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SUMMARY

An experimental investigation was conducted to evaluate the friction and wear characteristics of wire-brush skids fabricated from 17-7 PH stainless-steel wire. The testing technique consisted of towing the skids with a ground test vehicle over asphalt and concrete surfaces at ground speeds up to 80 km/hr (50 mph) and bearing pressures up to 689 kPa (100 psi) over sliding distances up to 1585 m (5200 ft).

Results of this investigation indicate that the friction coefficient developed by wire-brush skids is essentially independent of ground speed, is slightly increased with increasing bearing pressure, is noticeably affected by surface texture, and is not degraded by surface wetness. Skid wear is shown to increase with increasing bearing pressure and with increasing ground speed and is dependent on the nature of the surface. Runway surface damage caused by the skids was in the form of an abrasive scrubbing action rather than physical damage.

INTRODUCTION

Research programs to improve the stopping performance of aircraft, particularly under slippery runway conditions, have indicated a need to explore new braking concepts capable of assuring adequate braking and aircraft stability during landing and rejected take-off operations. Reference 1 describes a wheel and skid landing-gear concept in which the conventional brake is replaced by one or more wire-brush skids and has potential application to aircraft whose operations are almost exclusively in adverse weather. However, for spacecraft returning to Earth, a landing gear featuring only skids may be more appropriate. Without tires and wheels, this latter approach could require less storage volume, could be simpler and lighter in construction, and could be made of materials capable of withstanding the reentry environment. These conditions would negate the need for thermal protection. With skids alone, the spacecraft could land on a variety of runway surfaces, wet or dry, and require shorter stopping distances. Such a landing system, however, places severe demands on the shock strut, requires new steering techniques, and suffers from the lack of design and operational experience.

Skid research was conducted in the early sixties by NASA (ref. 2) and others (refs. 3 to 6). In reference 2 the friction-speed relationship of wire-brush skids appeared more desirable than that of flat-plate skids. However, those studies were made at relatively low skid bearing pressures (152 kPa (22 psi) in ref. 2). For skids to be appropriate as a landing gear for spacecraft and as a brake replacement for aircraft, the skids must operate at considerably higher bearing pressures since weight and available volume is restricted. In addition, the skids must be capable of developing the necessary drag to stop the vehicle within defined limits, must have good wear-resistant properties, and must cause minimum runway surface damage. The purpose of this investigation was to extend these early friction and wear studies on wire-brush skids to bearing pressures consistent with the potential needs of current and future aircraft and spacecraft.

Laboratory studies conducted on a number of wire types and reported in reference 1 identified several wires that would be suitable for use in the fabrication of a skid. For the purpose of this investigation, skids were fabricated from wire selected on the basis of good friction and wear characteristics combined with availability and low cost. The skids were tested on asphalt and concrete surfaces under bearing pressures of 345, 517, and 689 kPa (50, 75, and 100 psi) over a speed range of 32 to 80 km/hr (20 to 50 mph). Measurements were made of skid friction and wear over sliding distances up to 1585 m (5200 ft), and an attempt was also made to determine the extent of runway surface damage due to skid operations.

APPARATUS AND TEST PROCEDURE

Skids

Friction and wear tests were conducted on four wire-brush skids fabricated from two wire sizes. Figure 1 is a photograph of the test skids before and after testing and table I lists their significant characteristics. Also identified in the figure and in the table is a flat-plate skid which was tested on a limited basis for comparison purposes. The wire-brush skids differed in the diameter of the wire and in the size of the individual bundles or knots. The wire diameters were 0.76 and 0.51 mm (0.030 and 0.020 in.) and the diameters of the knots were 9.5 and 4.7 mm (0.38 and 0.19 in.). In all cases, the wire was 17-7 PH stainless steel, heat treated to spring temper (Cond. "CH"), with a density of 7670 kg/m^3 (0.277 lbm/in^3). This wire was chosen because of its favorable friction and wear characteristics determined from laboratory tests described in reference 1 and because of its reasonable cost. In constructing the skid, holes were drilled into a 1.59-cm- (0.625-in.-) thick aluminum backing plate and the appropriate number of wires were potted into each hole with a high-temperature potting compound. The holes were 9.5 cm (0.38 in.) in depth and either 9.5 or 4.7 mm (0.38 or 0.19 in.) in diameter, depending on the size of the knot employed. The free length or trim length of the wire prior to testing was 5.08 cm (2.0 in.), and the envelope of the wire contact area for the skids was maintained at approximately 12.4 cm wide by 33.3 cm long (4.9 in. by 13.1 in.). The flat-plate skid was fabricated from AISI type 416 stainless steel with a density of 7750 kg/m^3 (0.28 lbm/in^3) annealed to Condition A. The flat-plate skid was 19 cm (7.5 in.) long, 7.6 cm (3.0 in.) wide, and 1.27 cm (0.5 in.) thick to provide a bearing area with an aspect ratio comparable to that of the wire-brush skids.

Test Surfaces

Tests for this investigation were conducted on the asphalt and concrete surfaces available on the landing research runway at the NASA Wallops Flight Center. The asphalt test surface had a smooth sand finish and was 396 m (1300 ft) in length. The concrete test surface consisted of two sections -

one with a burlap-belt finish and the other with a canvas-belt finish. Each concrete section was approximately 152 m (500 ft) in length and a test on the concrete surface included both sections. The texture of the concrete with the burlap-belt finish was much coarser than that of the concrete with the canvas-belt finish or the asphalt surface as indicated by measurements taken of the average texture depth of the different surfaces using the grease sample technique described in reference 7. The average texture depth was 0.455 mm (0.0179 in.) on the burlap-belt finish, 0.254 mm (0.0100 in.) on the canvas-belt finish, and 0.244 mm (0.0096 in.) on the asphalt surface.

Ground Test Vehicle and Instrumentation

The ground test vehicle used in this investigation is shown in the photograph of figure 2 and a closeup of the test fixture mounted at the rear of the vehicle is presented in figure 3. The skids were attached to a dynamometer which was instrumented to measure the applied vertical load on the skid and the drag load developed when operating on the runway test surfaces. The dynamometer, in turn, was mounted in the test fixture which was equipped with pneumatic cylinders for raising and lowering the skids onto the test surface and for applying the vertical load to achieve the desired ground bearing pressure. The skids were restrained in yaw but free to move several degrees in both pitch and roll to accommodate minor surface irregularities, such as expansion joints. An instrumented trailing wheel (fig. 3) towed by the ground vehicle measured both ground speed and the distance traveled. Continuous time histories of the outputs of the instrumentation during testing were recorded by an oscillograph mounted in the test vehicle.

Test Procedure

The testing technique consisted of making a number of passes at a constant speed with a skid sliding along the runway surface and monitoring the test distance, the speed, the vertical and drag loads on the skid, and the extent of skid wear. During the course of a test, the ground vehicle was brought to the desired test speed and the skid was lowered onto the surface and allowed to slide for approximately 396 m (1300 ft) under the preselected applied vertical load. Wire-brush skid wear was obtained by removing the skid from the test fixture after each pass, cleaning it of dust particles, and measuring the weight and the wire trim lengths. This procedure was repeated on the same skid under the same test conditions for as many as four passes.

Each wire-brush skid was tested on asphalt and concrete surfaces at bearing pressures of 345, 517, and 689 kPa (50, 75, and 100 psi). The bearing pressures of this investigation were net bearing pressures in that they were determined by dividing the vertical load on the skid by the area in actual contact with the surface. In the case of the wire-brush skids this area was the total cross-sectional area of all the wires that constituted a skid.

A separate wire-brush skid was used for each bearing pressure and for each ground speed on the two test surfaces. Likewise, a separate flat-plate skid was used for each of the three bearing pressures over the range of ground speeds on asphalt, and another skid was used, at a bearing pressure of 517 kPa (75 psi) only, on the concrete surface.

Nominal ground speeds for these tests were 32, 64, and 80 km/hr (20, 40, and 50 mph). The majority of tests were made on a dry surface; however, some tests were made with each skid on a wetted asphalt surface. For these tests, the surface was wetted to a minimum depth of 0.76 mm (0.03 in.). For all tests, wet or dry, an effort was made during each pass to avoid previous skid tracks.

RESULTS AND DISCUSSION

The drag friction coefficient and wear were determined for each of the four skids at each test condition. The friction coefficient was obtained by dividing the drag force developed between the skid and the runway surface by the vertical load applied to the skid. Oscillations occurred in both the drag and vertical forces about a faired level which remained essentially constant throughout each pass. These oscillations were more pronounced on the concrete surface than on the asphalt and were attributed to motions in the test fixture and vehicle, runway roughness, and a self-excitation due to a stick-slip phenomenon typical of skids. Skid self-excitation can cause a skid-type landing gear to become dynamically unstable. This problem is examined in references 8 and 9. A wear index was obtained for each skid-surface combination by relating the skid wear to the sliding distance. The following sections discuss the friction coefficients and wear indexes obtained with the skids under the various test conditions.

Friction Coefficient

All the friction data obtained with the four wire-brush skids on the dry asphalt and concrete surfaces are presented in figure 4. The figure shows that the level of friction coefficient developed by these skids is typically between 0.4 and 0.8. Friction coefficients developed by the flat-plate skid on the same dry surfaces are presented in figure 5. The effect of ground speed and bearing pressures on the friction coefficient developed by the skids is discussed with the aid of these figures in the following paragraphs. Subsequent paragraphs, with the aid of figures 6 and 7, describe the effects on the friction level attributed to the runway surface and the surface wetness condition. The section concludes with a brief comparison of skids in terms of developed friction.

Ground speed.- The effect of ground speed on the friction coefficient for the different wire-brush skids is illustrated in figure 4 for the three test bearing pressures. The figure shows that at a given bearing pressure, the friction coefficient is essentially unaffected by changes in the ground speed. Friction coefficients developed by the flat plate, on the other hand, are seen (fig. 5) to decrease distinctly with increasing ground speed on both the asphalt and concrete surfaces.

Bearing pressure.- The data of figure 4 also indicate that, in general, the friction coefficient developed by the wire-brush skids at a given ground speed remained constant or increased slightly with increasing bearing pressure. This trend was observed in the tests of reference 1 on the same wire material. The flat-plate skid data of figure 5 suggest the opposite trend, as the friction coefficients for the higher bearing pressures appear to be slightly lower than those for the lower pressures.

