

# Laboratory Investigation of the Coefficient of Friction in the Tetrafluorethylene Slide Surface of a Bridge Bearing

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A laboratory study of the influences of four parameters—contact pressure, temperature, speed of travel, and roughness of the stainless steel surface—on the coefficient of friction in a tetrafluorethylene–stainless steel interface is described. The coefficient of friction is found to be a maximum during the first cycle of movement, to decrease rapidly during the next four cycles, and to show little variation thereafter. The coefficient of friction increases with an increase in speed of travel and roughness of the steel surface and with a decrease in contact pressure and temperature. It is concluded that the values of the coefficient of friction for tetrafluorethylene given in the Ontario Highway Bridge Design Code follow the proper trend and are conservative, but not unduly so, under the combination of low temperature, high speed of travel, and rough mating surface.

Bearings using tetrafluorethylene (TFE) to provide slide surfaces are widely used in bridge structures. A low-friction TFE surface is used to provide either rotation, by sliding over a curved surface, or translation, by sliding on a plane surface, or a combination of both. Stainless steel is commonly used for the surface mating with the TFE.

The coefficient of friction is the prime parameter in the design of a TFE sliding bearing for a bridge because it dictates the magnitude of the forces transmitted from the superstructure to the substructure of the bridge. A state-of-the-art report (1) has identified 14 parameters that affect the coefficient of friction of TFE sliding on a metallic plate. These parameters are lubrication, contact pressure, speed of travel, eccentric loading, temperature, creep, roughness of the mating surface, type of TFE, attachment of the TFE to the backing plate, surface contamination, length of the travel path, load and travel history, specimen size, and wear. The influence of some of these parameters is not clearly documented in the literature and contradictory statements exist, particularly in the case of lubricated surfaces.

Results from a laboratory testing program undertaken to study the influence of some of the parameters judged to be the most influential on the coefficient of friction of TFE are reported in this paper. The testing was carried out at Queen's University under the sponsorship of the Ministry of Transportation of Ontario with the aim of refining the provisions in the Ontario Highway Bridge Design Code (OHBD) (2) in relation to TFE slide surfaces.

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## LABORATORY TEST PROGRAM

A suggested expression (1) for the coefficient of friction,  $\mu$ , of TFE is

$$\mu = QP^{n-1} \quad (1)$$

where  $Q$  and  $n$  are parameters and  $P$  is the contact pressure on the TFE. It has been reported that  $Q$  is primarily a function of temperature and speed of travel, whereas  $n$ , which has a value less than unity, is mainly a function of filler content of the TFE, surface lubrication, surface finish of the metallic sliding plate, and loading history (3,4). Validation of such a relationship would simplify the requirements for the coefficient of friction for TFE slide bearings in bridge design codes.

The Ontario specification for bearings (OPSS 1203, 1988) stipulates that only dimpled, unfilled TFE resin with a silicone grease lubricant conforming to U.S. Military Specification Mil-S-8660C (1983) should be used in the slide surface of a bridge bearing. The parameters investigated in the test program were limited to contact pressure, temperature, speed of travel, and roughness of the metallic sliding plate. Loading history was kept uniform throughout the test program.

The ranges of the parameters considered for the test program are given in Table 1. These ranges reflect the conditions to which TFE slide bearings are likely to be subjected in practice and also limitations of the available test equipment. Maximum pressures of 30 MPa and 45 MPa are specified (2) for TFE slide surfaces in bridge bearings under dead load and total load, respectively. A temperature of  $-25^{\circ}\text{C}$  represents the lowest temperature attainable in the cold room facility at Queen's University. The range of speed of travel covers that from the relatively slow temperature-induced movement to the expected relatively fast speed during passage of traffic on a bridge structure, and are within the capabilities of the testing rig. A  $0.25\text{-}\mu\text{m}$  (arithmetic average) finish is required for a plane surface of the metallic plate, according to the Ontario specification for bearings (OPSS 1203, 1988). The two selected roughnesses ( $0.03$  and  $0.34\text{ }\mu\text{m}$ ), measured perpendicular to the direction of polishing, correspond to those for commercially available Nos. 8 and 4 finish stainless steel plates (ASTM A480-82a, 1982), respectively. The surface roughness is highest perpendicular to the direction of polishing. A No. 8 finish is normally used for the stainless steel plate in bridge bearings in Ontario.

The ranges of parameters given in Table 1 were covered in the series of 12 tests outlined in Table 2. In each series, five

TABLE 1 RANGES OF PARAMETERS

Parameter	Range
Pressure, $P$ (MPa)	10, 15, 25, 30, 45
Temperature, $T$ ( $^{\circ}\text{C}$ )	-25, 20
Speed of travel, $V$ (mm/s)	0.08, 1, 20
Roughness of metallic plate, $R$ ( $\mu\text{m}$ )	0.03, 0.34

individual specimens of lubricated, dimpled TFE were tested under contact pressures of 10, 15, 25, 30, and 45 MPa, respectively, whereas temperature, surface roughness, and speed of travel were maintained as indicated, giving a total of 60 tests. The contact pressure was computed using the gross area of the TFE surface.

The specimens of dimpled, lubricated TFE resin had a diameter of 75 mm and a thickness of 4.5 mm, and were recessed to a depth of 2.5 mm in a rigid steel backing plate. A diameter of 75 mm appears to be the accepted standard for TFE tests in Europe, and the minimum thickness and free height of the TFE specimens are stipulated in the Ontario specification for bearings. A dwell of load period of 12 hr was used before testing, as required by the American Association of State Highway and Transportation Officials (5).

