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EFFECTS OF PAVEMENT TEXTURE ON WET-RUNWAY BRAKING PERFORMANCE

by Trafford J. W. Leland, Thomas J. Yager, and Upshur T. Joyner

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SUMMARY

An extensive test program was conducted at the Langley landing-loads track to investigate the effect on braking of tire tread pattern and tread materials for a variety of runway surfaces. Some of the tire test results were excerpted from this program and are presented to show the importance of runway surface texture in determining braking friction coefficient levels on wet runways. A technique for measuring the average texture depth of a given surface is suggested, and a limited correlation is shown between the texture depth measurements of four runway surfaces and the average friction coefficients developed by a smooth tire when braking on these wet surfaces. Surface wear due to traffic and weathering is shown to have a marked influence on the braking friction coefficient levels attained on wet runways.

INTRODUCTION

A combination of airplane tire, braking system, and runway surface which provides satisfactory stopping characteristics when the surface is dry may prove to be unsatisfactory when the surface is damp or flooded with water. This degradation in wet-surface braking friction can be caused by the lubricating effect of a viscous film of water between the tire and the runway or by fluid-density effects which become apparent as speed is increased and hydrodynamic pressures are built up by water trapped between the tire and the runway (ref. 1). The magnitude of the friction loss in a particular case depends upon many factors, including speed of operation; tire tread pattern, tread material, and inflation pressure; and runway water depth and surface texture.

An extensive test program was conducted at the Langley landing-loads track to investigate the effect on braking of tire tread pattern and tread materials for a variety of runway surfaces. Some of the tire test results from this investigation have been excerpted to show how the interaction of tire pressure, forward speed, and runway surface texture can change the braking friction coefficients developed on damp, and flooded, concrete and asphalt surfaces. A method which was developed and used to measure runway surface texture depth is described, and experimental results which show the effect on braking of pavement surface wear due to traffic and weathering are presented.

SYMBOLS

d	inside diameter of measuring tube, in. (centimeters)
F_D	ground drag load, lb (newtons)
F_V	ground vertical load, lb (newtons)
l	length of measuring tube, in. (centimeters)
p	tire inflation pressure, lb/in^2 (newtons per square centimeter)
s_1	slip ratio, $\frac{\omega_o - \omega}{\omega_o}$
V_G	forward ground speed, knots
V_P	hydroplaning speed, knots
μ	instantaneous tire-ground friction coefficient, $\frac{F_D}{F_V}$
μ_{av}	average tire-ground friction coefficient between $s_1 = 0.1$ and 0.5
μ_{max}	maximum tire-ground friction coefficient
μ_{skid}	skidding tire-ground friction coefficient $(s_1 = 1.0)$
ω_o	free-rolling wheel angular velocity, rad/sec
ω	instantaneous wheel angular velocity, rad/sec

TEST APPARATUS AND PROCEDURE

The test program was conducted at the Langley landing-loads track, described in reference 2 and shown schematically in figure 1. The fixture for carrying the 32×8.8, type VII, aircraft tires used in the test is shown schematically in figure 2. As in previous braking investigations using this test fixture (for example, refs. 3 and 4), vertical and drag loads were measured at the axle and converted to ground loads by using the vertical and drag accelerometers shown in figure 2, while brake torque was measured separately by a system of torque links. Brake pressure was applied through an orifice to increase the brake-pressure rise time in order to make it possible to record and compute a complete time history of load and motion from free roll to locked wheel for each brake cycle.

Braking Test Surfaces

The test surface was arranged as shown schematically in figure 3 to provide a variety of runway surfaces ranging from very smooth to very rough. The surfaces are described as smooth concrete, textured concrete, small-aggregate asphalt, large-aggregate asphalt, and ice. Following wheel drop and spin-up on the 100-foot (30.5-meter) ramp, brake cycles were initiated on each test surface as the carriage proceeded down the track. The first braking surface (fig. 4(a)) was a very smooth, steel-trowel-finish concrete. The second surface (fig. 4(b)) was concrete which had been bag-dragged to provide a small-scale surface texture and was probably smoother than runway surfaces commonly in use today. The small-aggregate asphalt surface (fig. 4(c)) had an aggregate or stone size within accepted construction practices for runways today. The large-aggregate asphalt surface shown in figure 4(d) had an aggregate or stone size outside accepted runway practices, although the largest stone size did not exceed approximately 0.5 inch (1.3 cm). The ice surface shown in figure 4(e) was maintained by a refrigeration system which circulated brine through pipes located approximately 2 inches (5.1 cm) below the ice surface.

The first four braking surfaces were provided with water outlets at intervals along the track, and dams were placed along the edges to maintain the desired water level. This system insured the same wetness conditions for all tests, but because of differences in runway elevation characteristics, the actual water depth over the surface varied from 0.1 to 0.2 inch (0.25 to 0.51 cm). Cross dams were used during the high-speed tests to provide a dry area for wheel spin-up between braking cycles. The ice surface was maintained at essentially the same condition throughout the investigation with the surface being sprayed lightly with water just prior to the test to insure a wet surface.

Test Tires

The tires used were 32 × 8.8, type VII, 22-ply-rating, aircraft tires having the tread configurations shown in figure 5. The tires were specially molded for this test and had all-rubber treads (as opposed to fabric-reinforced treads) formed of a natural rubber compound. Tire I (fig. 5(a)) had a smooth tread whose thickness was equal to that of a new tire but had no tread pattern. Tire II (fig. 5(b)) had three equally spaced straight circumferential grooves approximately 0.5 inch (1.3 cm) in width, and tire III (fig. 5(c)) had four similar 0.5-inch (1.3-cm) grooves.

Test Procedures

Each tire or tire—test-surface combination was tested at nominal forward velocities of 25, 50, 75, and 100 knots. The smooth tire (tire I) was tested at intervals throughout the program as a control tire to detect any significant changes in test environment. Data measured and recorded manually for each run included tire pressure, ambient temperature, wind condition, water depth, and ice-surface temperature and condition. During the run, continuous measurements of vertical load, drag load, brake torque, brake pressure, carriage forward velocity, and wheel angular displacements, velocity, and acceleration were recorded on an 18-channel oscillograph on board the carriage.

PRESENTATION OF DATA

General Considerations

Instantaneous values of tire-ground friction coefficient μ were plotted for each brake cycle from free roll (slip ratio of 0) to full skid (slip ratio of 1.0). The data presented will express braking friction coefficient in terms of the average tire-ground friction coefficient μ_{av}, illustrated in figure 6. This parameter is defined as the average coefficient of friction obtained in the slip-ratio range of 0.1 to 0.5. Presenting the data in this manner tends to minimize the effects of localized differences in runway surface character covered during each brake cycle.

In those cases where comparisons are made between runway and tire conditions, successive test runs were chosen to illustrate the points under discussion and to minimize the effect of runway surface changes.

Dry-Runway Braking Effects

The number of dry-runway braking runs was limited because of prohibitive tire wear and runway surface wear. The results of these dry-runway tests are presented in figure 7 for tires II and III braking on the five test surfaces described in the preceding section. The ice surface is not dry but is included for comparison, as is the dry-runway rolling-resistance curve obtained from reference 4 for a similar tire. Although tires II and III have different tread patterns, the results of reference 3 indicate that tread pattern has very little effect on dry-runway braking. Tire II, operating at a tire inflation pressure of 140 pounds per square inch (97 N/cm^2) and vertical load of 12 000 pounds (53 400 N), developed significantly higher friction coefficients than did tire III operating at a tire inflation pressure of 290 pounds per square inch (200 N/cm^2) and vertical load of 13 200 pounds (58 700 N). This difference in friction coefficient agrees with previous work (ref. 5), which indicated that for dry-runway braking, the friction coefficient increased as tire pressure decreased, and is the effect of ground bearing pressure. Note that the ground bearing pressure for tire II is considerably lower than that for tire III.

No consistent variation of friction coefficient with variations in runway surface character seems to exist, with the exception of the smooth runway. These data points are in doubt, however, since the smooth surface was closest to the catapult, and at the higher speeds and/or with a following wind, this surface could easily have become contaminated with water sprayed from the jet catapult. Therefore, the lines shown in figure 7 were faired through the remaining test surfaces, and these lines will be used when other data are compared with dry-runway braking test results.