Runway surface.- The friction coefficients developed by wire-brush skids B and D at a bearing pressure of 689 kPa (100 psi) and the flat-plate skid at a pressure of 517 kPa (75 psi) are replotted in figure 6 to illustrate the effect runway surface has on the friction capability of skids. Skids B and D were chosen because most of the test data were acquired with these skids. The figure shows that, for all skids, the friction developed on the test surfaces used in this investigation was higher on the concrete than on the asphalt surface. This difference is attributed to surface texture. The relatively smooth asphalt surface produced less drag on the skids than the coarser concrete. Similarly, the coarse texture of the concrete with the burlap-belt finish created more drag on the skids than the smoother canvas-belt finish as indicated by the data for skid D. In addition, the friction level was probably influenced by the shear strength of the surface particles. The cement used in concrete runway construction is stronger than the binder used in asphalt runways; hence, a higher drag force is required to shear the concrete surface particles, and higher values of friction coefficient are produced.

Surface wetness.- For one series of tests the asphalt runway was wetted to a minimum water depth of 0.76 mm (0.03 in.) in an attempt to obtain an indication of the effect of the lubrication provided by surface wetness on the skid friction characteristics. The results from these tests are presented in figure 7 together with the results from corresponding tests conducted when the surface was dry. The data show that the friction coefficient developed by the wire-brush skids, unlike braked tires, was not degraded by surface wetness. In fact, the level of friction developed on the wet surface by the wire-brush skids was higher than that obtained on the dry surface, perhaps as a result of the cooling effect provided by the water which reduced structural losses in the skid due to heat. As expected, the level of friction developed by the flat-plate skid was lower on the wet surface than on the dry because of lubrication effects. The data obtained with the flat-plate skid show that friction coefficient was affected by ground speed on the wet surface as well as on the dry.

Comparison of skids.- The bar graph in figure 8 compares the friction coefficient developed by the different skids at two bearing pressures and two ground speeds on the asphalt runway. The figure shows that wire-brush skid A developed the highest value of friction coefficient and skid D the lowest. In general, the wire-brush skids fabricated of smaller wire diameter and/or smaller knot diameter developed the highest friction coefficients. The flat-plate skids developed respectable values of friction coefficient, but, as shown previously, are affected more by ground speed, bearing pressure, and surface wetness than are the wire-brush skids.

Although the tests in this investigation were made at low ground speeds, the data have indicated that a suitable friction coefficient was developed by wire-brush skids and was essentially independent of forward speed and surface wetness and is generally increased slightly with increasing bearing pressure. Hence, it appears that wire-brush skids are capable of developing constant friction levels as high as or higher than those developed by an antiskid-braked wheel with a rubber tire on a dry surface. The major improvement, however, would be anticipated at the high ground speeds, particularly when the surface is wet.

Skid Wear

Figure 9 shows the measured skid weight loss, which was confirmed by trim length measurements, at intervals of approximately 396 m (1300 ft) over a total sliding distance of 1585 m (5200 ft) for wire-brush skids B and D on the dry asphalt runway. The data of this figure include the three test bearing pressures, and the ground speed was a nominal 80 km/hr (50 mph). The data illustrate the linear relationship which exists between the skid wear and the traversed distance. Skid wear over a given distance is shown to increase with increasing bearing pressure. The slope of curves such as those of figure 9 describes the skid wear in terms of mass loss per unit sliding distance. A direct comparison of wear between the various test skids is not meaningful, however, since their contact areas differed. (See table I.) Thus, to permit skid comparisons, a wear index was calculated for each skid. The index is defined as the ratio of the volume of skid material removed to the skid contact area per unit sliding distance. Unlike friction measurements, wear measurements on the concrete surface included that which took place on the combined canvas-belt and burlap-belt finishes. The wear indexes for all wire-brush skids are summarized in figure 10 to show the effects of ground speed and bearing pressure. These effects, together with a comparison of skid wear characteristics, are discussed in the following paragraphs.

Ground speed.- The variation of the wear index with ground speed for the wire-brush skids at various bearing pressures on asphalt and concrete surfaces is shown in figure 10. The closed symbols are used to denote when some wires in the skid failed because of fatigue, which is attributed to frictional self-excitation. The wires in skids A and C, the smaller knot size, showed a greater tendency to fail than those in skids B and D, and this failure was especially pronounced on the concrete surface. In tests where wire fatigue occurred, the wear index was determined from the wire trim length rather than actual weight loss. The data of figure 10 indicate that at a given bearing pressure the wear increases with increasing ground speed on both test surfaces. The increase in wear is attributed to an increase in temperature which occurs with increasing speed at the skid contacting surface. The contact surface of some skids was discolored from heat after testing, and temperatures of this surface, measured by a pyrometer within 1 min after completion of each pass, reached values up to 176° C (350° F). Higher temperatures were noted when the skids were operating on the concrete surface than on the asphalt surface.

Bearing pressure.- Figure 10 also shows the effect of bearing pressure on wire-brush skid wear. The data indicate that on both asphalt and concrete surfaces at a given ground speed skid wear increased appreciably with increasing bearing pressure. The data also show that the rate of wear increase with ground speed typically was greater at the higher bearing pressure and was more pronounced on the concrete surface than on the asphalt surface. The increased wear at the higher bearing pressure is probably also influenced by the high temperatures generated at the skid contact surface.

Runway surface.- The effect of runway surface on skid wear for skids B and D at bearing pressures of 345 and 689 kPa (50 and 100 psi) is shown in figure 11. The data show that the level of skid wear and the rate of wear increased with ground speed and were higher on the concrete surface than on asphalt, probably for the same reasons given previously for the friction coefficient, namely, the greater shear strength and surface texture of the concrete.

Comparison of skids.- The bar graph in figure 12 compares the wear of the wire-brush skids on the asphalt surface at two bearing pressures and ground speeds. The data show that, in general, the skids fabricated from the larger diameter knots, skids B and D, exhibited the better wear characteristics. As was shown in figure 8, it appears that low wear rates are generally accompanied by low friction levels.

Runway Surface Damage

One possible detrimental effect of using skids to provide the braking force for an airplane or spacecraft is the damage the skids could impart to the runway surface. An indication of runway surface wear caused by the skids used in this investigation was obtained by measuring the average texture depth of the surface in the skid track and the average texture depth in an adjacent untrafficked area and comparing the two. The results gave no significant difference in the texture depths. Visual inspection of the skid tracks showed very little surface damage as evidenced by the photographs of the skid tracks in figure 13. These skid tracks were made by towing the skids over a concrete surface under a bearing pressure of 689 kPa (100 psi). Skid tracks on the asphalt surface were hardly visible. The surface damage that did occur appeared to be more in the form of an abrasive scrubbing action rather than physical damage, and movies as well as general observations showed that the skids created considerable dust during the tests. Perhaps more serious than the dust, runway contamination in the form of broken wires from skids A and C, the smaller knot size, could cause problems, especially on concrete surfaces such as those of this investigation.

CONCLUDING REMARKS

An investigation was conducted to examine the friction and wear characteristics of wire-brush skids and the friction characteristics of a flat-plate skid. The testing technique consisted of attaching the skids to a test fixture mounted on a ground vehicle and sliding the skids over both asphalt and concrete surfaces. Skid drag force and wear behavior were monitored at bearing pressures from 345 to 689 kPa (50 to 100 psi) over distances up to 1585 m (5200 ft) at ground speeds from 32 to 80 km/hr (20 to 50 mph).

Under the test conditions of this investigation, the friction coefficient developed by wire-brush skids was found to be essentially independent of ground speed, increased slightly with increasing bearing pressure, and was noticeably a function of runway surface texture. Friction coefficients ranged from 0.4 to 0.6 on the asphalt surface and from 0.4 to 0.8 on concrete. These constant levels of friction are as high as or higher than those developed by an antiskid-braked wheel with a rubber tire on a dry surface. However, unlike braked tires, the skid friction coefficient was not degraded by a wet surface. Surface wetness and increases in ground speed and bearing pressure appeared to have an adverse effect on the friction coefficient developed by the flat-plate skid. Skid wear was shown to increase with increasing bearing pressure and ground speed and was greater on the concrete surface than on the asphalt surface.

No runway surface damage was caused by the skids other than an abrasive scrubbing action. However, runway contamination in the form of broken wires from the brushes with a smaller knot size could create problems.

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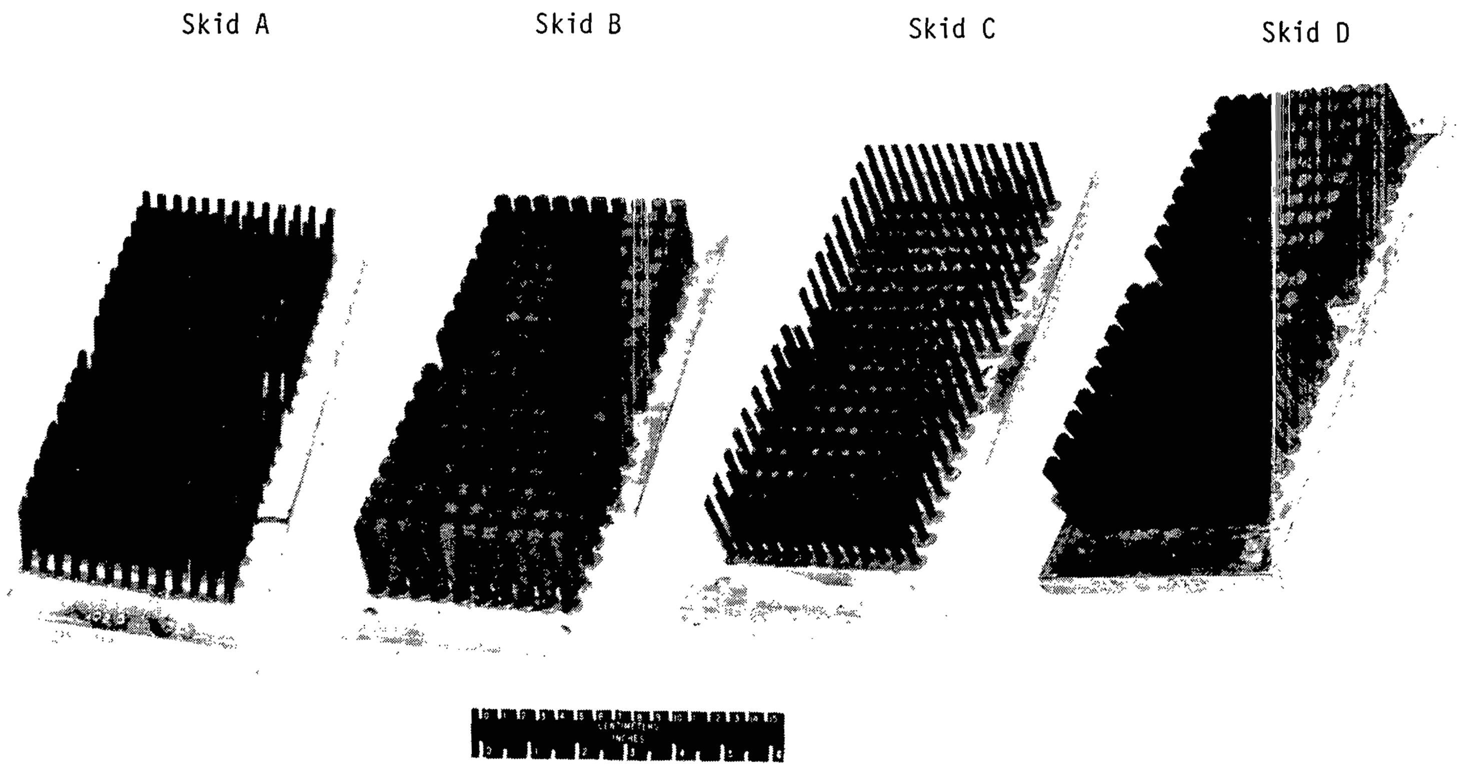
TABLE I.- TEST SKID PARAMETERS

