficient of friction, \( \mu_s \), that corresponds to this velocity. It is also known as kinetic friction. There is a continuous drop of the value of sliding (or kinetic) coefficient of friction with increasing number of cycles. Of importance in practical applications are the breakaway and maximum sliding coefficients of friction. The latter occurs usually at the first cycle.

A detailed presentation of the experimental results may be found in the publication by Mokha et al. (1988). Only results in graphical form are presented herein. Figs. 3–5 present the variation of the maximum value of the coefficient of sliding friction, \( \mu_{\text{max}} \), with velocity of sliding and pressure in the four cases of: (1) Unfilled Teflon sliding parallel to lay; (2) unfilled Teflon sliding perpendicular to lay; (3) glass-filled Teflon at 15% sliding parallel to lay; and (4) glass-filled Teflon at 25% sliding parallel to lay. Fig. 7 presents the variation of breakaway coefficient of friction with pressure in the four cases.

A certain phenomenon known as stick-slip was observed in six experiments (identified in Figs. 3–6). The recorded frictional force in these experiments showed a short duration increase that was followed by a rapid fall. It is caused by momentary sticking of the interfaces. It was mostly observed in high-frequency tests (above 1 Hz).

It should be noted that the recorded values of friction were that of Teflon always restored to its original condition. As such, the presented values must be regarded as upper-bound values.

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INTERPRETATION OF RESULTS

Effect of Type of Test

Most of the conducted tests were with sinusoidal motion. In this type of motion, both the sliding velocity and acceleration vary with time. It has been expected and confirmed in these tests that acceleration has only a minor effect on the measured coefficient of friction; velocity being the most influential parameter.

Constant velocity test (cyclic sawtooth displacement) is another test that is appropriate for measuring the friction of Teflon-steel interfaces. Presumably, in a constant velocity test, the acceleration is zero and, therefore, it appears to be a more appropriate test than a sinusoidal one, because the results cannot be masked by the influence of acceleration. This is not exactly true because the acceleration at the start and at every reversal in a cyclic constant velocity test is markedly different than zero. It should be noted that in both tests the peak velocity occurs at a time at which acceleration is zero.

Fifteen of the sinusoidal tests were repeated with constant velocity motion of the same amplitude, but at different frequency, in order to yield same peak velocity. The recorded values of sliding friction were almost identical in the two sets of tests. Some minor difference was observed on the recorded breakaway coefficient of friction. This is apparently caused by the acceleration impulse at the start of constant velocity tests.

Effect of Specimen Size

Six tests at pressure of 3,000 psi (20.7 N/mm²) were conducted with 5- and 10-in. (12.7- and 25.4-cm) diameter specimens. In three of these tests, significant stick-slip was observed, and comparisons of recorded values of friction for the two specimen sizes were not good. In the other three cases, the recorded values agreed fairly well. Comparable results have been reported by Taylor (1982).

Effect of Acceleration

In five tests, the peak sliding velocity was about 8 in./sec (20 cm/s) but frequency, amplitude, and type of test were different. The peak recorded sliding acceleration in these tests was between 0.08 and 0.85 g. The recorded values of $\mu_{e}$ and $\mu_{max}$ compare very well [for details see Mokha et al. (1988)]. Clearly, the acceleration effect is minimal.

Effect of Velocity

It is apparent in Figs. 3-6 that the coefficient of sliding friction increases rapidly with sliding velocity, up to a certain value of velocity beyond which it remains almost constant. This value of velocity is between 4 and 8 in./sec (10 and 20 cm/s). Above this value, sliding velocity has relatively little effect. The difference between minimum and maximum value of sliding friction is larger at low bearing pressure. For example, in the case of unfilled Teflon with sliding parallel to lay (Fig. 3), the minimum value is 0.027 and the maximum is about 0.12. Such a four-fold increase is substantial and indicates the significant deviation of the frictional behavior of these interfaces from Coulomb’s theory.

We now focus on the breakaway value of the coefficient of friction. This value appears to be substantially larger than the sliding value. The writers
believe that the significance of the breakaway value at high velocities of sliding has been overstated (Tyler 1977). Under laboratory conditions, a Teflon-steel interface may be subjected to high initial velocities that are associated with an impulse of acceleration (Mckee et al. 1988). However, such conditions are very unlikely, or impossible, to occur. Sliding initiates (breakaway) at essentially zero velocity. This condition also occurs at each reversal of motion where the interface undergoes a momentary sticking. The writers assert that only the breakaway value of friction at very low velocity is of interest. This value is mobilized only at initiation of sliding. When sliding occurs, the frictional resistance of the interface is characterized by the value of $\mu_{max}$, which depends on velocity.