The TFE-stainless steel interface was subjected to a certain number of cycles of movement, using a stroke of  $\pm 10$  mm/cycle to give a travel path of 40 mm/cycle. Fifty cycles were selected for the slow speed (0.08 mm/sec) tests in order to limit the test to a reasonable time period. Three hundred

TABLE 2 DETAILS OF TEST SERIES

Series	Temperature ( $^{\circ}\text{C}$ )	Surface Roughness ( $\mu\text{m}$ )	Travel Speed (mm/s)
1	20	0.03	0.08
2	20	0.03	1.0
3	20	0.03	20.0
4	20	0.34	0.08
5	20	0.34	1.0
6	20	0.34	20.0
7	-25	0.03	0.08
8	-25	0.03	1.0
9	-25	0.03	20.0
10	-25	0.34	0.08
11	-25	0.34	1.0
12	-25	0.34	20.0

cycles were usually completed in the intermediate speed (1.0 mm/sec) tests and a minimum of 8,000 cycles completed in the fast speed (20 mm/sec) tests.

A diagrammatic representation of the self-straining rig used for the testing program is shown in Figure 1. This rig is capable of subjecting a TFE-stainless steel interface to cyclic sliding movement at different speeds under different levels of contact pressure. The TFE specimen is compressed against a stainless steel plate by means of a vertical hydraulic ram acting through a spherical bearing to ensure concentric loading. This plate is attached to a sliding platform that moves horizontally on steel rollers. The speed and stroke of the horizontal movement are controlled by an MTS closed-loop testing system. A triangular displacement-time function was used to provide a uniform speed over the stroke. Load cells were used to measure the vertical and horizontal loads transmitted to the TFE

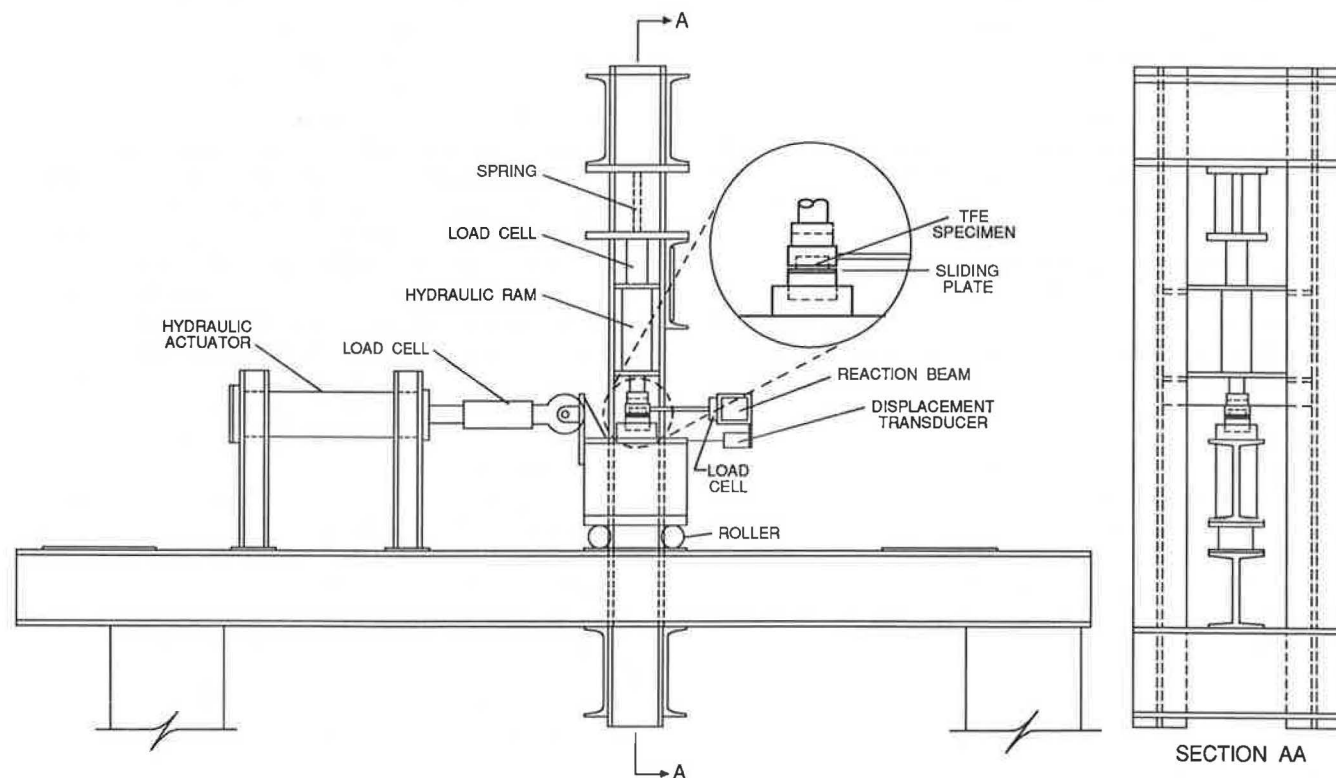


FIGURE 1 Diagrammatic representation of testing rig.

specimen. The temperature of the TFE-stainless steel interface was monitored, together with the temperature and the humidity of the environment of the rig. The tests at  $-25^{\circ}\text{C}$  were conducted with the rig located in a cold room facility.

The coefficient of friction at the TFE-stainless steel interface is determined from the ratio of the horizontal to the vertical load in the interface. A typical variation of the coefficient of friction over a complete cycle of movement is shown in Figure 2. The static and dynamic coefficients of friction, which relate to the forces required to initiate movement and to maintain movement, respectively, are identified. The static coefficient is taken as the maximum value and the dynamic coefficient as the minimum value.