[Wire-brush skid initial trim length, 5.08 cm (2.00 in.); 17-7 PH stainless-steel wire]

Wire-brush skid	Wire diameter		Knot diameter		Wires per knot	Knots per skid	Skid contact area		Initial mass of wire	
	mm	in.	mm	in.			mm^2	in^2	kg	lbm
A	0.51	0.020	4.7	0.19	50	243	2464.6	3.82	0.96	2.11
B	.51	.020	9.5	.38	225	186	8484.4	13.15	3.30	7.28
C	.76	.030	4.7	.19	26	243	2877.6	4.46	1.12	2.47
D	.76	.030	9.5	.38	115	186	9755.4	15.12	3.80	8.39
Flat-plate skid (AISI type 416 stainless steel)	Dimensions - 19 × 7.6 × 1.27 cm (7.5 × 3 × 0.5 in.) Contact area - 145.0 cm^2 (22.5 in^2) Initial mass - 1.5 kg (3.31 lbm)									



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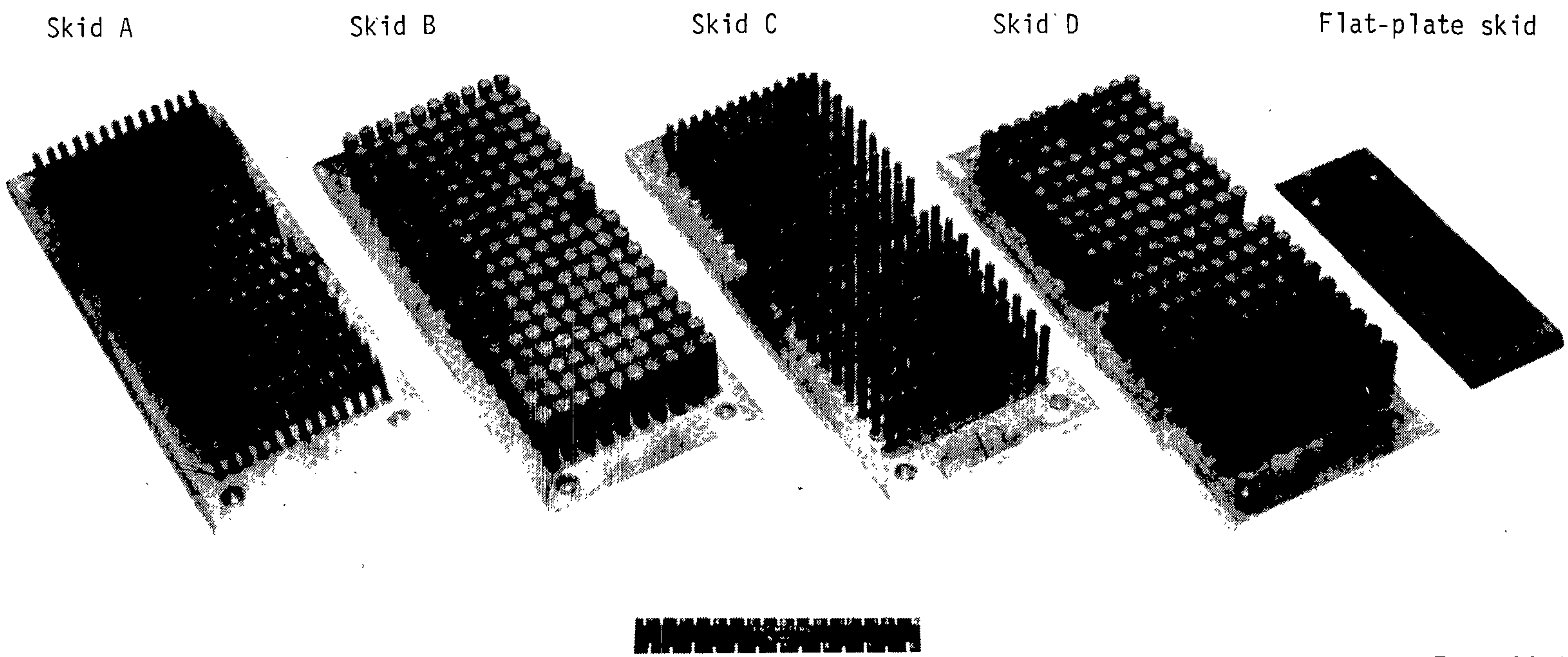
(a) Before tests.

Figure 1.- Photograph of test skids.



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(b) After tests.

Figure 1.- Concluded.

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Figure 2.- Ground test vehicle used in tests.