Damp-Runway Braking Effects

Although no significant differences in dry-runway braking friction coefficients were observed on the various textured test surfaces, figure 8 shows a pronounced surface texture effect and a large degradation in friction coefficient as a result of the addition of a small amount of water to the test surface. For this series of tests, a damp surface was obtained by wetting the entire surface until uniform discoloration was noted and then brushing out all standing water just prior to the run. The surface in this condition closely resembled a runway as it might look following a heavy dew. The smooth tire (tire I) used for this series was inflated to 140 pounds per square inch (97 N/cm^2) and carried a vertical load of 12 000 pounds (53 400 N).

When moisture is present, as shown in figure 8, surface character plays a significant role. Friction losses on the damp asphalt surfaces are on the order of 25 percent of the dry-surface values, but the smooth concrete reveals an almost total loss of available friction coefficient at the higher speeds (compare with the rolling-resistance coefficients shown in fig. 7). Since there was no standing water, it would seem that these large losses in braking effectiveness must be due to viscous, or lubricating-film, effect rather than a fluid-density effect. It is thought that the data in figure 8 show that a rougher textured surface tends to break up or penetrate through more of the fluid film than does a smooth surface because, in general, the friction coefficients shown are higher for the rougher surfaces.

Flooded-Runway Braking Effects

The difference between the viscous effects noted in figure 8 and fluid-density effects, which occur in significant water depths, is shown in figure 9 in which the results of braking the smooth tire (tire I) on the smoothest and roughest test surfaces are compared for damp-runway and flooded-runway conditions. (The term "flooded" in this case means that the water depth on the test surface varied from 0.1 to 0.2 inch (0.25 to 0.51 cm).) As shown in figure 9, at low speeds on the large-aggregate asphalt surface, there is little difference between the friction coefficient for the damp-runway and flooded-runway conditions. This fact indicates a predominant viscous fluid-film effect. As speed is increased, fluid-density effects increase and cause partial hydroplaning and a significant decrease in friction coefficient. Near the hydroplaning speed, as predicted by the method of reference 1, the available tire-ground friction drops to a very low value as the entire footprint area becomes supported by the water.

The smooth-concrete results in figure 9 show little significant difference with greater water depth and indicate that on this very smooth surface a slight amount of moisture provides a viscous film which remains unbroken by the smooth tire, so that the addition of more water causes very little change in friction coefficient.

Effect of Ground Bearing Pressure

A definite ground bearing pressure effect was observed during braking on a dry runway (fig. 7) and the same bearing pressure effect can be noted when braking occurs on a flooded runway, as shown in figure 10. This figure compares the braking friction developed by the smooth tire (tire I) braking on three of the test surfaces at two conditions of vertical load and tire inflation pressure. At the lower speeds on the rougher surfaces, a ground bearing pressure effect similar to that shown in figure 7 can be noted with the lower pressure resulting in somewhat higher average friction coefficients. However, as forward speed is increased and fluid-density effects become predominant, a more rapid degradation in tire-ground friction can be noted for the lower tire inflation pressure as the predicted hydroplaning speed (ref. 1) is approached. Although the hydroplaning speed at the higher tire pressure is beyond the speed capability of the test carriage, the results in figure 10 indicate that large losses in braking friction coefficient can be delayed to a higher speed by increasing the tire inflation pressure, at the expense of somewhat lower friction levels at the lower speeds.

Braking on the smooth concrete surface, as shown in figure 10, appears quite insensitive to ground bearing pressure. Thus, it can be inferred that the pressure necessary to break the viscous fluid film is considerably greater than any realistic value of tire inflation or ground bearing pressure. However, as indicated previously, this film may be broken by providing areas of extremely high local bearing pressure in the tire-ground contact region, such areas being provided by pavement texture, as discussed previously, by improved trend patterns or by pavement grooving.

The effect of pavement wear due to traffic and weathering is illustrated by comparing figures 9 and 10. In figure 10, the smooth tire (tire I) was tested on the flooded surfaces at the two conditions of vertical load and tire pressure shown. Three months and 140 test runs later, the smooth tire (tire I) was again tested at the smaller vertical load and tire pressure on flooded and damp surfaces as shown in figure 9. The difference in friction coefficient on the flooded surfaces in figures 9 and 10 is then due to pavement texture changes caused by traffic and weathering during the period between the two tests.

MEASUREMENTS OF SURFACE TEXTURE

A Method for Evaluating Surface Texture

The foregoing results have clearly indicated that runway surface texture has a major effect on the wet-runway braking friction coefficient developed by a tire. It is extremely difficult to convey a meaningful word description of a given surface, and even the photographs shown in figure 4 do not permit any sort of rating or classification of the surface or provide the reader with a clear indication of the actual roughness or smoothness of the surface. In an attempt to provide a quantitative measure of the effective runway surface roughness, a simple method has been evolved with the use of the apparatus shown in figure 11. Essentially, this method consists of working a known volume of grease into the runway surface and measuring the resulting grease-covered area. Dividing the initial grease volume by the area thus measured gives an average runway surface texture depth. Details of the apparatus and the procedure used in applying the method are discussed in the appendix.

Correlation of Surface-Texture Measurements

The method previously described should, for most reliable results, be statistical in nature with many different samples being taken of the surface. However, the limited length of the test sections used in this investigation made it possible to take only one sample on each of the four surfaces. The results were most encouraging, as shown in figure 12 in which the average friction coefficient developed on a flooded surface by the smooth tire at four forward speeds is plotted against the average texture depth for the four surfaces investigated. Increasing texture depth, or surface roughness, is seen to improve tire-ground friction at all speeds tested, and at the lower speeds, a friction level which is nearly equal to the dry-runway friction coefficients shown in figure 7 is reached. This effect probably accounts for the leveling off of the curve near the roughness level of the small-aggregate asphalt surface and suggests some speed-dependent limiting value of surface roughness beyond which no great improvement in braking can be realized, and the rougher surface might well increase tire wear.

Measurements of Surface Wear

The correlation of friction coefficients with surface measurements obtained by the grease technique was made coincidental with the first series of runs on the smooth control tire (tire I). The results of this correlation were so encouraging that the method was applied at intervals throughout the remainder of the testing period. The construction of the test carriage and fixture (figs. 1 and 2) constrained the test tire to the same path for each run. Thus, the traffic over the test section can be evaluated quite closely and is summarized in table I. The results of the continuing surface-texture studies are shown in figure 13 in which the average texture depths as measured by the grease technique for the four surfaces are plotted against the total number of passes made over each surface prior to the measurement. Although there is some scattering of data in figure 13, probably due to the restricted number of samples, a change in surface character is noted for the three rougher surfaces and little change is noted for the smooth concrete surface. This surface change is taken to be a deterioration of the surface, since the average texture depth is becoming smaller. The surface change undoubtedly arises from a combination of traffic and weathering, and although the two effects cannot at this time be separated, a time scale is included at the bottom of figure 13 for reference.

The smooth control tire (tire I) was tested at approximately the intervals shown by the vertical lines in figure 13. In figure 14, the average friction coefficient developed by the smooth tire on each of the four test surfaces at four nominal forward velocities shows how the measured surface wear affected the braking friction levels attained by this tire. At the higher speeds, the large-aggregate asphalt surface (fig. 14(a)) showed the greatest degradation in braking friction coefficient, and as shown in figure 13, this surface also experienced the greatest change in surface character. The small-aggregate asphalt (fig. 14(b)) and the textured concrete (fig. 14(c)) show similar trends and again the trends are reflected by the surface-wear measurements shown in figure 13.

The smooth concrete, shown in figure 14(d), exhibits somewhat different characteristics in that the friction coefficient tends to increase slightly with increasing surface wear, although little change was noted in the smooth concrete surface-texture measurements of figure 13. This increase is thought to be due to the peculiar way in which the smooth concrete surface weathered. The surface of the concrete developed hairline cracks resembling, in the final stages, a mosaic pattern. It is believed that the viscosity of the grease used in the texture measurements made the measurements insensitive to these cracks but that the cracks did offer a small measure of relief to the water trapped between the tire and the ground and, thus, improved the friction coefficient.