The TFE, stainless steel, and lubricant used in the tests were obtained from the same sources as those used by a Canadian bearing manufacturer. The dimples on the TFE surface have a diameter of 8 mm and a depth of 2 mm, and are arranged in the pattern shown in Figure 3. Molykote 44, which is a silicone oil thickened with lithium soap, was used as the lubricant. The stainless steel specimens were mounted on the sliding platform so that the direction of movement was perpendicular to the direction in which the stainless steel was polished. The backing plate containing the TFE specimen was placed on the stainless steel plate in the test rig, with the TFE specimen aligned so that the direction of the movement of the TFE relative to the stainless steel was as indicated in Figure 3. This alignment of the dimples ensured that the lubricant was smeared uniformly over the entire region of movement of the TFE.

## OBSERVATIONS FROM TEST DATA

Data from all 60 tests have been presented and discussed in detail (6). Phenomena observed during the tests and trends exhibited by the test data are summarized as follows.

During the tests using the rough (No. 4 finish) stainless steel plate, the lubricant became darker in color and stiffer in consistency with the increasing number of cycles compared

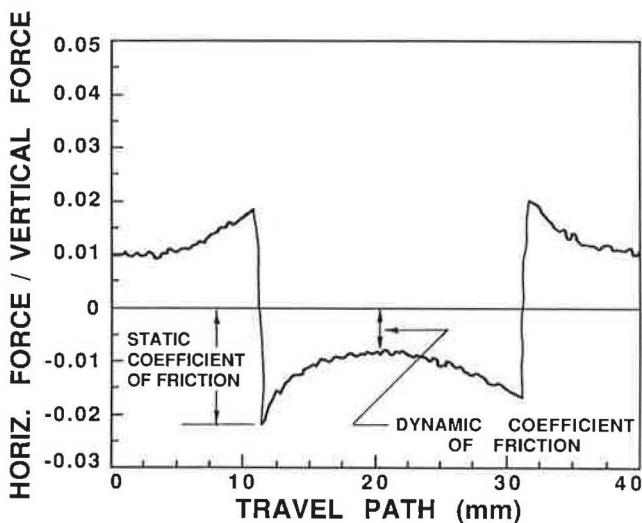


FIGURE 2 Variation of the ratio of horizontal to vertical force over a cycle.

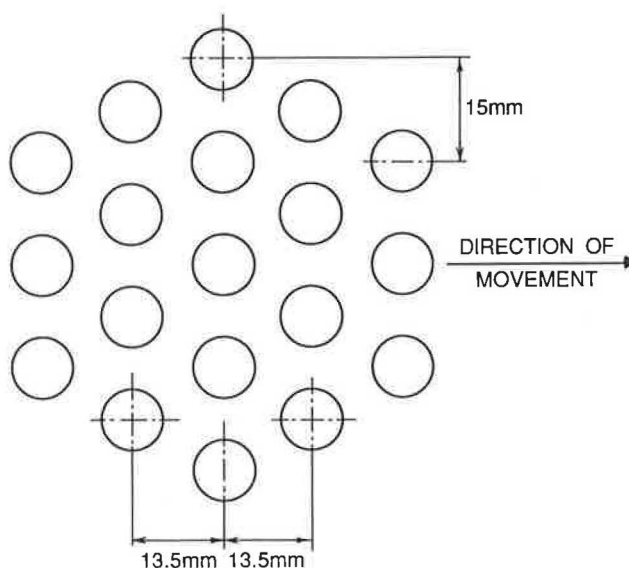


FIGURE 3 Arrangement of grease dimples.

with the corresponding tests using the smooth (No. 8 finish) stainless steel plate. The grease from the smooth stainless steel plate tests was found to be discolored by the presence of embedded particles of TFE. The color of the grease from the tests using the rough stainless steel plate was very dark, presumably as a result of contamination with residuals of the abrasive used in polishing the stainless steel.

Significant wear of the TFE was observed in the test carried out using a smooth stainless steel plate at a contact pressure of 45 MPa, a sliding speed of 20 mm/sec, and a temperature of  $-25^{\circ}\text{C}$ . Wear was characterized by a deposit of flakes of TFE on the stainless steel plate at each end of the stroke. A loss in weight of 4 percent was measured after 8,000 cycles in this test. By comparison, in the corresponding test using the rough stainless steel, the loss in weight was only 0.5 percent. The reason for the significantly larger amount of wear with the smooth stainless steel plate was not immediately obvious. Traces of wear were also observed in the test using the smooth stainless steel plate at a contact pressure of 30 MPa, a sliding speed of 20 mm/sec, and a temperature of  $-25^{\circ}\text{C}$ . No wear, as characterized by TFE deposits, was detected in any other test.

The shape of the force ratio-displacement trace for a cycle differed, particularly during the early cycles of movement, for the rough and smooth stainless steel plates. Figure 4 shows traces from the second cycle of movement in tests with a smooth stainless steel plate [Figure 4(a)] and a rough stainless steel plate [Figure 4(b)]. Figure 4(b) shows a more pronounced difference between the ratio of the horizontal to the vertical force at mid-stroke and at the end of the stroke than does Figure 4(a). After about 30 cycles, the shape of the trace for the rough plate approached that of the smooth plate.

The temperature of the TFE specimen increased with the number of cycles in the fast speed tests using both smooth and rough stainless steel plates. After 8,000 cycles at  $20^{\circ}\text{C}$ , the increase was approximately  $2^{\circ}\text{C}$  for the smooth plate and  $3^{\circ}\text{C}$  to  $4^{\circ}\text{C}$  for the rough plate, whereas at  $-25^{\circ}\text{C}$  the corresponding increase was from  $5^{\circ}\text{C}$  to  $10^{\circ}\text{C}$  for both plates and the temperature increased with contact pressure.