**Effect of Pressure**

It is apparent in Figs. 3-5 that the coefficient of sliding friction reduces with increasing pressure. The pressure at which leveling off occurs depends on the sliding velocity. This limit value of pressure increases with increasing velocity of sliding. At very low velocity, it is about 5,000 psi (34.5 N/mm²). At velocities exceeding 10 in/sec (25.4 cm/s) it appears to be larger than 6,500 psi (44.9 N/mm²). Furthermore, the rate of reduction of the sliding coefficient of friction with increasing pressure depends strongly on the sliding velocity. This rate is largest at high velocity of sliding.

The dependency on pressure of breakaway coefficient of friction at very slow speeds (0.1 in/sec = 0.25 cm/s) follows a pattern similar to that of the sliding friction coefficient at the same velocity (Fig. 7).

**Effect of Surface Finish**

Measurements of the surface roughness of the stainless steel plate in the two directions parallel to lay (P) and perpendicular to lay (T) have shown that the roughness in the T direction is about 30% more than in the P direction. This is a small difference. The recorded values of friction in the latter case are less than in the former case. The difference diminishes at 6,500 psi (44.9 N/mm²) pressure. At the pressure of 1,000 psi (6.9 N/mm²), the recorded friction in the P direction is about 15% less than that in the T direction. As such, Teflon sliding bearings exhibit an orthotopic behavior, i.e., the frictional properties depend on the direction of sliding.

**Effect of Type of Teflon**

The addition of glass filler to Teflon results in an increase in breakaway and sliding coefficient of friction that appears to be related to the quantity of filler and bearing pressure. At a pressure of 6,500 psi (44.9 N/mm²), the coefficient of friction is practically unaffected by the amount of filler. At lower pressures, glass-filled Teflon exhibits higher friction than unfilled Teflon. The difference appears to increase with decreasing pressure.

The amount of glass filler has a rather complicated effect on friction. At a pressure of 1,000 psi (6.9 N/mm²), friction of 15% glass-filled Teflon is higher than that of 25% glass-filled Teflon. The opposite is observed at higher pressures.

**Comparison with Other Studies**

Comparison of experimental data obtained by different researchers is important but difficult because in many cases the conditions under which the
<table>
<thead>
<tr>
<th>Pressure (psi)</th>
<th>Peak velocity (in./sec)</th>
<th>( h_y ) (in.)</th>
<th>Pressure (psi)</th>
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</table>

*Approximate value.

1 Calculated from frequency and stroke.

Note: 1 in. = 2.54 cm; 1,000 psi = 6.9 N/mm²; t = loaded overnight; and \( h_y \) = loaded for 2-1/4 hr.

tests are conducted are inadequately reported. One cannot ignore the influence a laboratory test method may have on the recorded data.

One of the earliest studies of Teflon-steel interfaces was reported by Thompson et al. (1955). Tests were conducted on unfilled Teflon sliding against stainless steel of a \( R_y \) value (RMS) of 2 µm (0.05 µm) and velocity of about 0.1 in./sec (0.25 cm/s). Thompson’s results on the sliding value of the coefficient of friction were 0.022, 0.017, and 0.016 for pressure of 1,000, 2,000, and 3,000 psi (6.9, 13.8, and 20.7 N/mm²), respectively. The results of this study were 0.027, 0.017, and 0.015. The agreement is excellent.

Tyler’s (1977) study is certainly the most interesting one, as it has been carried out at conditions of interest in base isolation. Tyler did not take measurements of the stainless-steel surface roughness but rather assumed that is in the range of 0.05–0.15 µm in the \( R_y \) scale (mirror finish). The tests were conducted at different frequencies and amplitudes than our tests. Furthermore, Tyler concentrated on the breakaway value of the coefficient of friction, which appears to be sensitive on the interface condition at the start of each experiment.