Other Surface-Texture Considerations

The suggested surface-texture measurement technique is, by its nature, insensitive to the type or configuration of the surface texture being measured. Surface texture configuration, however, does have a pronounced effect on the friction level developed, as shown in figure 15, in which the average friction coefficient developed by the smooth tire on the four flooded test surfaces is plotted against the measured texture depth of the surfaces. The velocity lines are faired in to show trends only. In figure 13 texture depth was seen to decrease with wear on the rougher surfaces. Figure 15 indicates that the texture depth of the large-aggregate asphalt surface degraded with wear to a level nearly equal to the new, small-aggregate asphalt surface (area A); yet there is a distinct difference in friction level developed by the smooth tire. This difference must then be due to some surface texture characteristic other than depth and is thought to be caused by differing texture shapes. The asperities in the large-aggregate asphalt probably become polished with wear and, while still large enough to give large values of texture depth, were not as rough as the asperities in the new, small-aggregate asphalt surface. The same parallel can be drawn between the worn small-aggregate asphalt surface and the textured concrete when about half worn (area B in fig. 15). In this case, the measured texture depth was exactly the same for the two surfaces, but the greater braking friction developed on the asphalt surface clearly indicates that the braking performance on a given surface cannot be accurately predicted on the basis of texture depth alone.

The effect of operating speeds over a given surface is also clearly evident from figure 15. In these tests, with a tire inflation pressure of 140 pounds per square inch (97 N/cm^2), the predicted hydroplaning speed, by the method of reference 1, is 106.5 knots. As the tire approaches this speed, 100 knots in figure 15, the character of the pavement surface is seen to have a rather small effect as a result of partial hydroplaning of the tire (ref. 1). As speed is increased, more and more of the tire footprint is forced off the pavement, and this suggests that for each tire there is a critical speed, based on tire inflation pressure, at which the pavement surface character is of minor importance. Therefore, to determine a given level of surface texture roughness which will provide acceptable friction levels when wet, the average surface texture depth, the configuration of the surface texture, and the anticipated operational speeds over the surface must be considered.

CONCLUDING REMARKS

The results presented have shown the effects which differences in runway surface texture can have on the wet-runway braking friction coefficients developed by aircraft tires. A technique for quickly and easily obtaining numbers to define the average texture depth of a given surface has been suggested. Although the method suggested is imprecise because the only texture characteristic measured is average depth, a limited correlation between texture depths thus obtained for a surface and average friction coefficient developed by a tire on the same surface has given some confidence in the method. Operational speed has been shown to be of importance in determining the wet-runway friction levels attained on a given surface. Surface wear due to traffic and weathering has been demonstrated to have a marked influence on the friction coefficient levels attained with the same tire run at different times during the test program.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., July 6, 1967,
126-61-05-01-23.

APPENDIX

A PROPOSED SIMPLE METHOD FOR QUANTITATIVELY MEASURING RUNWAY SURFACE TEXTURE

Review of the Problem

It has long been recognized that the friction forces which a pneumatic tire can develop for the purposes of braking, cornering, or driving are greatly influenced by the finish of the runway or road surface. In past work on the measurement of tire-runway friction, the nature of the ground test surface has generally been defined qualitatively but a quantitative measure of the effective runway roughness has been lacking. Work toward the development of such a quantitative measure of roughness has come rather slowly, in spite of its recognized need. Recently, however, essentially the same idea has been applied in several places. Meyer (refs. 6 and 7) published a description of a method for measuring surface roughness by use of a profilometer, which measures the roughness along a line on the surface. The friction coefficient can then be correlated either with the average height of the roughness peaks or asperities, or with the drainage area, which is taken to be the integrated sum of the cross-sectional area of the voids under a line connecting the peaks of the major asperities along the length of the profile. An outflow meter, designed to assess the drainage ability of various surfaces, has been developed by D. F. Moore and is described in reference 8. A "sand patch" method of classifying surface textures by measuring the quantity of fine sand that can be worked into the surface with a straightedge is presented in reference 9.

Langley Technique for Measuring Surface Roughness

At the Landing and Impact Branch of Langley Research Center, a system similar in principle has been tried. A selected volume of grease is applied to the runway or road surface between parallel lines of masking tape and then worked into the runway voids with an aluminum squeegee faced with rubber having a hardness approximately equivalent to that of tire tread rubber. Dividing the volume of grease used by the runway area covered gives an average depth of the runway voids. This average depth of voids is taken to be a measure of surface roughness.

A photograph of a measurement being taken by the grease method of measuring runway or road roughness is presented in figure 11. The selected volume of grease has been worked into the voids in the runway surface, and the operator is again going over the surface with the rubber squeegee to be sure that no excess grease has been left. The technique shown has proved to be easy to apply and convenient for field applications.

APPENDIX

In the description to follow, equations are given to convert measurements taken and obtain average depth of runway roughness in millimeters. The lines of masking tape were placed about 10 centimeters or 4 inches apart and the distance along the lines covered by the grease was measured to obtain the area covered. The effective roughness was then obtained by dividing the known volume of grease applied by the area covered.

A convenient volume of grease has been found to be either 15 cubic centimeters or 1 cubic inch. A simple way of measuring this volume is given in the following section entitled "Description of equipment."

After the measurements are obtained, the following equations can be used to calculate the average depth of the runway surface voids:

$$\text{Roughness (mm)} = \frac{10 \times \text{Volume of grease} \quad \text{(cu cm)}}{\text{Area covered} \quad \text{(sq cm)}} \tag{A1}$$

or

$$\text{Roughness (mm)} = \frac{25.4 \times \text{Volume of grease} \quad \text{(cu in.)}}{\text{Area covered} \quad \text{(sq in.)}} \tag{A2}$$

Description of equipment.- The equipment required is limited to that shown in figures 11 and 16. On the left of figure 16 is shown the tube which is used to measure the selected volume of grease. On the right is shown the tight-fitting plunger which is used to expel the grease from the tube, and in the center is shown the rubber squeegee which is used to work the grease into the voids in the runway or road surface. The sheet rubber of the squeegee was cemented to a piece of aluminum for ease in use. The grease used was a general purpose lubricant. At this time it is thought that any general purpose grease can be used.

Use of equipment.- The tube for measuring the selected volume of grease is packed full with a tool like a putty knife in such a way as to avoid entrapped air, and the ends are squared off as shown in figure 17. The grease is then expelled from the measuring tube with the plunger and deposited between previously placed lines of masking tape. It is then worked into the voids of the runway surface with the rubber squeegee. Care is taken that no grease is left on the masking tape or on the squeegee. Measurements are then taken, the area is computed, and the roughness in millimeters is obtained by use of either equation (A1) or equation (A2).

Selection of measuring tube.- As a convenience in the selection of the length of the measuring tube, figure 18 gives the relation between the tube inside diameter and tube length for an internal tube volume of 1 cubic inch or 15 cubic centimeters. The plunger can be made of cork, rubber, or other resilient material to achieve a tight fit in the measuring tube.