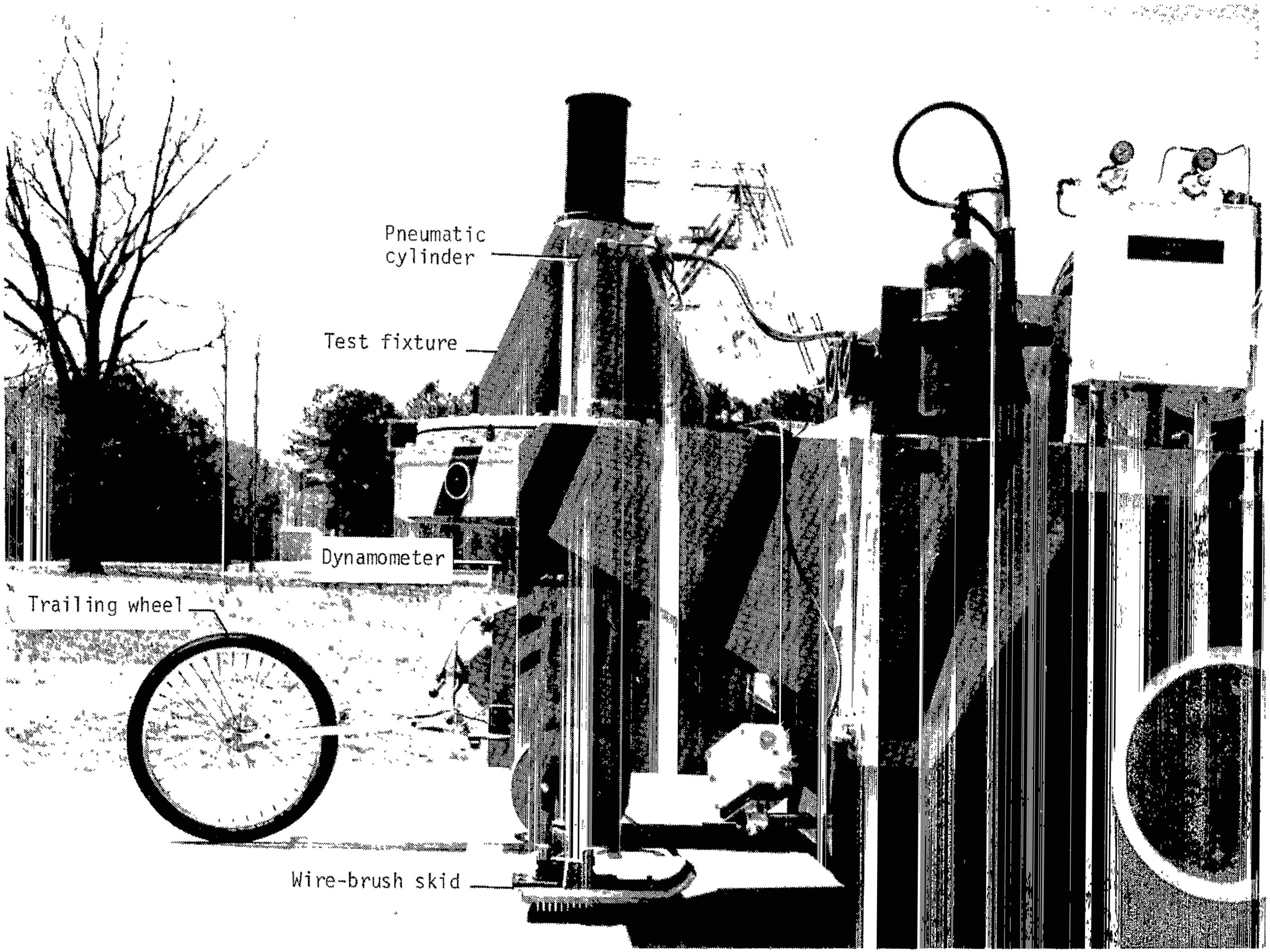

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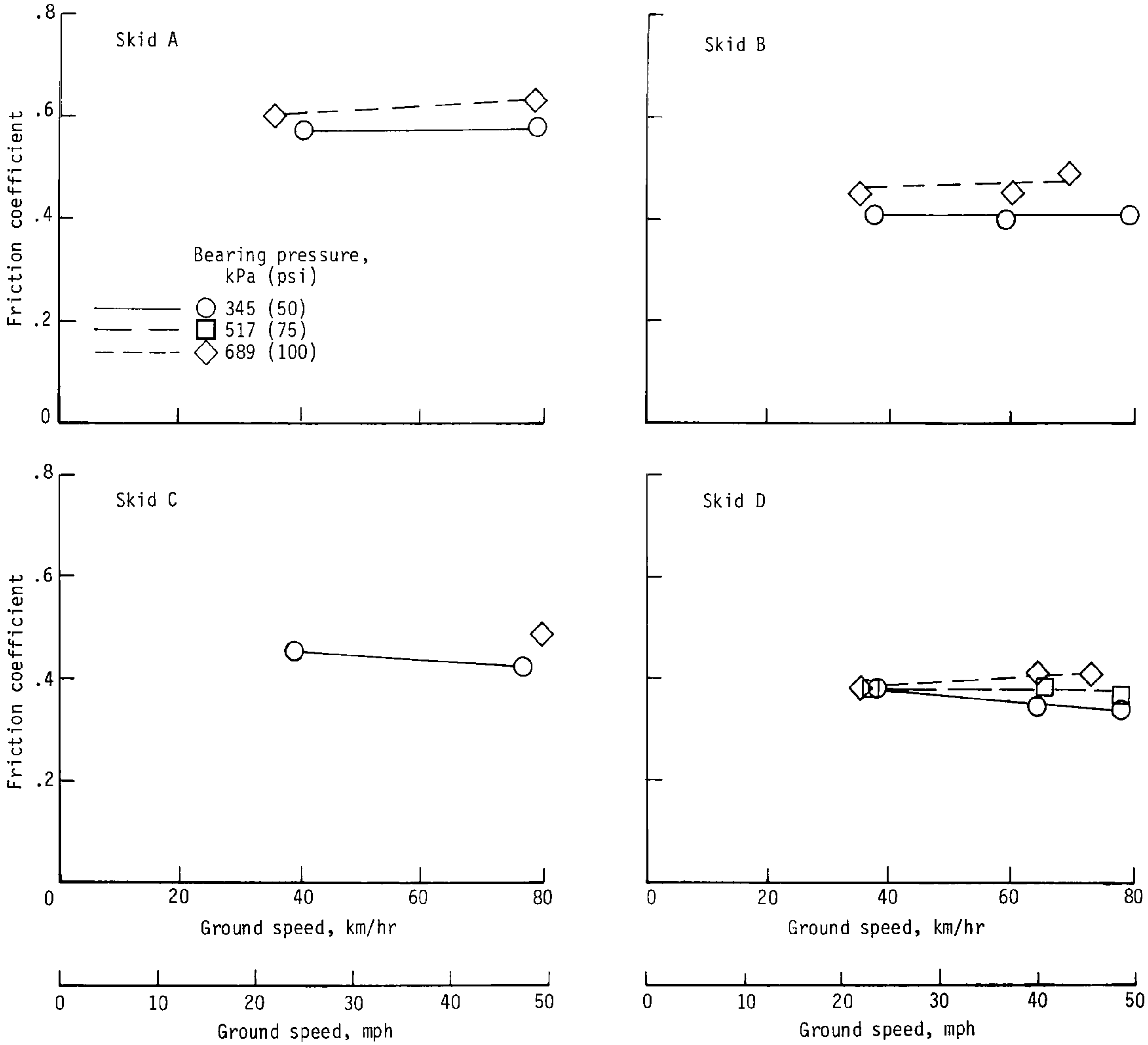
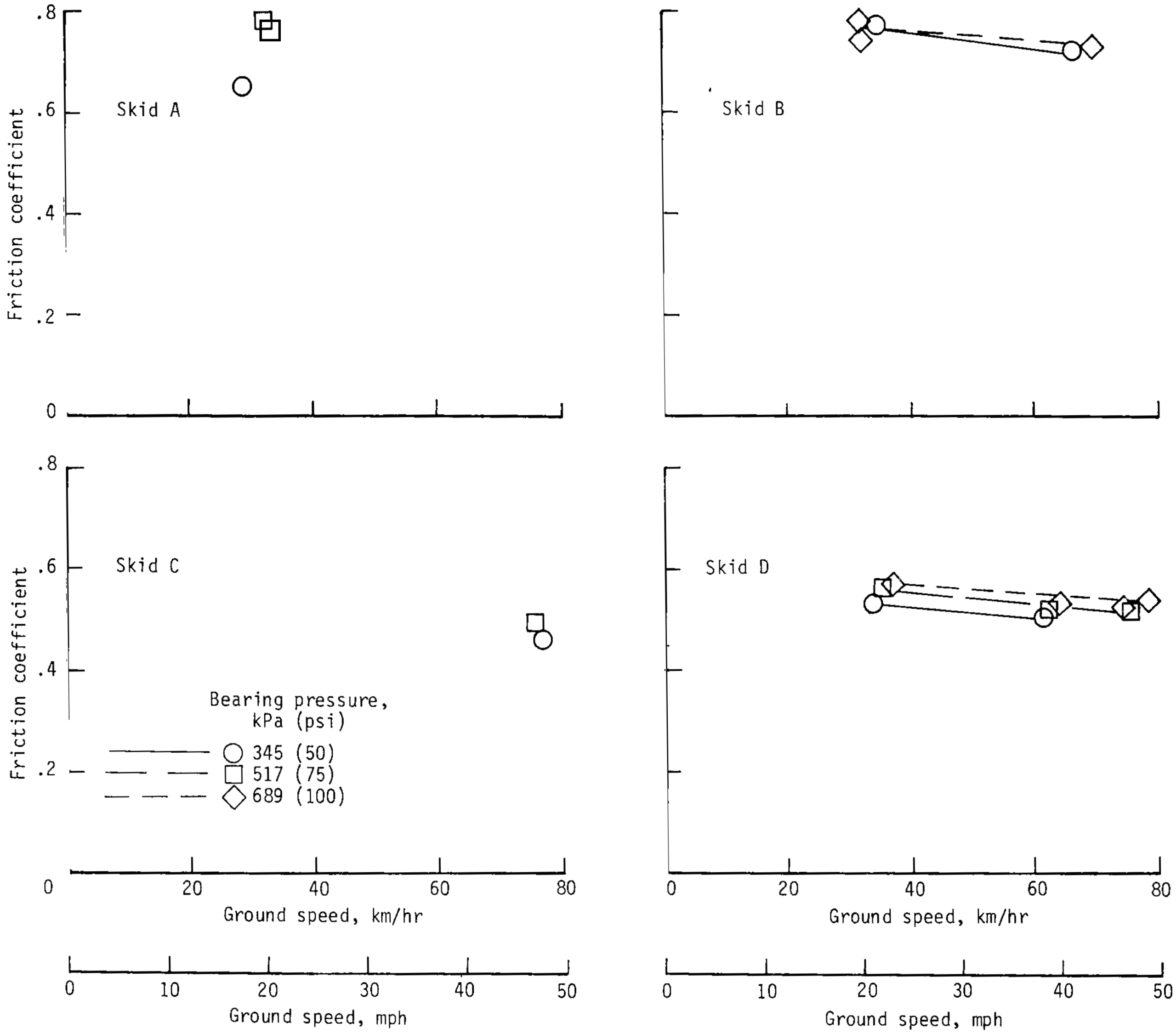
Figure 3.- Closeup of test fixture mounted on ground test vehicle.



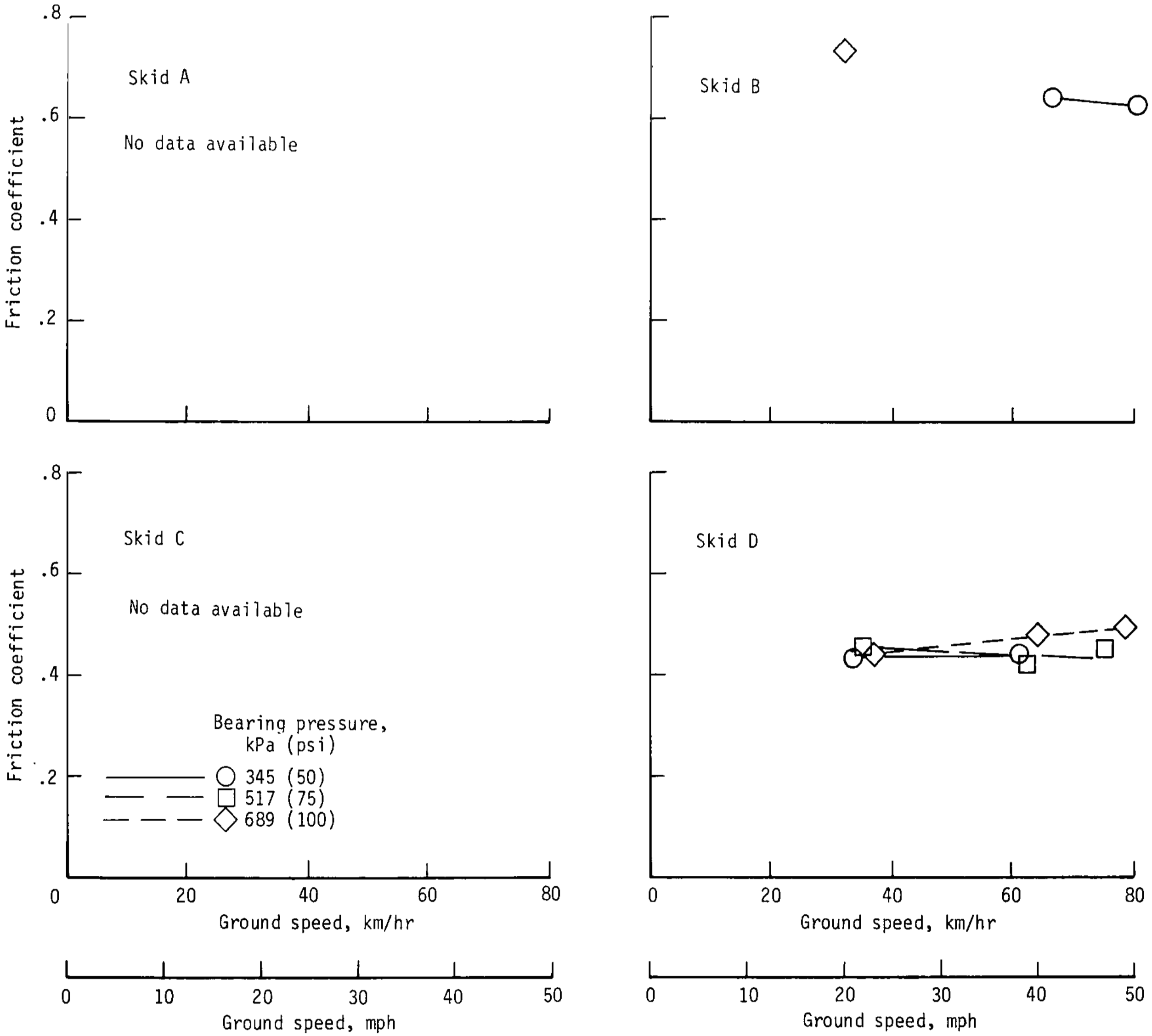
(a) Asphalt.