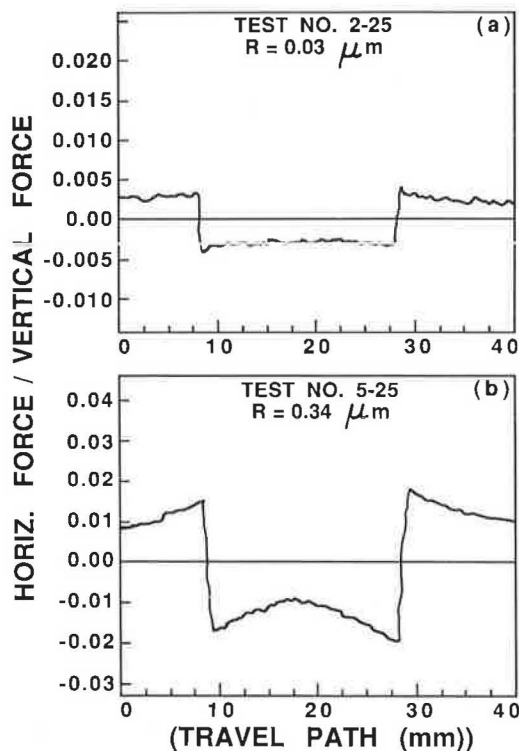


FIGURE 4 Traces of variation of horizontal to vertical force ratio for rough and smooth stainless steel plates.

Typical data obtained from one of the tests (Test 6-30) are shown in Figure 5. Test 6-30 is the test in Series 6 using a contact pressure of 30 MPa. Values for both the static and dynamic coefficients of friction, obtained after various cycles in the tests at 20°C and -25°C, are given in Tables 3 and 4, respectively.

Generally, the highest value of the coefficient of friction, both static and dynamic, was recorded during the initial movement from the mid-stroke position. A rapid drop in the magnitude of both coefficients of friction occurred after 1 cycle of movement, and the magnitude of the drop increased with speed of movement. A further decrease occurred up to about 5 cycles, after which both coefficients appeared to stabilize and remain fairly constant up to 50 cycles. For each test, the difference between the static and dynamic coefficients of friction remained fairly constant with increasing number of cycles. Data obtained beyond 50 cycles indicated an increase in both the coefficients of friction up to about 1,000 cycles, after which the values stabilized and remained fairly constant up to as many as 18,000 cycles. However, some exceptions to this general trend were observed.

In Series 4 and 5, at low and intermediate speeds, respectively, as can be seen from column (1)/(2) of Table 3, the initial static coefficient of friction was lower than that at 50 cycles, except in Tests 5-15 and 5-45. The maximum value of the static coefficient of friction in each of these two tests was recorded at the end of the stroke during the first cycle rather than at initial movement from the mid-stroke position. Subsequent to the first cycle, the static coefficient decreased and stabilized after about 5 cycles. On the other hand, in all the tests of Series 4 and 5, the dynamic coefficient of friction

increased over the first 5 cycles and then stabilized. This deviation from the general trend may be due to the effectiveness with which the lubricant is spread during the first cycle of movement of the TFE on the rough stainless steel plate. The lower value of the static coefficient of friction occurred at mid-stroke when the lubricant had been present under pressure for the 12-hr preloading period, whereas the peak coefficient of friction occurred at the end of the stroke when part of the surface of the stainless steel plate was receiving lubricant for the first time. The absence of this deviation in the Series 6 tests suggests that, for the rough plate, the influence

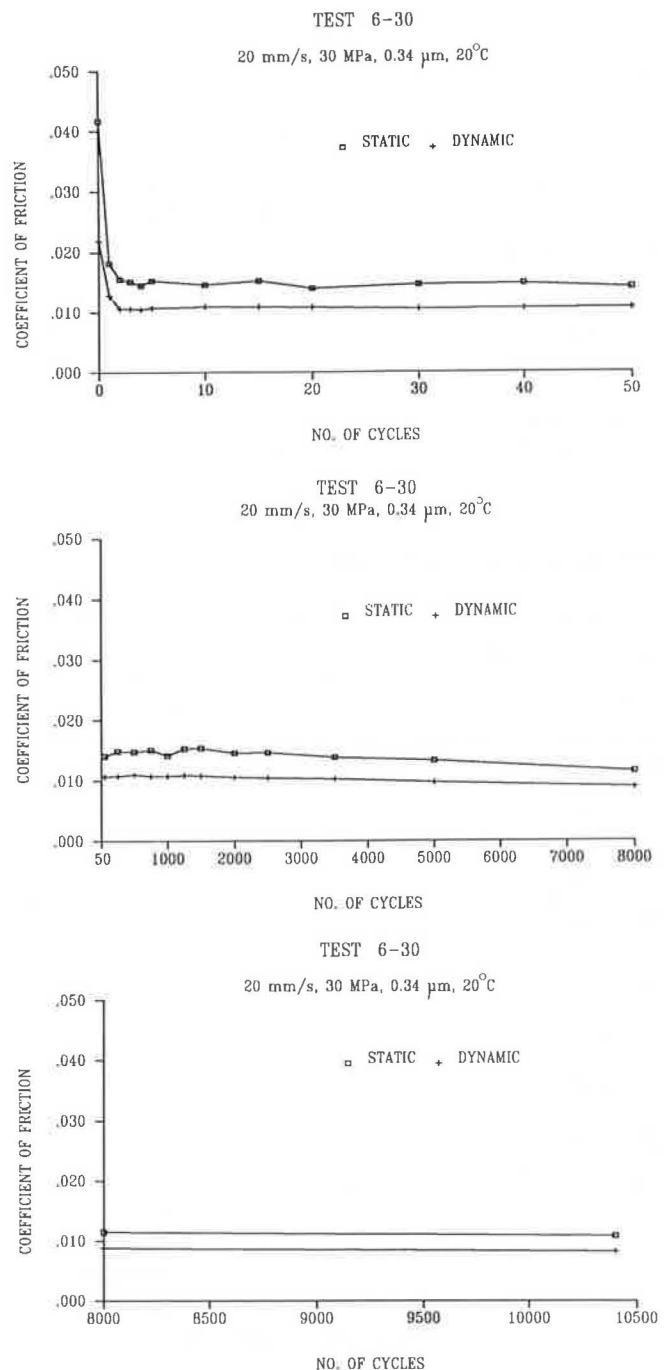


FIGURE 5 Typical test data.