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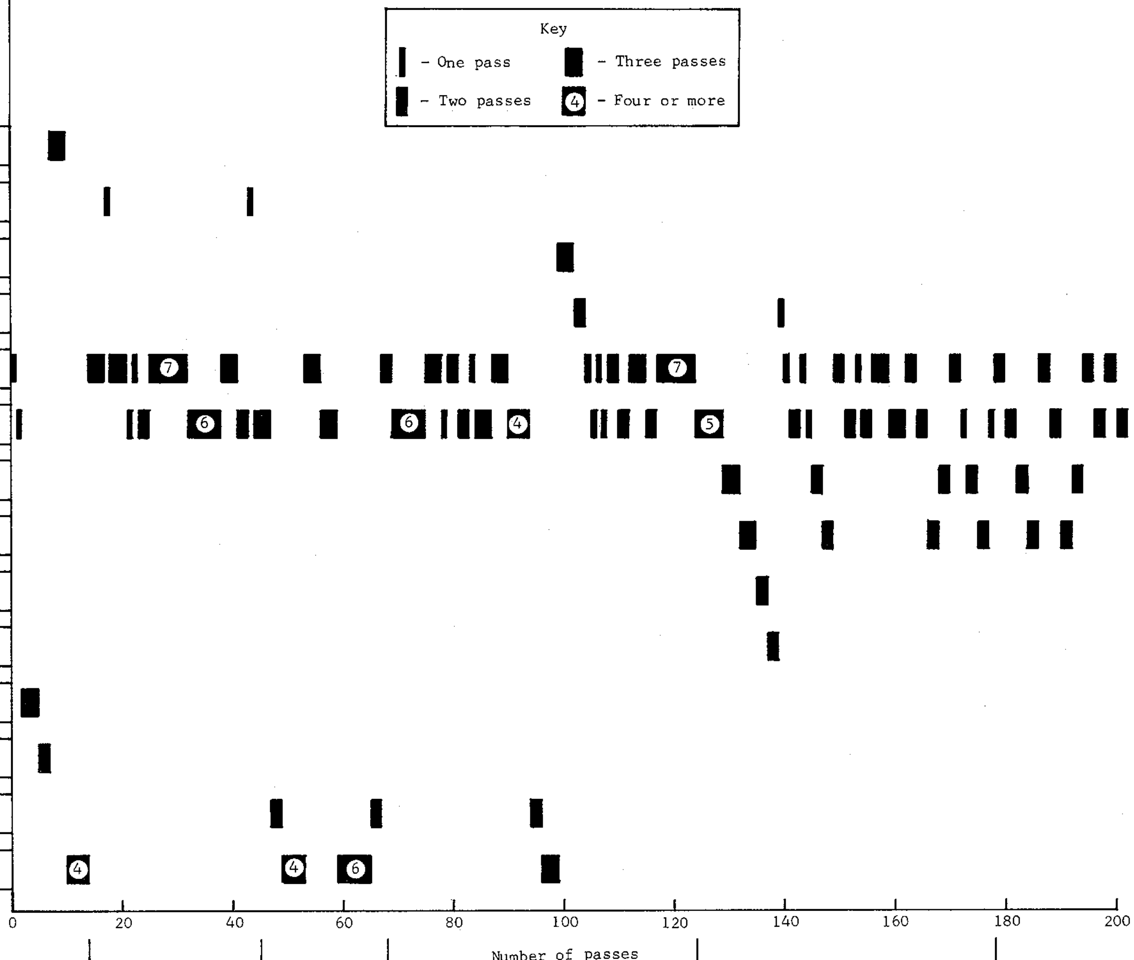
TABLE I.- SUMMARY OF TRAFFIC OVER RUNWAY TEST SECTION

Vertical load range, 10^3 lb (kN)	Tire pressure, lb/in^2 (N/cm^2)	Velocity range, knots	Rolling condition	Runway condition	Total passes at each test condition
10-15 (44-66)	90 (62)	50-80	Free	Wet	3
10-15 (44-66)	140 (97)	50-80	Free	Wet	2
10-15 (44-66)	140 (97)	25-50	Braked	Dry	3
10-15 (44-66)	140 (97)	50-100	Braked	Dry	3
10-15 (44-66)	140 (97)	25-50	Braked	Wet	66
10-15 (44-66)	140 (97)	50-100	Braked	Wet	67
10-15 (44-66)	290 (200)	25-50	Braked	Wet	13
10-15 (44-66)	290 (200)	50-100	Braked	Wet	13
10-15 (44-66)	290 (200)	25-50	Braked	Dry	2
10-15 (44-66)	290 (200)	50-100	Braked	Dry	2
22 (98)	290 (200)	25-50	Free	Wet	3
22 (98)	290 (200)	50-100	Free	Wet	2
22 (98)	290 (200)	25-50	Braked	Wet	6
22 (98)	290 (200)	50-100	Braked	Wet	17
					202



Month and ambient temperatures, °F (°C)	Sept.-Dec.	January	February	March	April	May
	30° - 80° (-1° - 27°)	35° - 65° (2° - 18°)	40° - 68° (4° - 20°)	40° - 71° (4° - 20°)	47° - 83° (8° - 28°)	66° - 90° (19° - 32°)

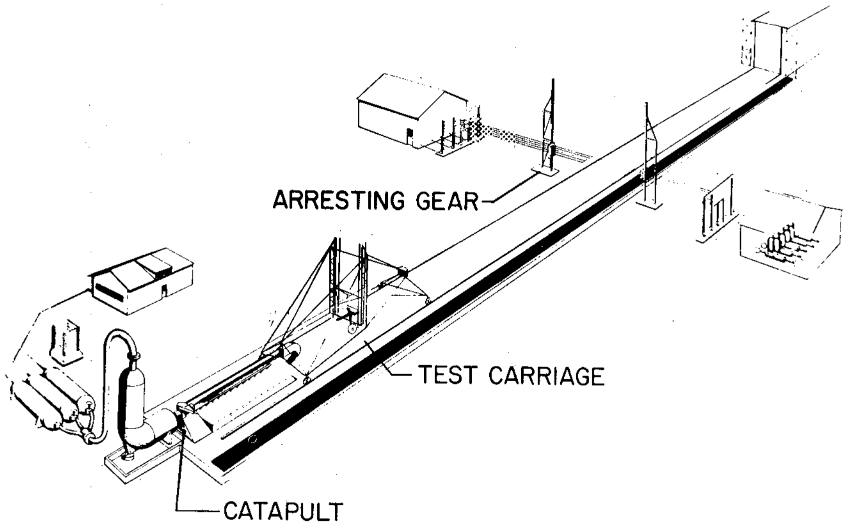


Figure 1.- Schematic of the Langley landing-loads track.

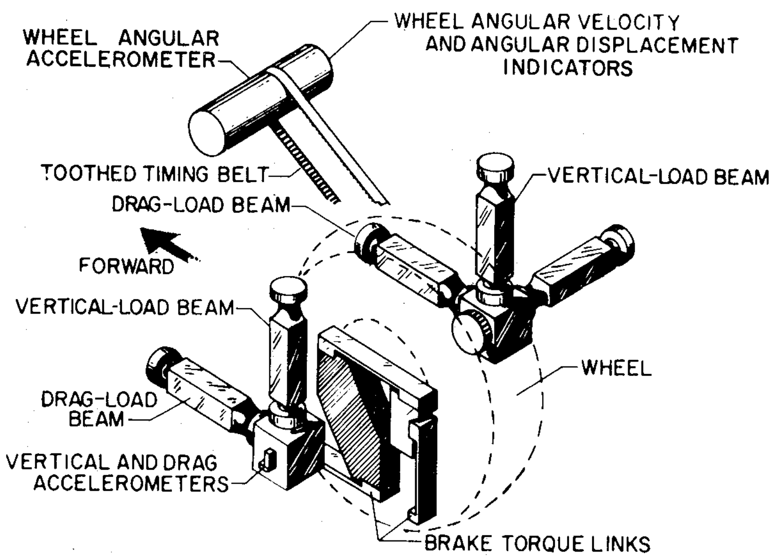


Figure 2.- Schematic of test fixture.