A comparison of some of our data to those obtained by Tyler is presented in Table 2. Only pressure and peak velocity are shown in this table, which, anyway, are the most influential parameters. Our data have been compiled from the data obtained in the parallel-and perpendicular-to-lay direction of sliding. The two sets of data compare quite well.

**CONCLUSIONS**

Several tests were conducted on unfilled and glass-filled Teflon in contact with polished stainless steel at bearing pressure of 1,000, 2,000, 3,000, and 6,500 psi (6.9, 13.8, 20.7, and 44.9 N/mm²) and sliding velocity of 0.1–
20 in./sec (0.25–50 cm/s). The effects on friction of pressure, velocity, acceleration, type, and condition of interface and type of test were investigated. The following conclusions have been derived.

1. The type of test (sinusoidal or saw-tooth displacement input) has an insignificant effect on the value of the sliding coefficient of friction. Only a minor effect on the recorded value of breakthrough friction was observed.

2. The effect of relative acceleration at the sliding interface is not important. Friction increases rapidly with increasing velocity up to a certain value of velocity beyond which it remains constant. This value of velocity is between 4 and 8 in./sec (10 and 20 cm/s).

3. Friction decreases with increasing bearing pressure. The rate of reduction depends strongly on the sliding velocity. It is greatest at high velocity. The value of pressure beyond which friction is independent of pressure is about 5,000 psi (34.5 N/mm²) at 0 in./sec (0.25 cm/s) velocity and more than 6,500 psi (44.9 N/mm²) at velocities exceeding 10 in./sec (25.4 cm/s).

4. Friction of unfilled Teflon is lower than friction of glass-filled Teflon under identical conditions of testing. The difference appears to reduce with increasing pressure and it almost diminishes at the pressure of 6,500 psi (44.9 N/mm²).

5. The friction of glass-filled Teflon at 15% by weight composition is lower than that of glass-filled Teflon at 25% composition at pressures exceeding 2,000 psi (13.8 N/mm²). The opposite was observed at the pressure of 1,000 psi (6.9 N/mm²). Differences were not substantial.

6. For sliding parallel to lay, friction of unfilled Teflon was slightly less than when sliding was perpendicular to lay. The surface roughness of stainless steel in the latter case was about 30% more than in the former case (0.04 μm versus 0.03 μm Rₚ). The difference in the recorded value of friction showed a reduction with increasing pressure, and diminished at the pressure of 6,500 psi (44.9 N/mm²). The interface is effectively orthotropic, i.e., the frictional properties depend on the direction of sliding.

7. For sliding parallel to lay, friction of unfilled Teflon was slightly less than when sliding was perpendicular to lay. The surface roughness of stainless steel in the latter case was about 30% more than in the former case (0.04 μm versus 0.03 μm Rₚ). The difference in the recorded value of friction showed a reduction with increasing pressure, and diminished at the pressure of 6,500 psi (44.9 N/mm²). The interface is effectively orthotropic, i.e., the frictional properties depend on the direction of sliding.

8. For sliding parallel to lay, friction of unfilled Teflon was slightly less than when sliding was perpendicular to lay. The surface roughness of stainless steel in the latter case was about 30% more than in the former case (0.04 μm versus 0.03 μm Rₚ). The difference in the recorded value of friction showed a reduction with increasing pressure, and diminished at the pressure of 6,500 psi (44.9 N/mm²). The interface is effectively orthotropic, i.e., the frictional properties depend on the direction of sliding.

9. In cases of momentary sticking after initial breakthrough, the recorded value of friction was essentially the same as the sliding value. This is caused by the transfer of a thin film of Teflon to the stainless steel plate during previous sliding. This transfer of Teflon caused also a continuous drop in the recorded frictional force as the bearing was worked (in all tests, five cycles of motion were completed).

10. The recorded values of breakthrough and sliding coefficient of friction appear to compare well with data reported by other investigators.

11. Teflon-steel interfaces exhibit a behavior that deviates significantly from Coulomb’s theory of friction.

The development and calibration of mathematical models and the application of the results in the analysis/design of sliding isolation systems is presented in an accompanying paper. Furthermore, the effect on friction of
prolonged loading without sliding is currently under assessment. A Teflon-steel interface has been under load of 160 kips (713 kN) since May, 1988. It will be tested at a later time in order to determine the effect of adhesion that may develop over time on the breakaway coefficient of friction.

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APPENDIX. REFERENCES