TABLE 3 COEFFICIENTS OF FRICTION AFTER VARIOUS CYCLES AT 20°C

TEST NO.	COEFFICIENT OF FRICTION						RATIOS			
	INITIAL		AT 50 CYCLES		AT SPECIFIED CYCLES		CYCLES	(1)/(2)	(4)/(2)	(3)/(2)
	STATIC (1)	DYNAMIC	STATIC (2)	DYNAMIC (3)	STATIC (4)	DYNAMIC				
1-10	.0116	.0087	.0108	.0080				1.07		.74
1-15	.0135	.0820	.0072	.0051				1.88		.71
1-25	.0058	.0046	.0038	.0028				1.53		.74
1-30	.0055	.0037	.0038	.0027				1.45		.71
1-45			.0031	.0021	.0033	.0025	106		1.06	.68
2-10	.0136	.0068	.0077	.0050	.0100	.0060	375	1.77	1.30	.65
2-15	.0140	.0092	.0052	.0032				2.69		.62
2-25			.0040	.0026						.65
2-30			.0040	.0018						.45
2-45	.0086	.0079	.0033	.0011				2.61		.33
3-10	.0334	.0172	.0126	.0064	.0198	.0112	8000	2.65	1.57	.51
3-15	.0473	.0258	.0081	.0028	.0127	.0041	8000	5.84	1.57	.35
3-25	.0338	.0181	.0063	.0035	.0106	.0065	8000	5.37	1.68	.56
3-30	.0290	.0175	.0066	.0044	.0120	.0078	18000	4.39	1.82	.67
3-45	.0230	.0160	.0045	.0030	.0059	.0040	5000	5.11	1.31	.67
4-10	.0149	.0100	.0169	.0112				.88		.66
4-15			.0146	.0101						.69
4-25	.0089	.0063	.0092	.0066				.97		.72
4-30	.0062	.0039	.0082	.0060				.76		.73
4-45	.0054	.0054	.0062	.0047				.87		.76
5-10	.0167	.0132	.0253	.0212	.0318	.0250	400	.66	1.26	.84
5-15	.0430	.0280	.0300	.0260	.0253	.0208	360	1.43	.84	.87
5-25	.0146	.0118	.0176	.0140	.0201	.0153	400	.83	1.14	.80
5-30	.0114	.0095	.0141	.0128	.0175	.0142	360	.81	1.24	.91
5-45	.0143	.0125	.0124	.0106	.0117	.0910	305	1.15	.94	.85
6-10	.0689	.0530	.0387	.0310	.0406	.0276	8000	1.78	1.05	.80
6-15	.0528	.0381	.0274	.0233	.0270	.0217	10600	1.93	.99	.85
6-25	.0331	.0191	.0169	.0136	.0170	.0140	10600	1.96	1.01	.80
6-30	.0417	.0218	.0141	.0107	.0109	.0830	10400	2.96	.77	.76
6-45	.0328	.0185	.0104	.0078	.0077	.0610	8000	3.15	.74	.75

Blanks indicate that data were not available

TABLE 4 COEFFICIENTS OF FRICTION AFTER VARIOUS CYCLES AT -25°C

TEST NO.	COEFFICIENT OF FRICTION						RATIOS			
	INITIAL		AT 50 CYCLES		AT SPECIFIED CYCLES		CYCLES	(1)/(2)	(4)/(2)	(3)/(2)
	STATIC (1)	DYNAMIC	STATIC (2)	DYNAMIC (3)	STATIC (4)	DYNAMIC				
7-10	.0603	.0279	.0286	.0213				2.11		.74
7-15	.0232	.0140	.0172	.0118				1.35		.69
7-25	.0225	.0112	.0183	.0136				1.23		.74
7-30	.0143	.0105	.0097	.0070				1.47		.72
7-45	.0084	.0055	.0080	.0059				1.05		.74
8-10	.0549	.0251	.0220	.0168	.0341	.0233	335	2.50	1.55	.76
8-15	.0387	.0197	.0200	.0149	.0253	.0187	335	1.94	1.26	.75
8-25	.0576	.0420	.0254	.0200	.0267	.0220	200	2.27	1.05	.79
8-30	.0229	.0139	.0103	.0080	.0125	.0874	136	2.22	1.21	.78
8-45	.0537	.0340	.0178	.0155	.0225	.0193	235	3.02	1.26	.87
9-10	.1000	.0526	.0328	.0290	.0814	.0686	7400	3.05	2.48	.88
9-15	.1120	.0673	.0277	.0223	.0552	.0467	8000	4.04	1.99	.81
9-25	.0809	.0489	.0265	.0230	.0317	.0270	9546	3.05	1.20	.87
9-30	.0844	.0505	.0266	.0238	.0331	.0128	8000	3.17	1.24	.89
9-45	.0590	.0395	.0187	.0163	.0280	.0263	8000	3.16	1.50	.87
10-10	.0420	.0247	.0291	.0154				1.44		.53
10-15	.0264	.0161	.0299	.0159				.88		.53
10-25	.0158	.0102	.0156	.0078				1.01		.50
10-30	.0256	.0173	.0252	.0196				1.02		.78
10-45	.0156	.0109	.0208	.0167				.75		.80
11-10	.0660	.0528	.0648	.0488	.0613	.0476	350	1.02	.95	.75
11-15	.0486	.0259	.0372	.0276	.0461	.0336	300	1.31	1.24	.74
11-25	.0469	.0307	.0267	.0226	.0340	.0293	235	1.76	1.27	.85
11-30	.0240	.0166	.0148	.0118	.0259	.0223	358	1.62	1.75	.80
11-45	.0296	.0225	.0205	.0165	.0296	.0257	350	1.44	1.44	.80
12-10	.1480	.0770	.0500	.0434	.0573	.0434	8200	2.96	1.15	.87
12-15	.0945	.0559	.0430	.0365	.0680	.0570	8000	2.20	1.58	.85
12-25	.0928	.0515	.0432	.0370	.0468	.0382	8000	2.15	1.08	.86
12-30	.0704	.0467	.0220	.0212	.0350	.0303	8000	3.20	1.59	.96
12-45	.0796	.0595	.0247	.0209	.0240	.0209	8000	3.22	.97	.85