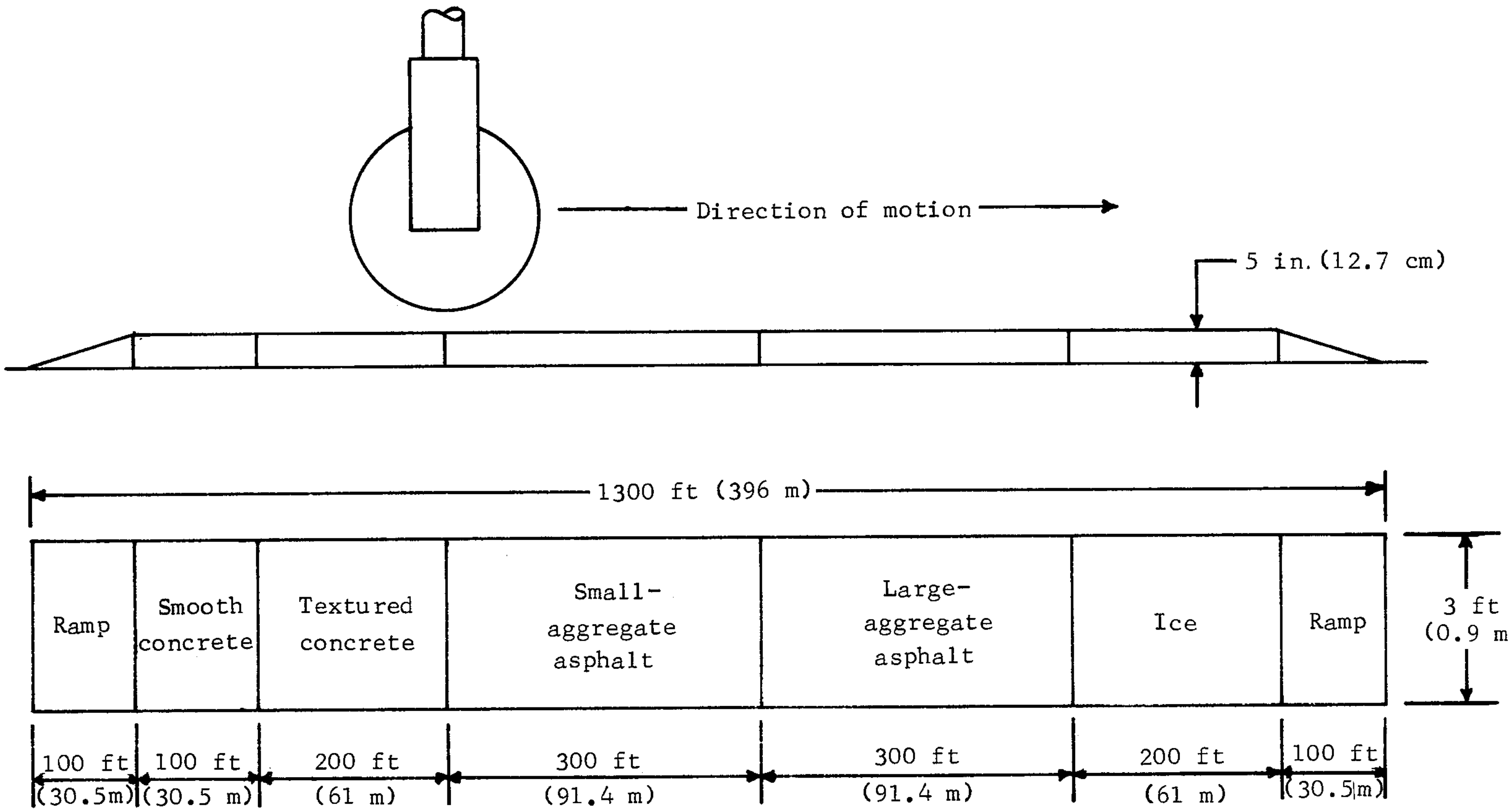
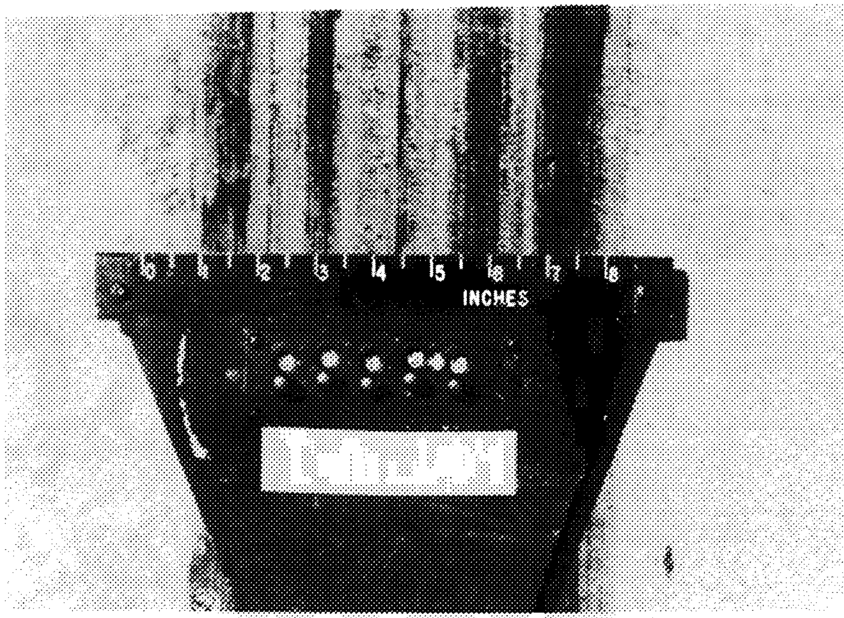
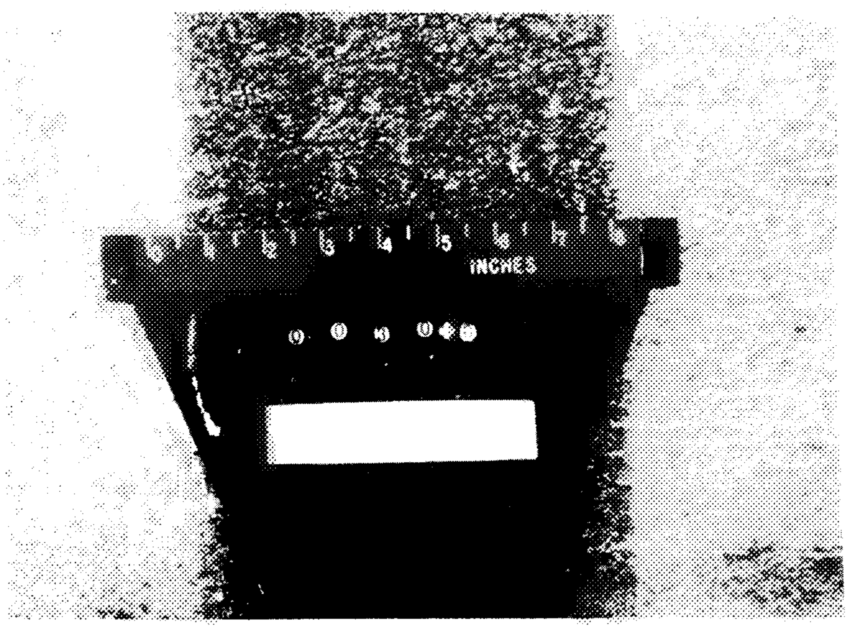


Figure 3.- Schematic of test section.

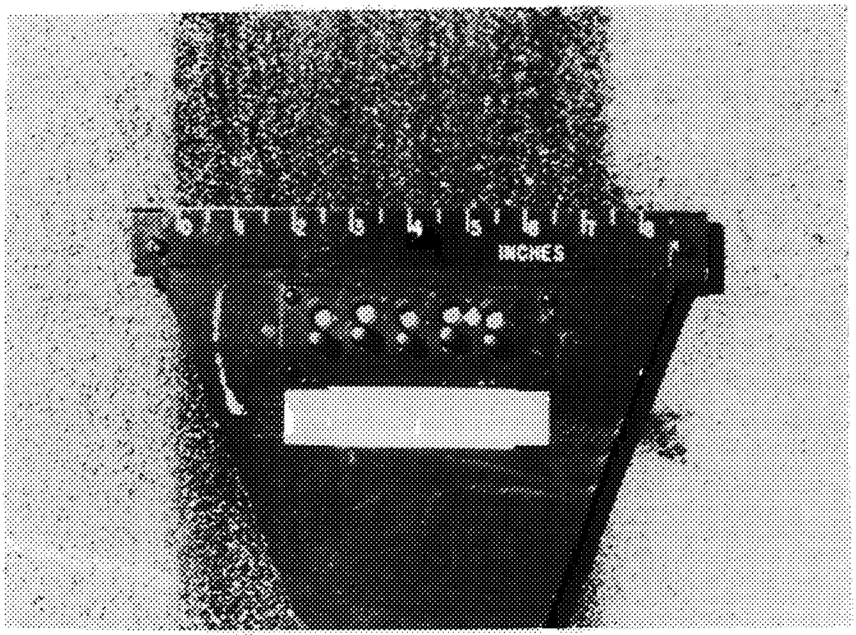


(a) Smooth concrete surface.