Figure 4.- Variation of friction coefficient with ground speed for wire-brush skids on the various dry test surfaces.



(b) Burlap-belt finish concrete.

Figure 4.- Continued.



(c) Canvas-belt finish concrete.

Figure 4.- Concluded.

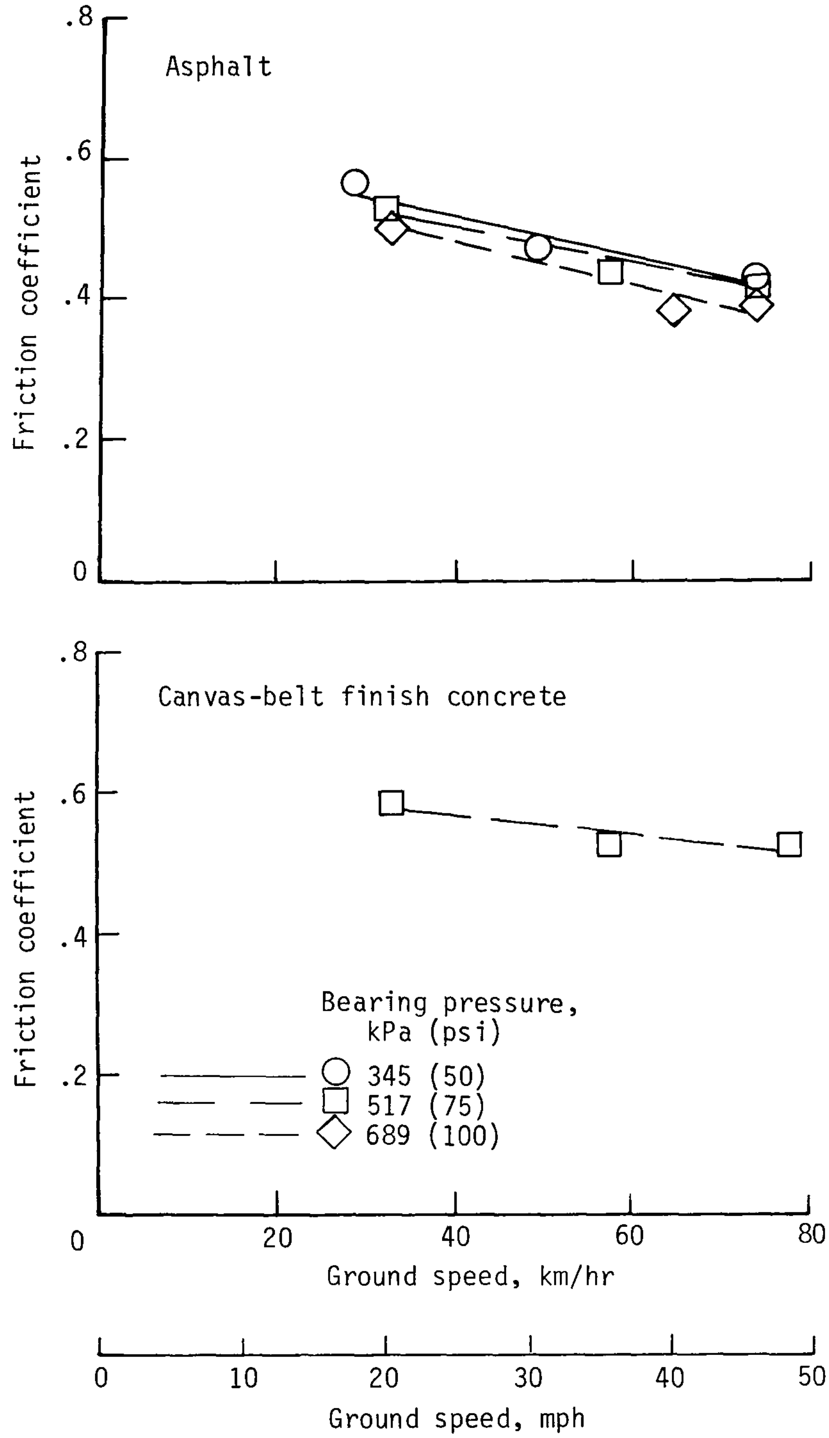


Figure 5.- Variation of friction coefficient with ground speed for flat-plate skid on asphalt and concrete.

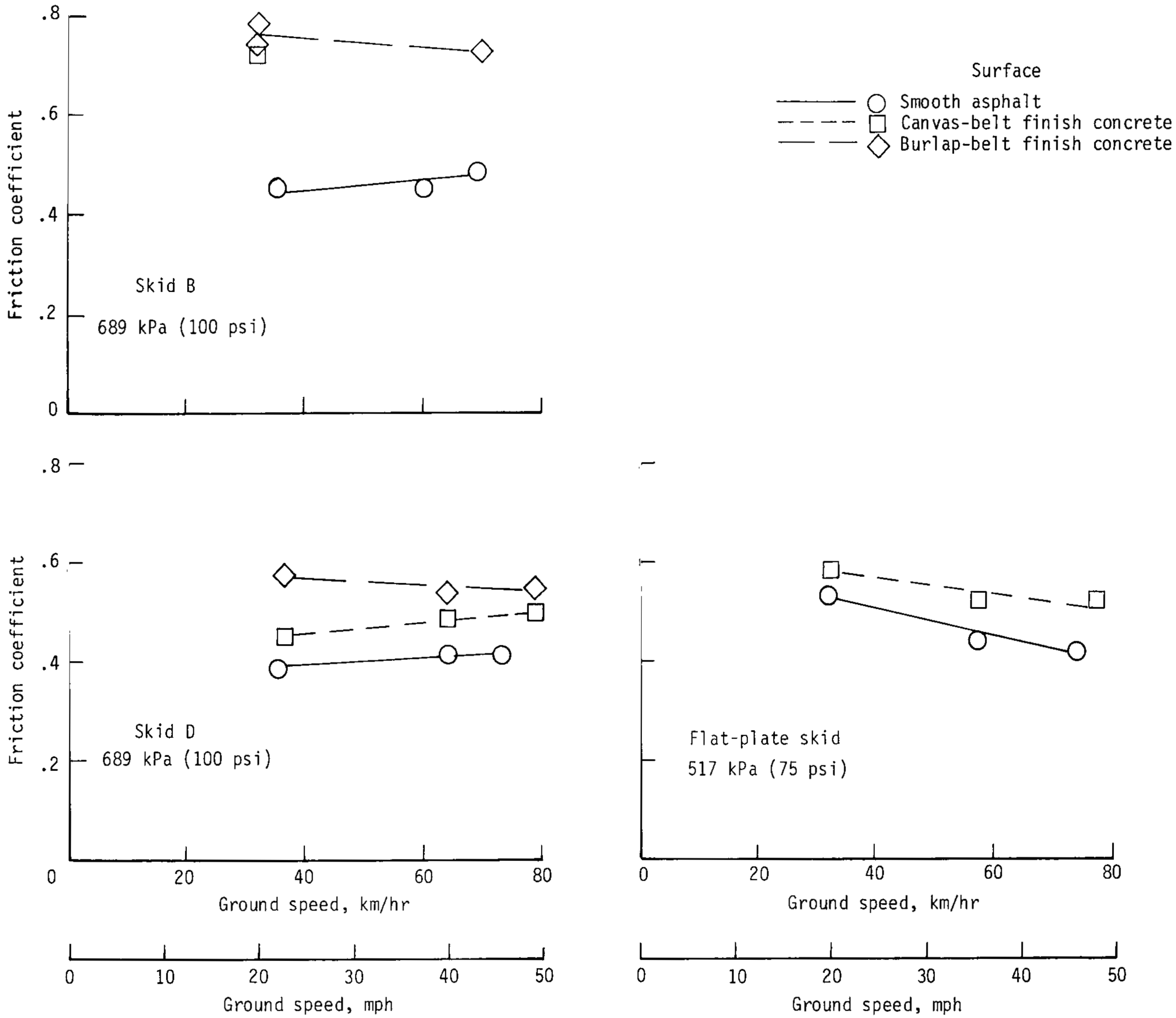


Figure 6.- Effect of runway surface on friction coefficient developed by skids.