Blanks indicate that data were not available

of the lubricant on the coefficient of friction may not be as significant during the initial cycles at higher speeds.

The trends in the Series 7 and Series 10 tests were similar to those in Series 4 and 5. In the Series 7 tests, both the static and dynamic coefficients decreased over the first 2 cycles but increased and stabilized after about 10 cycles. The general trend in the Series 10 tests, carried out at  $-25^{\circ}\text{C}$  using No. 4 stainless steel, was for an increase in the static coefficient of friction over the first 5 cycles followed by relatively stable values up to 50 cycles. The appearance of this trend in Series 7, where the smooth stainless steel plate is used, indicates that the spread of the lubricant may be hindered by the lower temperature of this test. However, the lack of this trend in the comparison Series 11 tests, in which rough stainless steel plate is used, suggests that the influence of the lubricant on the coefficient of friction is less pronounced at low temperature. The behavior in the low temperature tests may also be influenced by icing in the TFE-stainless steel interface.

### ANALYSIS OF TEST DATA

On the basis of the preceding observations, it may be concluded that, with the exception of the first 5 cycles of move-

ment, the values of the coefficients of friction after 50 cycles of movement are representative. Consequently, further analyses are based on the static coefficient of friction at 50 cycles. Both static and dynamic values appear to follow the same basic trends.

The column headed (1)/(2) in both Tables 3 and 4 shows that the ratio of the initial coefficient of friction to that at 50 cycles does not appear to be dependent on contact pressure. However, this ratio increases with speed of movement and was as high as 5 in the Series 3 tests, in which the speed of movement was 20 mm/sec. The ratios in column (4)/(2) of Tables 3 and 4 indicate in most cases an increase in the coefficient of friction beyond 50 cycles. From column (3)/(2) in Tables 3 and 4 it can be seen that the ratio of the dynamic to static friction at 50 cycles varies from an average of 0.54 in Series 2 to 0.88 in Series 12. This ratio appears to be independent of contact pressure.

Data at 50 cycles from a number of the test series are presented in Figures 6, 7, and 8 in the form of plots of coefficient of friction against contact pressure. Also shown on each plot is the best fit to the data of the relationship given in Equation 1. It can be seen that reasonable fits are obtained for the data, particularly from the tests at  $20^{\circ}\text{C}$ . More scatter is apparent in the data from the tests at  $-25^{\circ}\text{C}$ . Values of

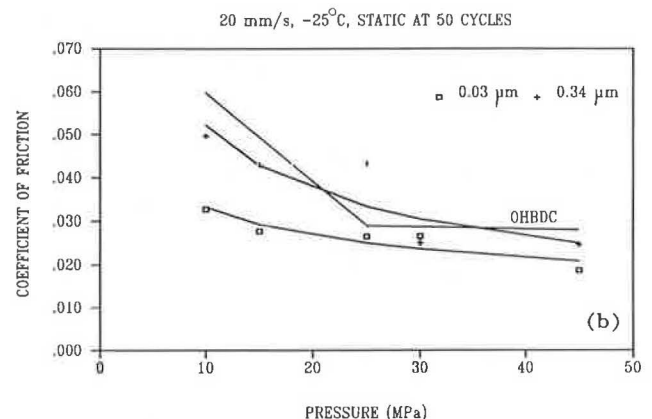
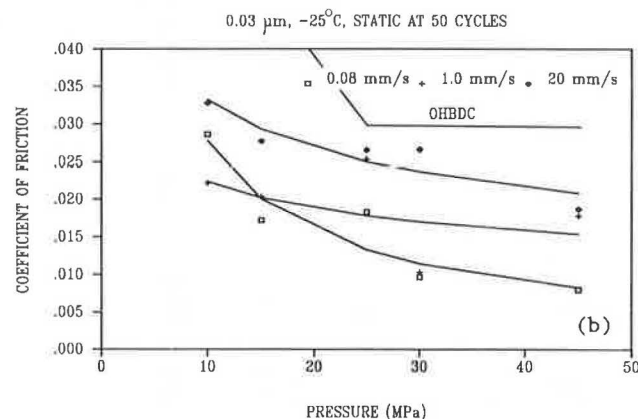
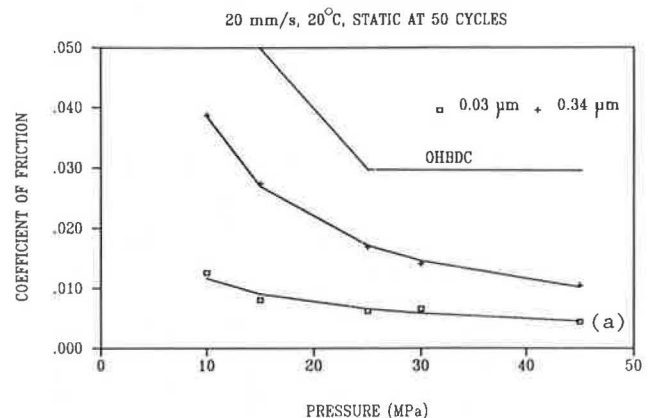
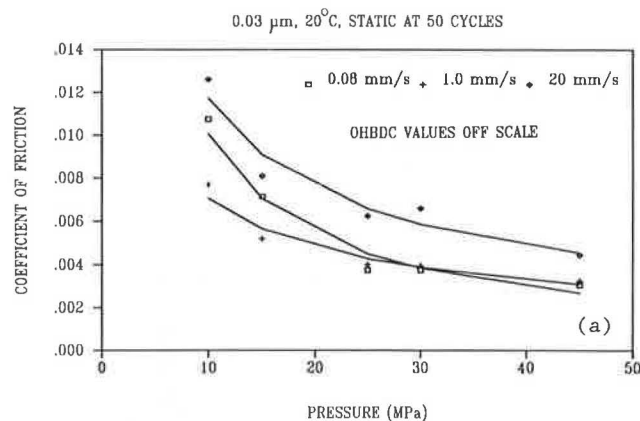