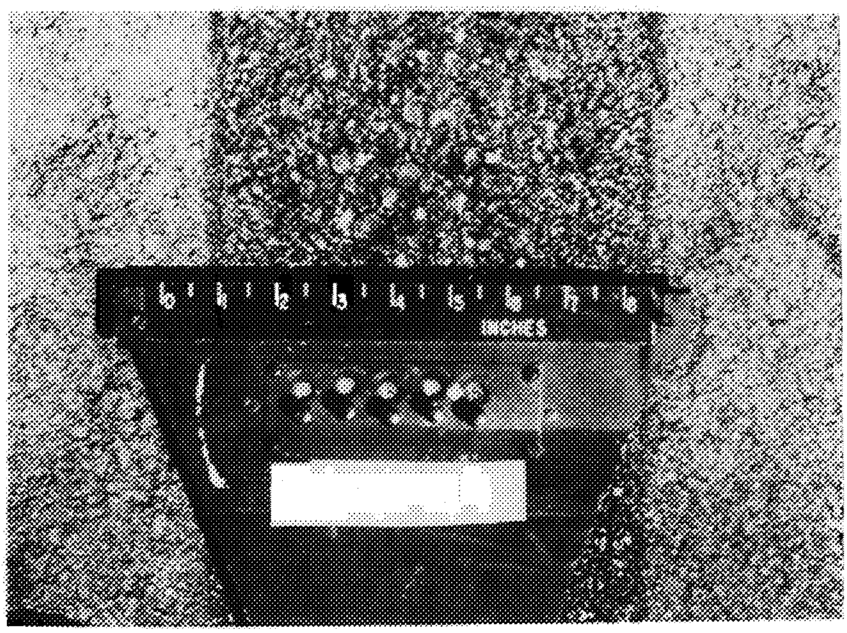


(b) Textured concrete surface.

Figure 4.- Photographs of test runway surfaces. L-67-6648

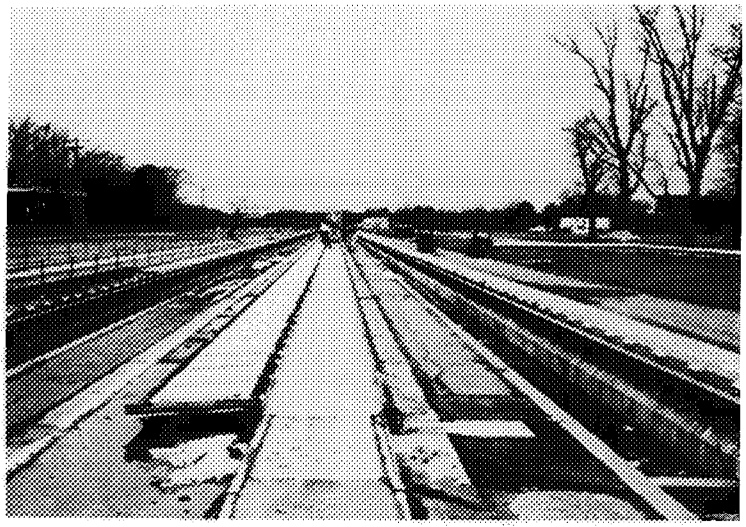


(c) Small-aggregate asphalt surface.



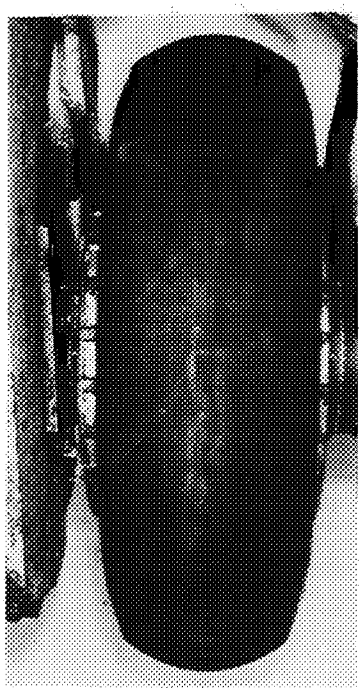
(d) Large-aggregate asphalt surface. L-67-6649

Figure 4.- Continued.

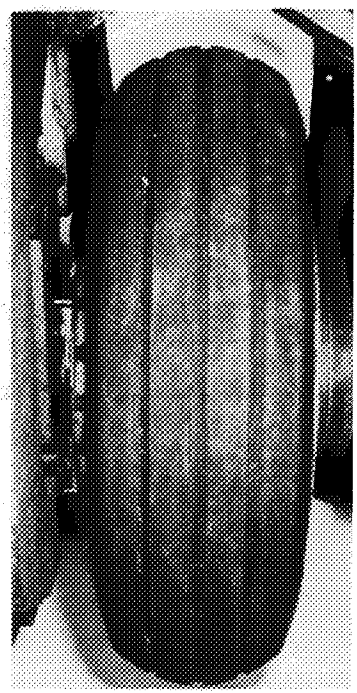


(e) Ice runway surface.

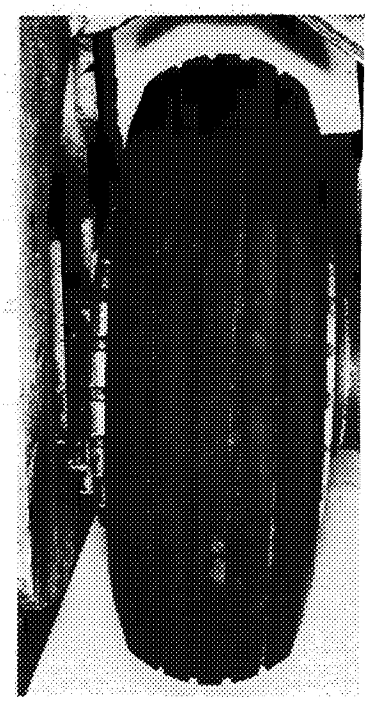
Figure 4.- Concluded.



(a) Tire I.



(b) Tire II.



(c) Tire III.

Figure 5.- Tires used in investigation.

L-67-6650

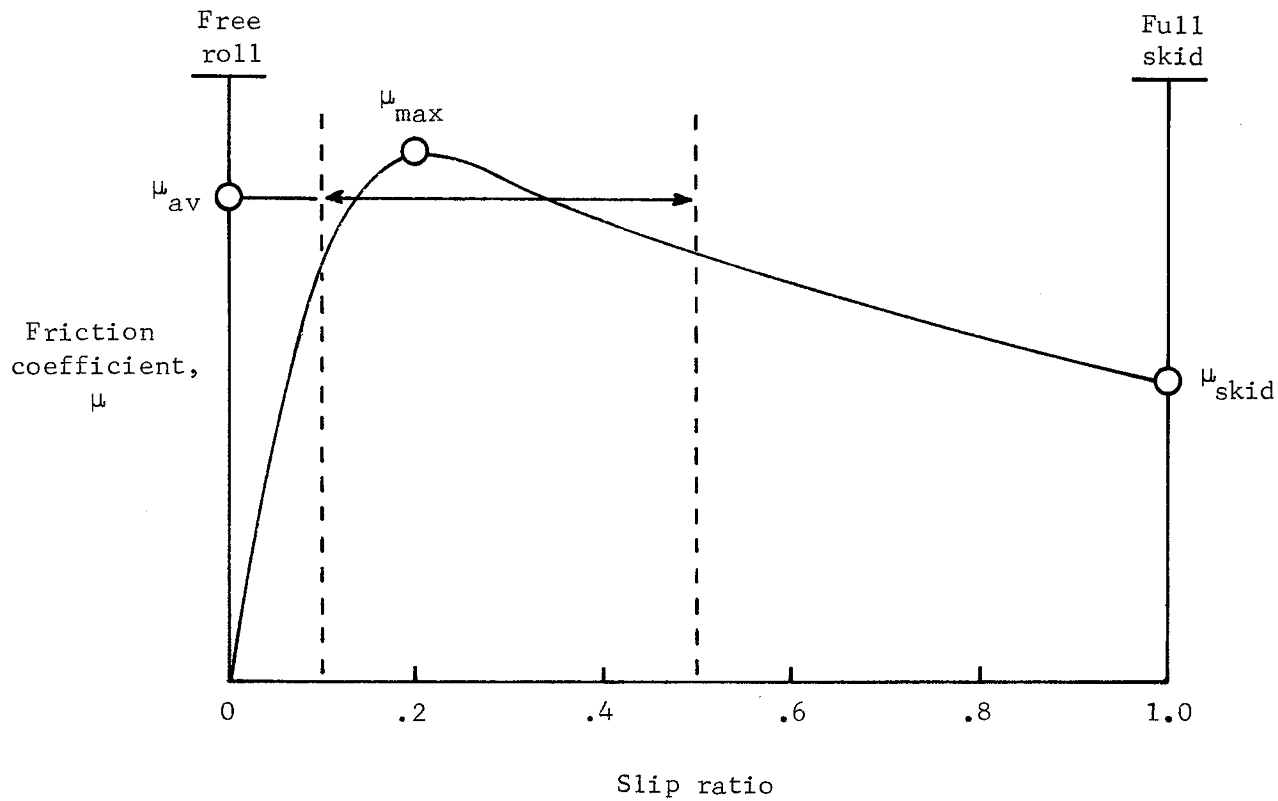


Figure 6.- Schematic comparison of various friction coefficients.