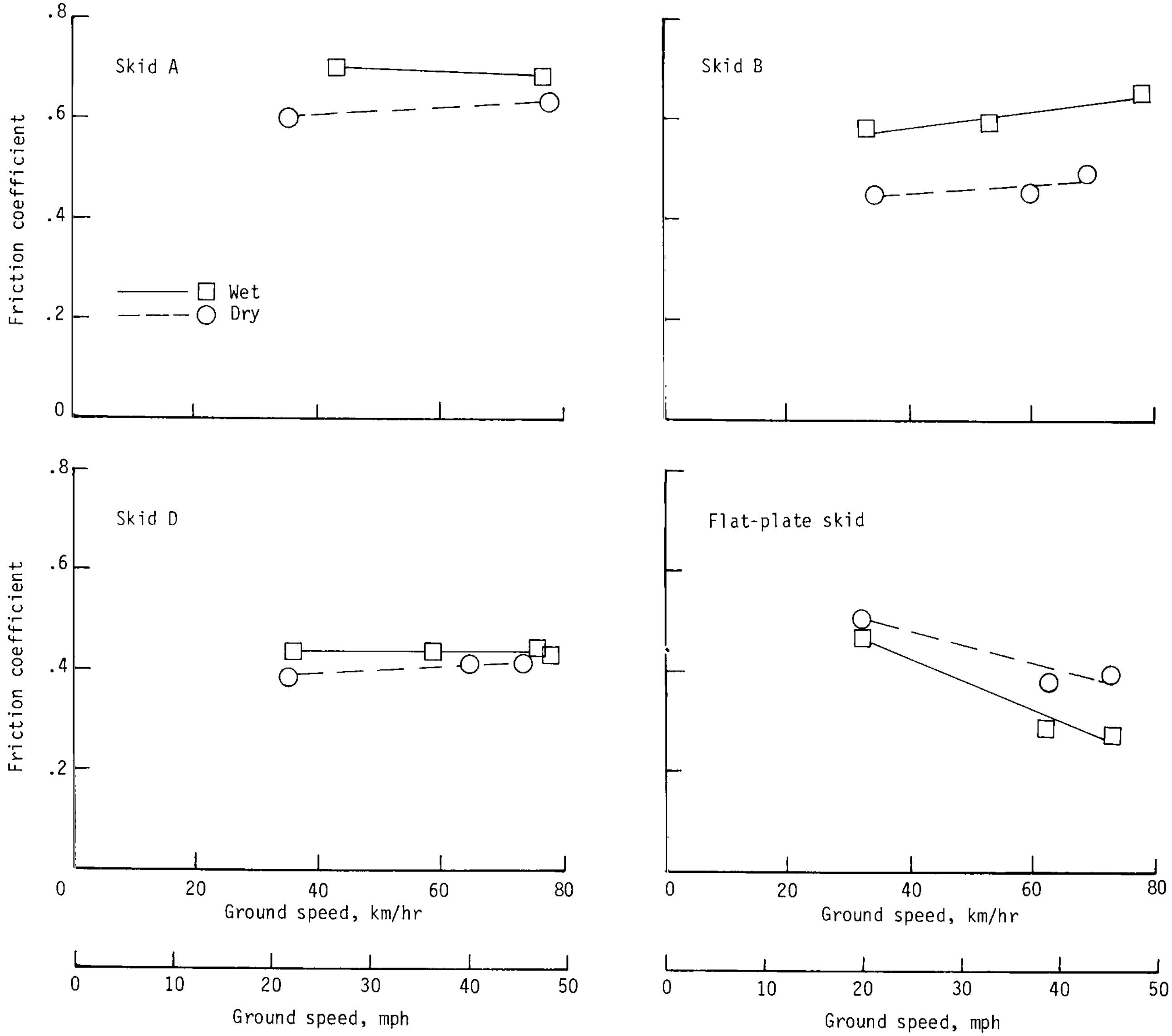


Figure 7.- Effect of surface wetness on friction coefficient developed by skids on the asphalt surface. Bearing pressure, 689 kPa (100 psi).

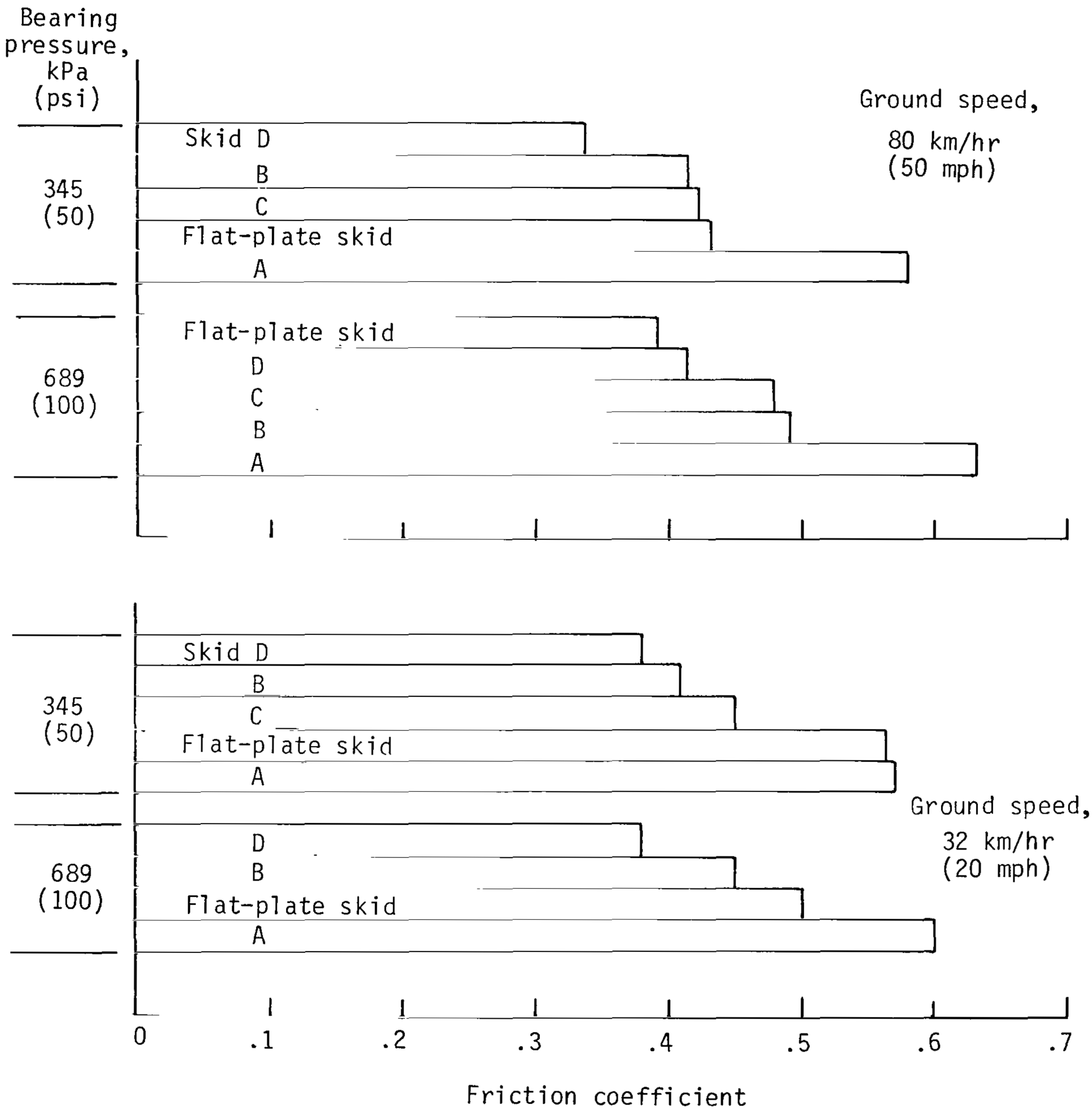


Figure 8.- Comparison of friction coefficient developed by skids on dry asphalt surface.