FIGURE 6 Influence of pressure, speed of movement, and temperature on the coefficient of friction.

FIGURE 7 Influence of pressure, surface roughness, and temperature on the coefficient of friction.

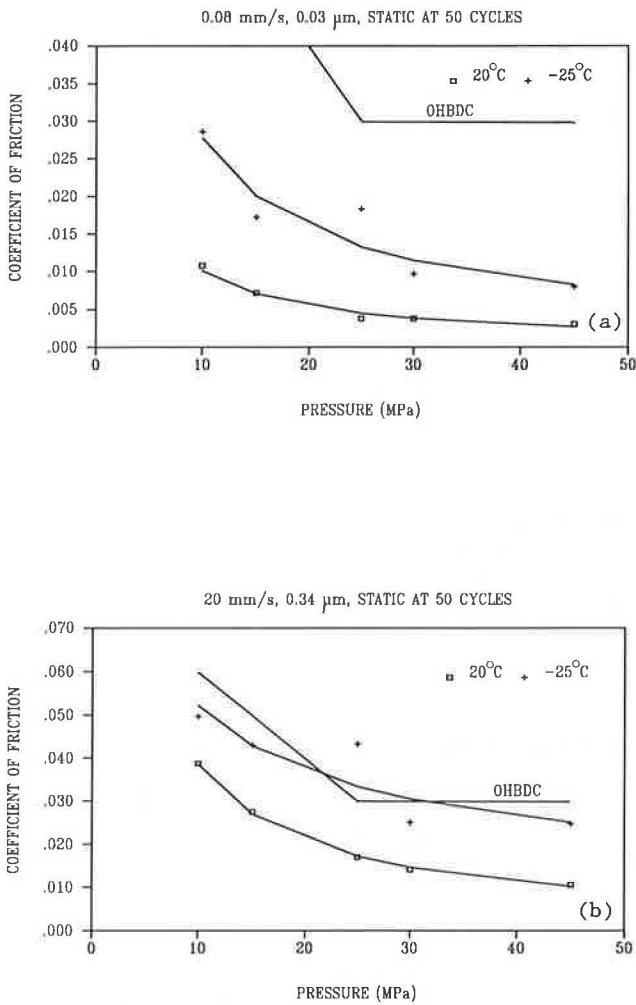


FIGURE 8 Influence of pressure, temperature, and surface roughness on the coefficient of friction.

the coefficient of friction specified in the Ontario Highway Bridge Design Code (2) for unfilled lubricated TFE sliding surfaces are shown on most of the plots in Figures 6, 7, and 8.

The influence of speed of movement for a particular temperature and surface roughness of the stainless steel is indicated in Figure 6, whereas the influence of surface roughness for a particular temperature and speed of movement and the influence of temperature for a particular speed of movement and surface roughness are indicated in Figures 7 and 8, respectively. All the plots in Figures 6, 7, and 8 show the established trend, in that the coefficient of friction of TFE decreases with increasing pressure under all conditions.

Data from tests using No. 8 finish stainless steel at 20°C and -25°C, respectively, are shown in Figures 6(a) and 6(b), which reflect the general trend observed by others that the coefficient of friction increases with speed of movement. It can be seen, however, that this is not the case under all conditions. Figure 6(a), relating to the tests at 20°C, indicates that the coefficient of friction at 0.08 mm/sec is greater than that at 1 mm/sec at contact pressures below 25 MPa, whereas Figure 6(b), relating to the tests at -25°C, indicates a similar

trend at contact pressures below 15 MPa. Further, it can be seen in Figure 6 that for the relevant combinations of the parameters, all measured values of the coefficient of friction are less than the specified values for unfilled TFE in the OHBDC (2).

The coefficient of friction is higher for the rougher (No. 4 finish) stainless steel, as seen in Figure 7. However, it appears that for a particular contact pressure the difference between the values of the coefficient of friction for the two finishes (Nos. 4 and 8) is similar at -25°C and 20°C. It is indicated in Figure 7(b) that the measured coefficient of friction exceeds the OHBDC value at contact pressures in the 20- to 30-MPa range at -25°C with a No. 4 finish stainless steel plate and a speed of movement of 20 mm/sec. However, this finish (0.34 μm) is rougher than the 0.25-μm finish permitted by the OHBDC.

It can be seen from Figure 8 that the coefficient of friction is larger at -25°C than at 20°C. Also it appears that the rate of decrease in the coefficient of friction with increasing contact pressure is lower for the rough stainless steel plate.

A single value of each of the two parameters,  $Q$  and  $n$ , used in Equation 1 to relate the coefficient of friction and the contact pressure, was obtained from each of the test series by means of a regression analysis. These 12 data points were insufficient to develop general relationships for the variation of  $Q$  and  $n$  with speed for the two conditions of temperature and roughness of the stainless steel. More test data are required.