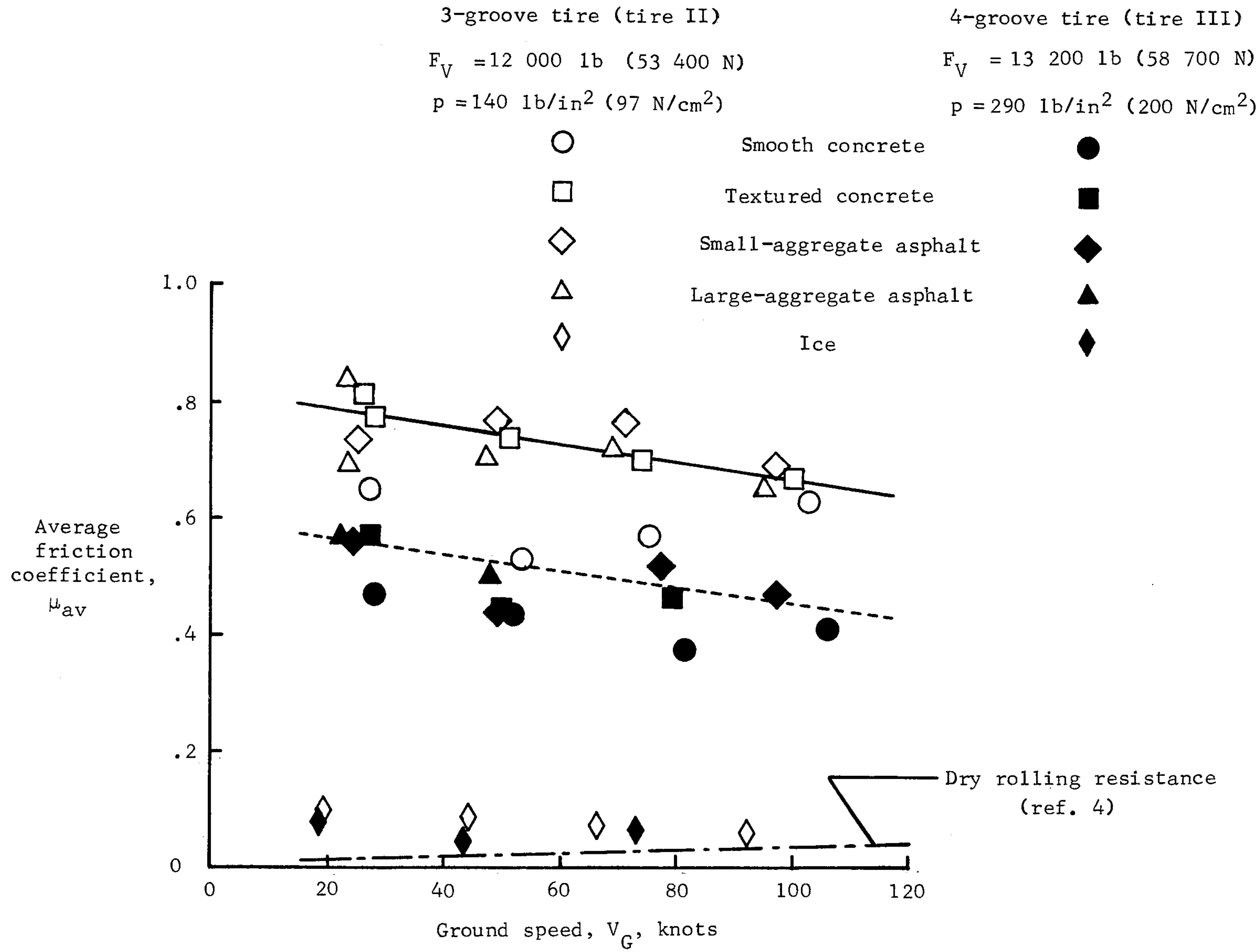


Figure 7.- Effect of surface texture and ground bearing pressure on dry-runway braking effectiveness for tires II and III.

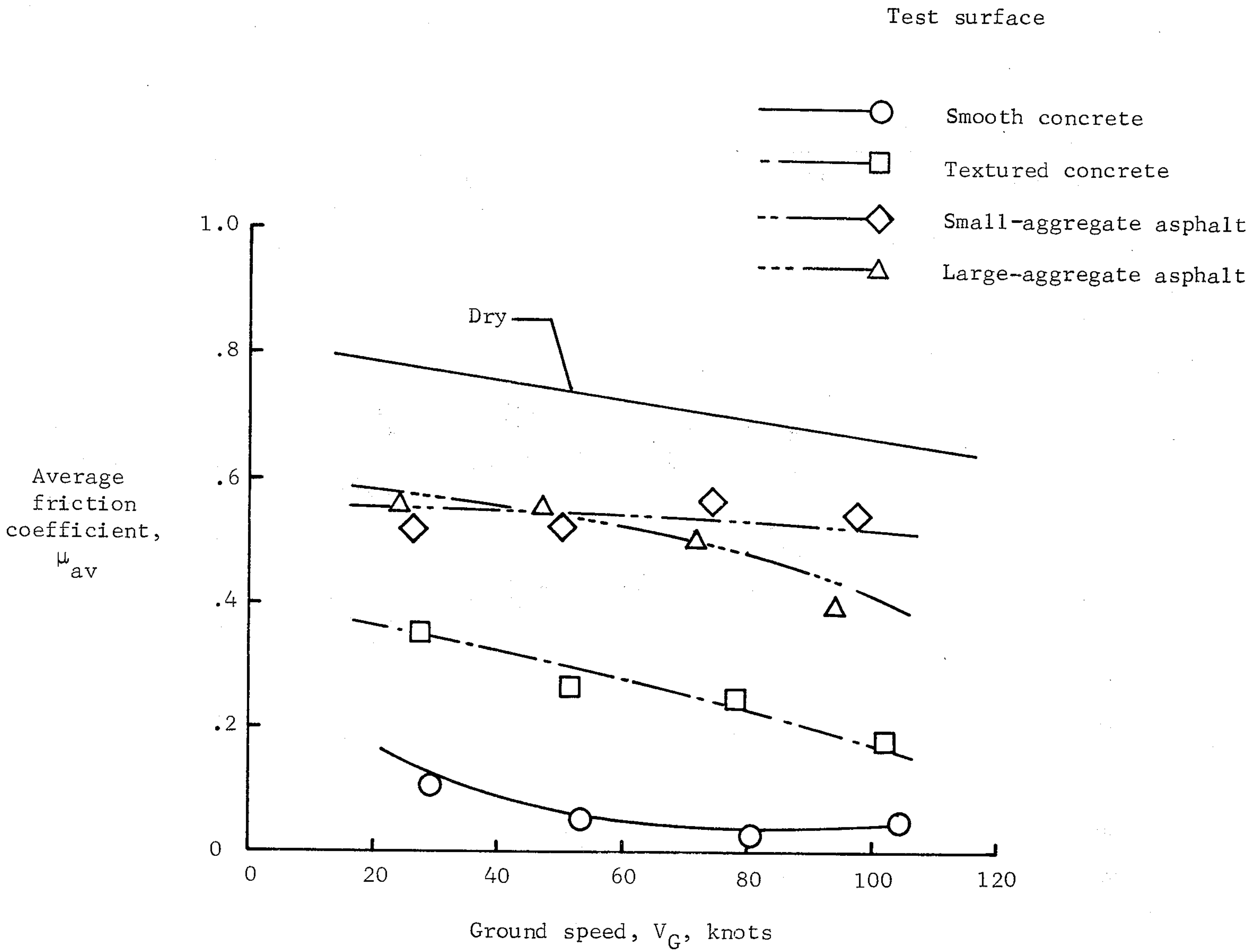


Figure 8.- Effect of surface texture on damp-runway braking effectiveness. Smooth tire (tire I); vertical load, F_V = 12 000 lb (53 400 N); tire inflation pressure, p = 140 lb/in^2 (97 N/cm^2).