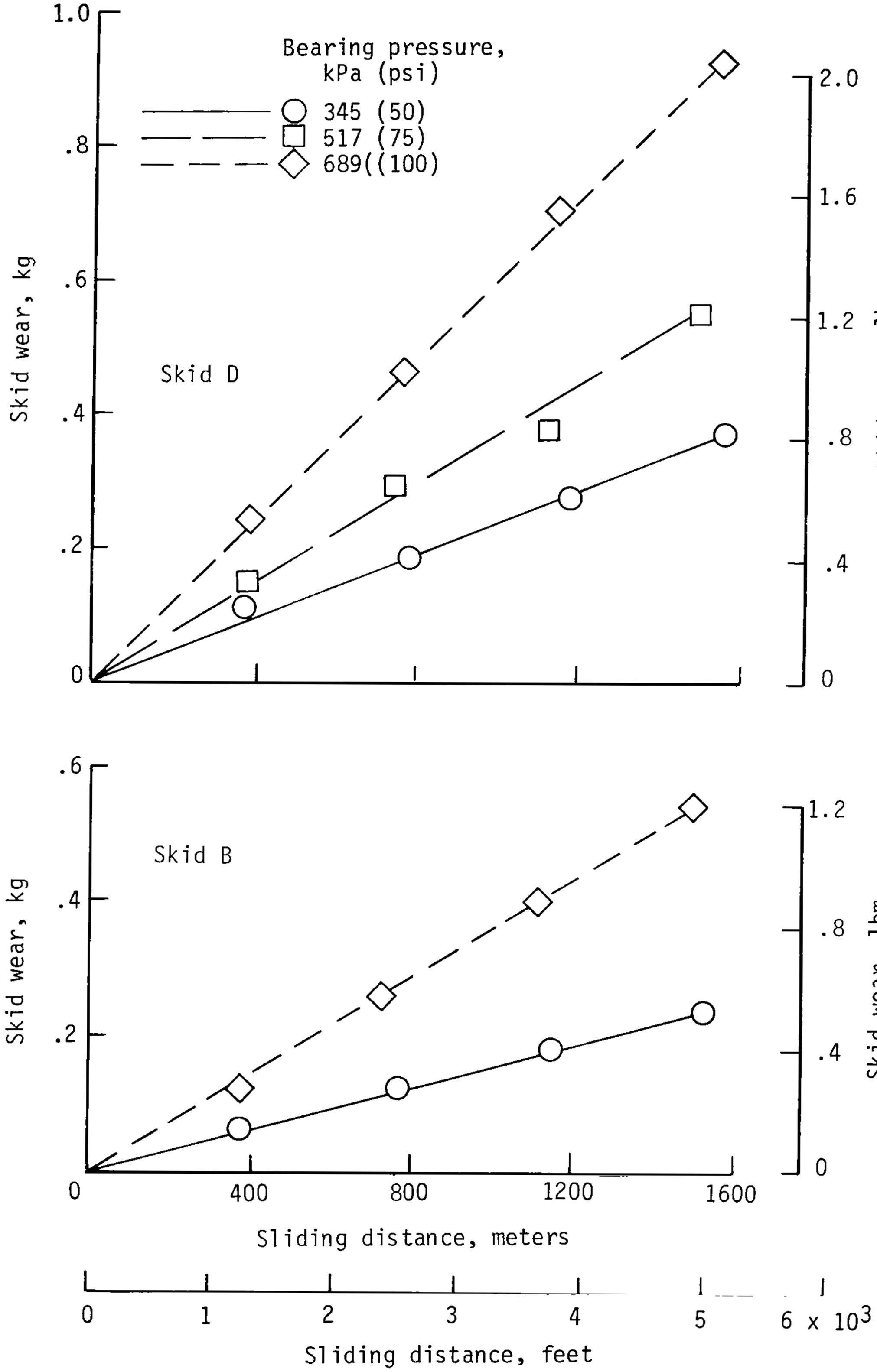
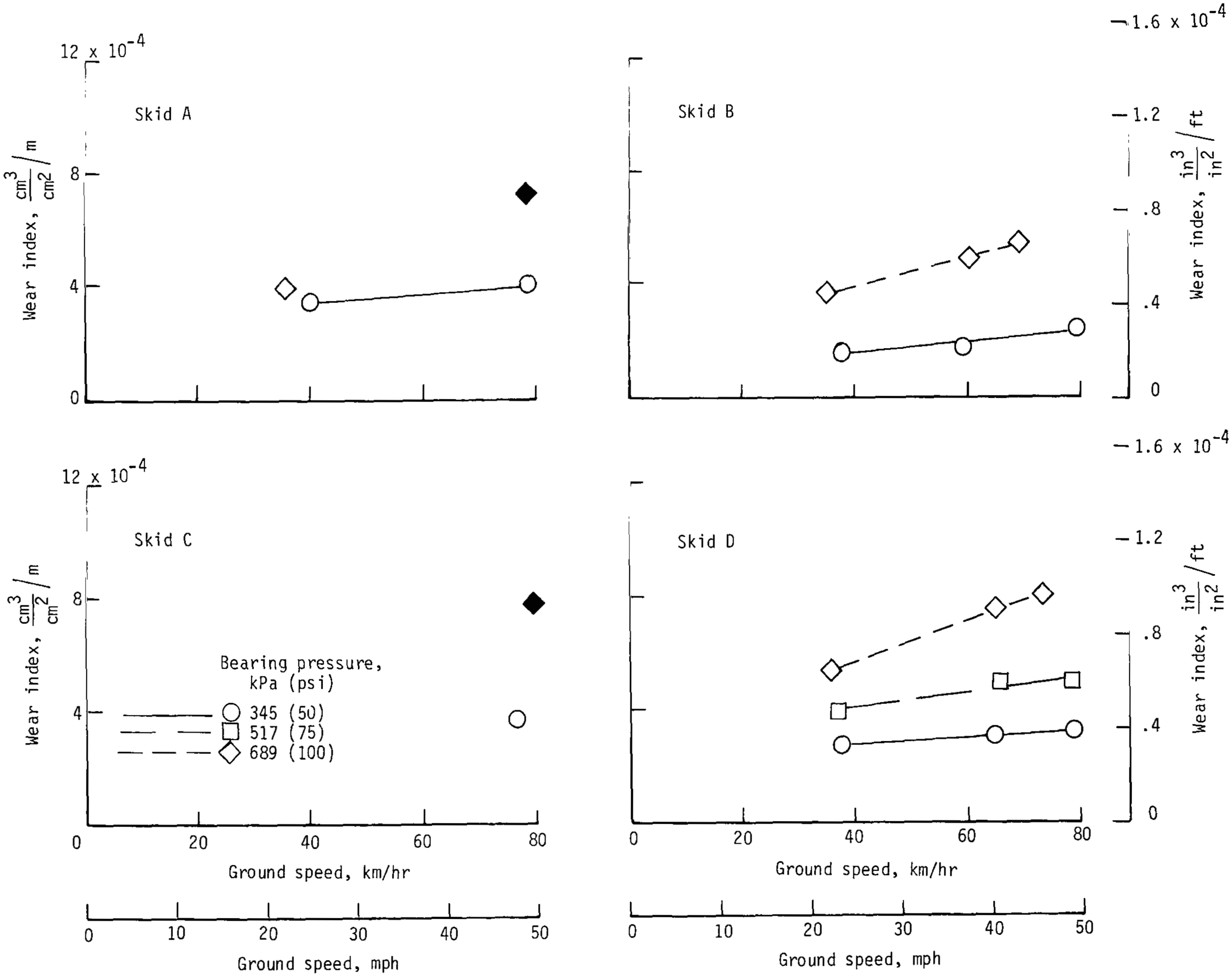
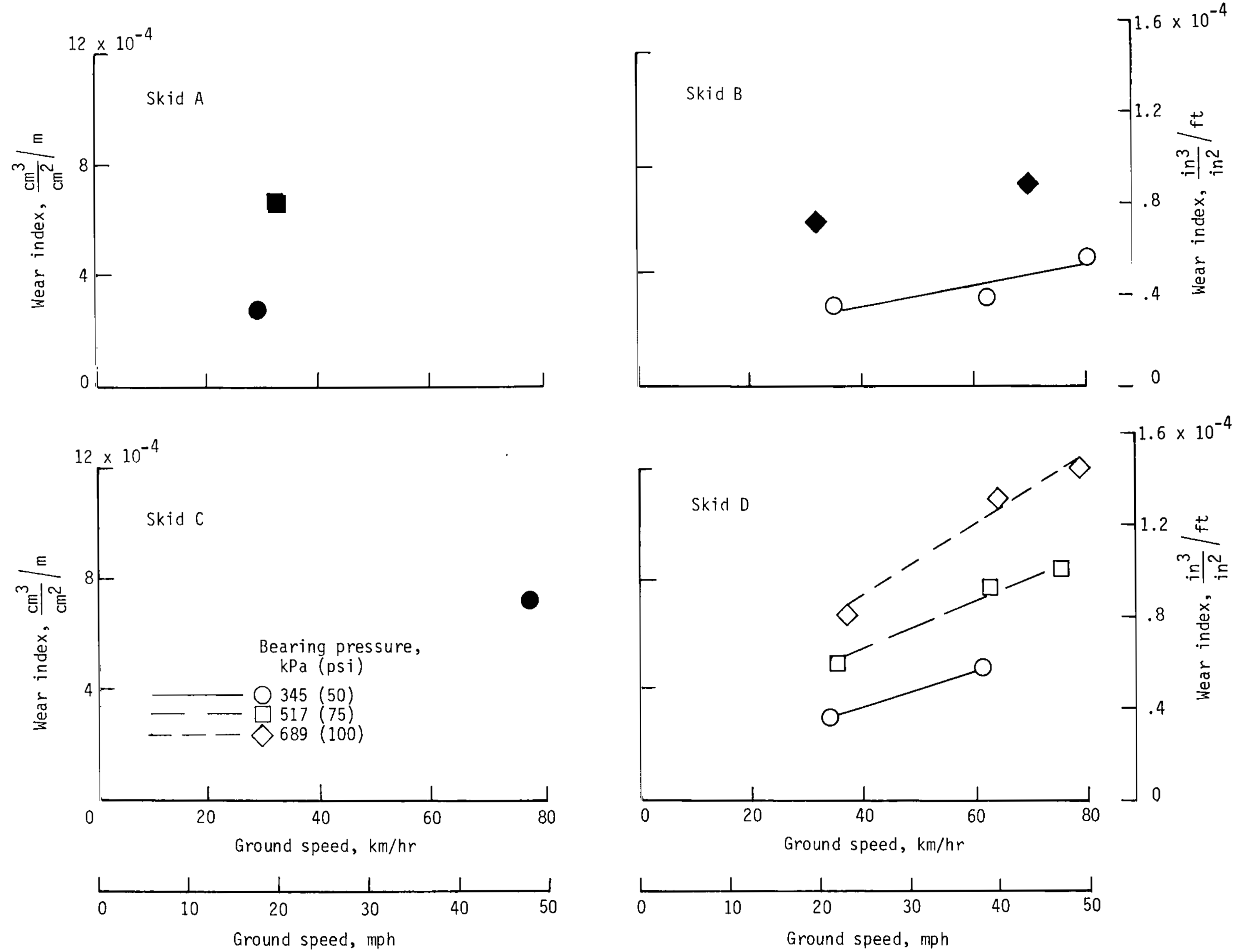


Figure 9.- Typical variation of wire-brush skid wear with sliding distance on dry asphalt surface. Ground speed, 80 km/hr (50 mph).



(a) Asphalt surface.

Figure 10.- Variation of skid wear with ground speed. Closed symbols denote wire loss due to fatigue.



(b) Concrete surface.

Figure 10.- Concluded.