## RECOMMENDATIONS FOR DESIGN AND FURTHER RESEARCH

The values of the coefficient of friction for unfilled TFE, as given by the OHBDC, are higher than those obtained after 50 cycles for all conditions simulated in the test program, with the exception of the high-speed tests at -25°C using a rough stainless steel plate in the 20- to 30-MPa range. Because smooth (No. 8 finish) stainless steel is normally used for bearings manufactured in Ontario, the OHBDC values may be considered conservative for temperatures as low as -25°C and speeds of movement up to 20 mm/sec, provided that it is permissible to design structures for the static coefficient of friction at 50 cycles.

A comparison between the values of the initial static coefficient of friction from the tests using the No. 8 finish stainless steel and those specified in the OHBDC is shown in Table 5. It can be seen that if structures are to be designed for the initial level of friction, the OHBDC values may be unconservative, particularly at a temperature of -25°C and a speed of 20 mm/sec (Series 9 tests). The initial coefficient of friction in this case may be as high as 2.8 times the OHBDC value.

Because the coefficient of friction decreases rapidly during the first few cycles of movement and changes little between 5 and 50 cycles, it appears that significant benefits, in the form of a reduction in the specified coefficient of friction for design, could be achieved if the initial coefficient of friction of TFE could be reduced. This may be possible by subjecting the sliding surface to cyclic movement before installation of a bearing. Other possible means of reducing the initial coefficient of friction should also be explored.

TABLE 5 COMPARISON OF TEST AND OHBDC VALUES FOR THE COEFFICIENT OF FRICTION

Test No.	Coefficient of Friction		Initial/OHBDC
	Initial	OHBDC	
1-10	0.0116	0.06	0.193
1-15	0.0135	0.05	0.270
1-25	0.0058	0.03	0.193
1-30	0.0055	0.03	0.183
1-45		0.03	
2-10	0.0136	0.06	0.227
2-15	0.0140	0.05	0.280
2-25		0.03	
2-30		0.03	
2-45	0.0086	0.03	0.287
3-10	0.0334	0.06	0.557
3-15	0.0473	0.05	0.946
3-25	0.0338	0.03	1.127
3-30	0.0290	0.03	0.967
3-45	0.0230	0.03	0.767
7-10	0.0603	0.06	1.005
7-15	0.0232	0.05	0.464
7-25	0.0225	0.03	0.750
7-30	0.0143	0.03	0.477
7-45	0.0084	0.03	0.280
8-10	0.0549	0.06	0.915
8-15	0.0387	0.05	0.774
8-25	0.0576	0.03	1.920
8-30	0.0229	0.03	0.763
8-45	0.0537	0.03	1.790
9-10	0.1000	0.06	1.667
9-15	0.1120	0.05	2.240
9-25	0.0809	0.03	2.697
9-30	0.0844	0.03	2.813
9-45	0.0590	0.03	1.967

The ratio of the initial coefficient of friction to that at 50 cycles increases with sliding speed, as shown in Columns (1)/(2) of Tables 3 and 4. Sliding speeds at the bearings of typical bridge structures should be determined from field tests in order to establish upper limits for the sliding speed.

## CONCLUSIONS

On the basis of the coefficient of static friction after 50 cycles of movement, unless otherwise stated, the following conclusions may be drawn from the data obtained in this test program:

1. The coefficient of friction decreases with increasing pressure over the range 10 to 45 MPa.
2. The general trend is an increase in the coefficient of friction with sliding speed over the range 0.08 to 20 mm/sec.

3. The coefficient of friction increases with roughness of the stainless steel plate over the range 0.03 to 0.34  $\mu\text{m}$ .

4. The coefficient of friction increases with decrease in temperature over the range 20° to 25°C.

5. Values of the coefficient of friction given for unfilled TFE in the OHBDC indicate the proper trend and are conservative except for the rough stainless steel plate at -25°C and a travel speed of 20 mm/sec.

6. The initial coefficient of friction can be as high as five times that after 50 cycles of movement.

7. The coefficient of friction generally decreases rapidly during the first 5 cycles of movement, remains fairly constant up to 50 cycles, increases slightly from 50 to 1,000 cycles, and then again remains fairly constant up to as many as 10,000 cycles.

8. The dynamic coefficient of friction is lower than the static coefficient but follows the same trend with an increasing number of cycles.

9. The relationship of Equation 1 gives a reasonably good fit to the test data, but more data are required in order to establish values of the parameters  $Q$  and  $n$ .

10. Possible means of reducing the initial coefficient of friction should be explored.

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## REFERENCES

1. T. I. Campbell and W. L. Kong. *TFE Sliding Surfaces in Bridge Bearings*. Report ME-87-06. Ministry of Transportation and Communications, Downsview, Ontario, Canada, July 1987, 57 pp.
2. *Ontario Highway Bridge Design Code*, 2nd ed. Ministry of Transportation and Communications, Downsview, Ontario, Canada, 1983.
3. M. E. Taylor. *PTFE in Highway Bridge Bearings*. Report TRRL-LR-491. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, 1972, 62 pp.
4. W. I. J. Price. *Transmission of Horizontal Forces and Movements by Bridge Bearings, Joint Sealing and Bearing Systems for Concrete Structures*. ACI Publication SP-70, Vol. 2. American Concrete Institute, Detroit, Mich., 1982, pp. 761-784.
5. *Standard Specifications for Highway Bridges*, 13th ed. American Association of State Highway and Transportation Officials, Washington, D.C., 1983.
6. T. I. Campbell and W. L. Kong. *Laboratory Study of Friction in TFE Sliding Surfaces for Bridge Bearings*. Report MAT-89-04. Ministry of Transportation, Downsview, Ontario, Canada, Feb. 1989, 66 pp.

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