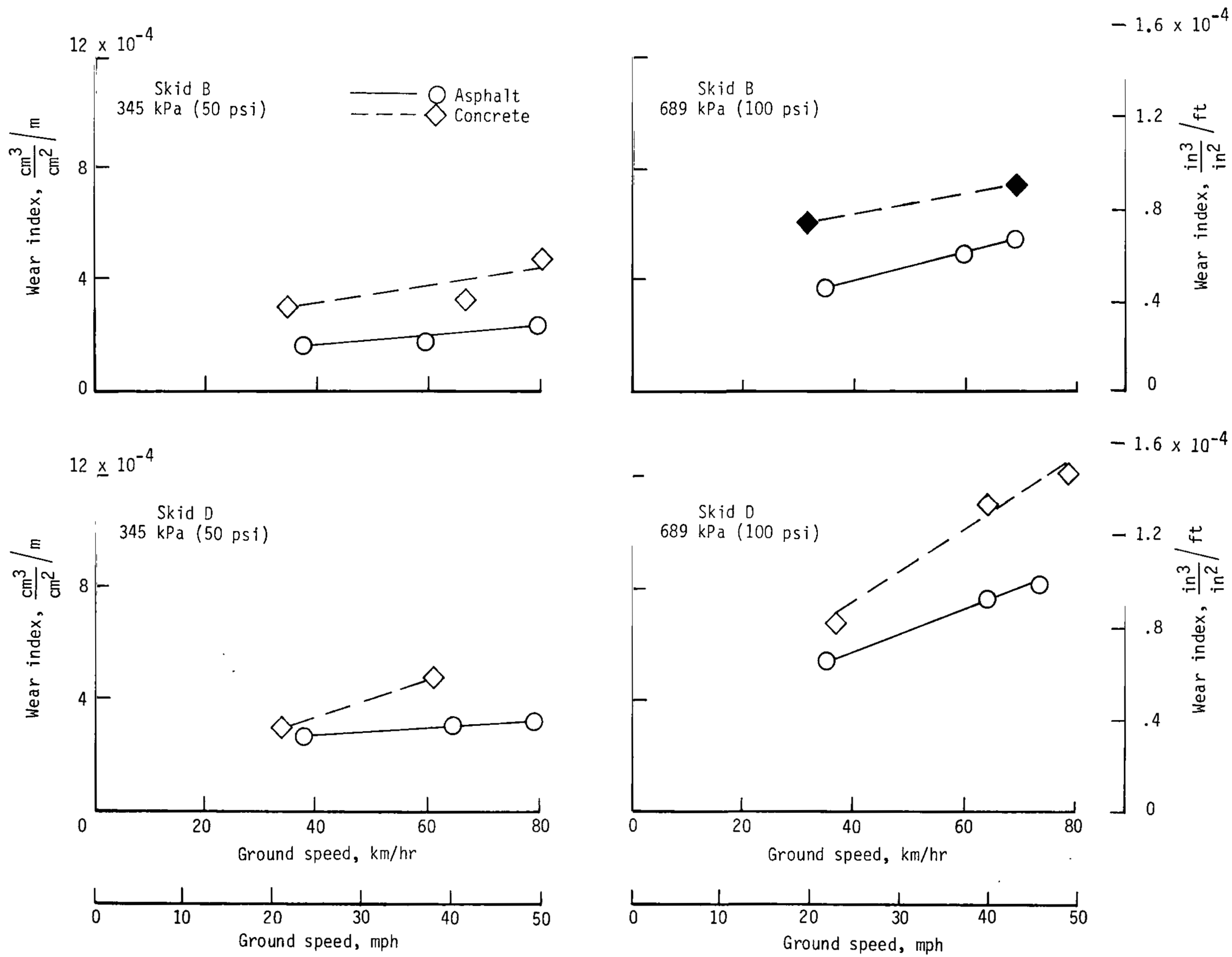


Figure 11.- Effect of runway surface on skid wear. Closed symbols denote wire loss due to fatigue.

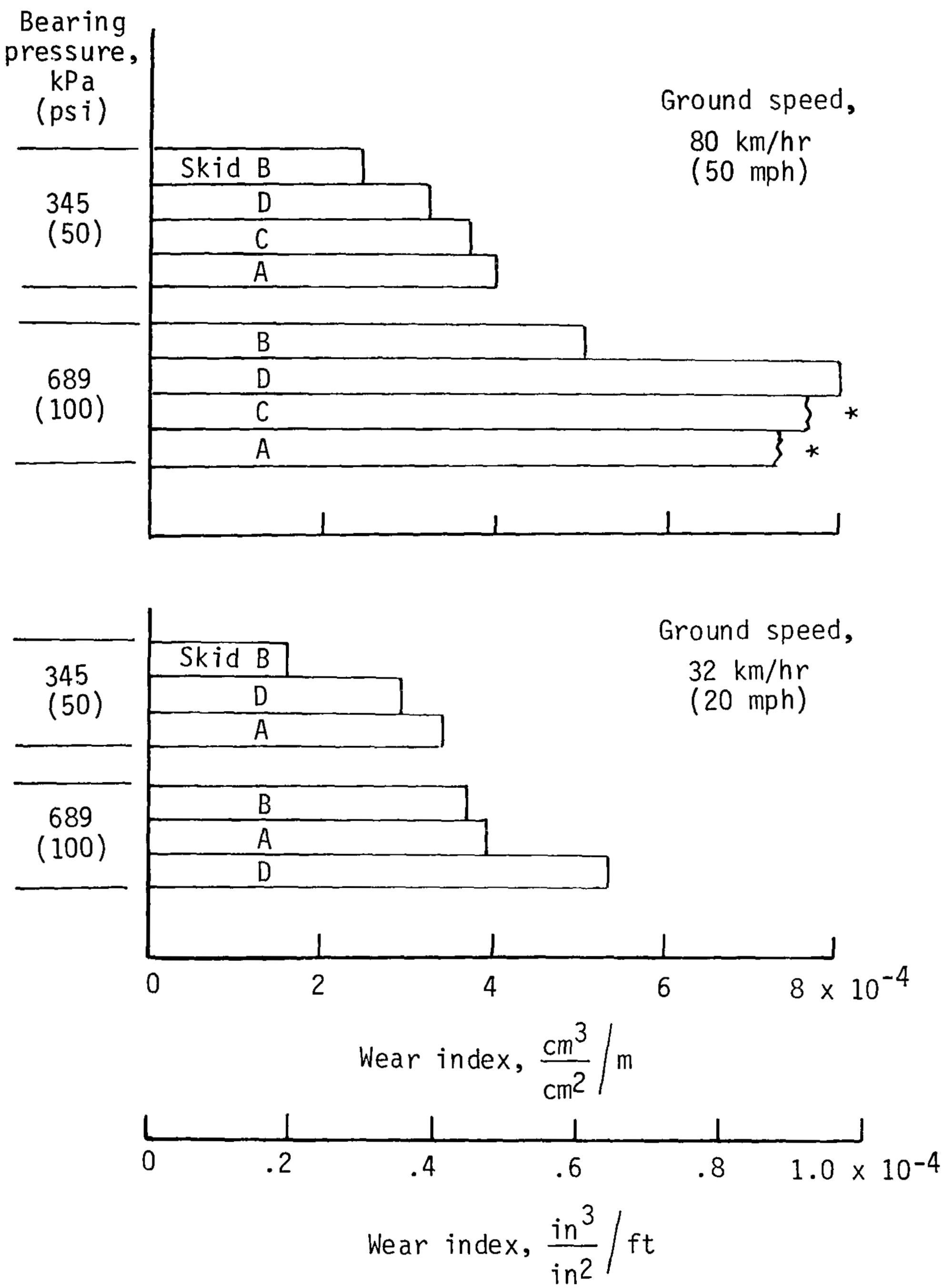


Figure 12.- Comparison of skid wear on dry asphalt surface. A star denotes excessive wire loss due to fatigue.

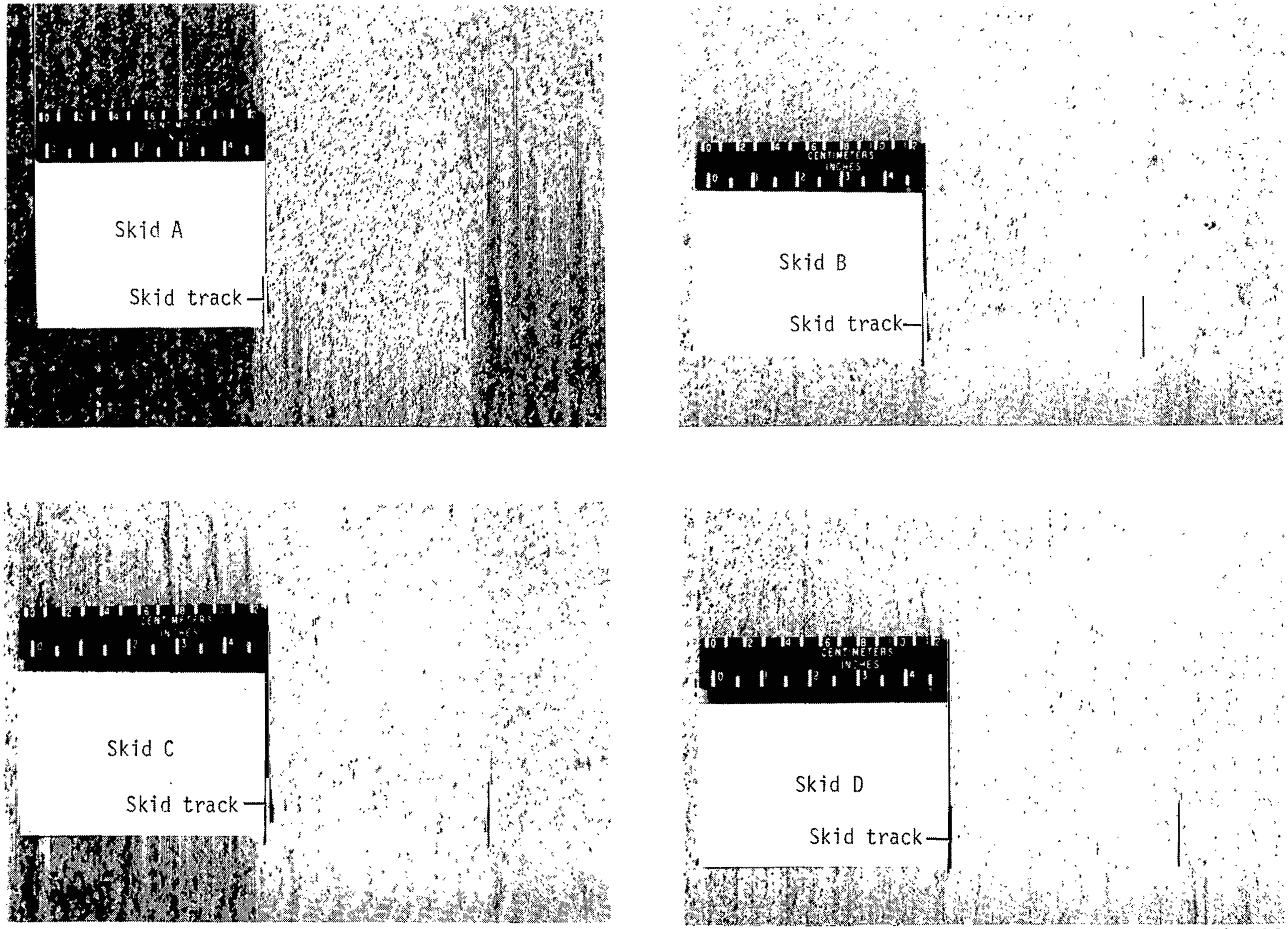


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Figure 13.- Tracks made by skids under a bearing pressure of 689 kPa (100 psi) on concrete surface.

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16. Abstract

An experimental investigation was conducted to evaluate the friction and wear characteristics of wire-brush skids fabricated from 17-7 PH stainless-steel wire. The testing technique consisted of towing the skids with a ground test vehicle over asphalt and concrete surfaces at ground speeds up to 80 km/hr (50 mph) and bearing pressures up to 689 kPa (100 psi) over sliding distances up to 1585 m (5200 ft).

Results of this investigation indicate that the friction coefficient developed by wire-brush skids is essentially independent of ground speed, is slightly increased with increasing bearing pressure, is noticeably affected by surface texture, and is not degraded by surface wetness. Skid wear is shown to increase with increasing bearing pressure and with increasing ground speed and is dependent on the nature of the surface. Runway surface damage caused by the skids was in the form of an abrasive scrubbing action rather than physical damage.

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