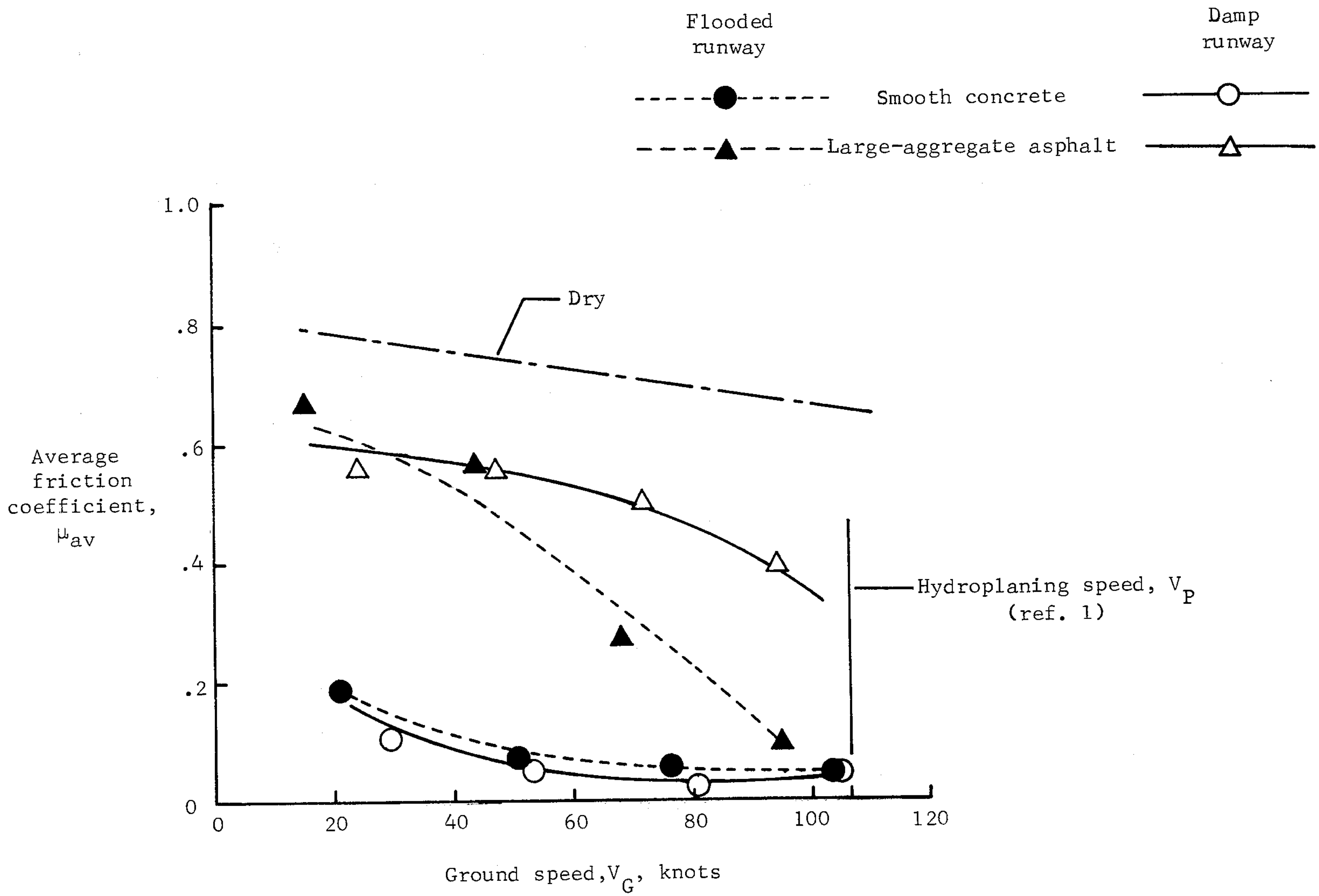


Figure 9.- Comparison of surface texture effects on damp and flooded runways. Flooded water depth = 0.1 to 0.2 inch (0.25 to 0.51 cm); smooth tire (tire I); vertical load, F_V = 12 000 lb (53 400 N); tire inflation pressure, p = 140 lb/in^2 (97 N/cm^2).

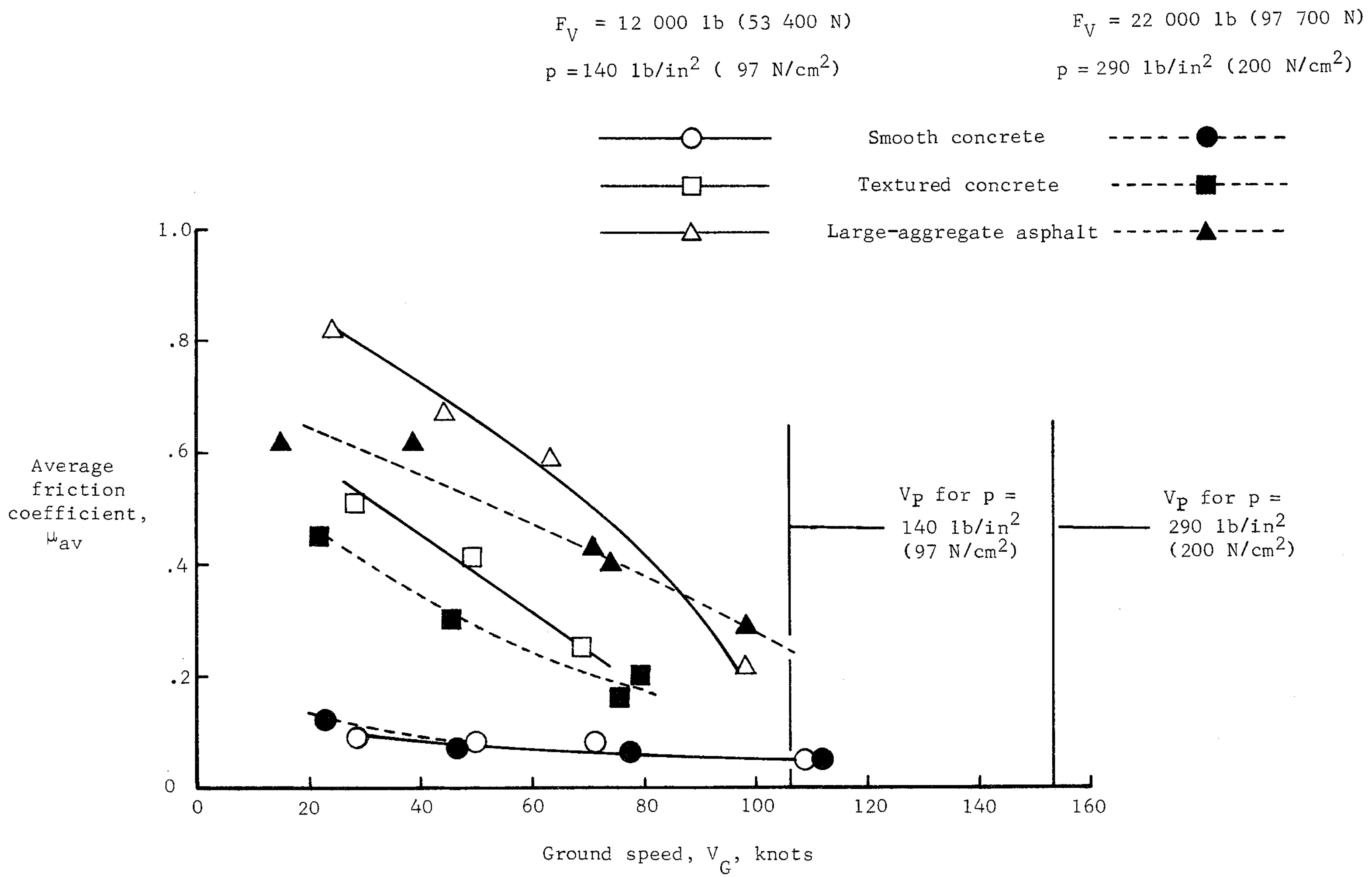


Figure 10.- Effect of ground bearing pressure on flooded-runway braking effectiveness for a smooth tire (tire I). Water depth = 0.1 to 0.2 inch (0.25 to 0.51 cm).

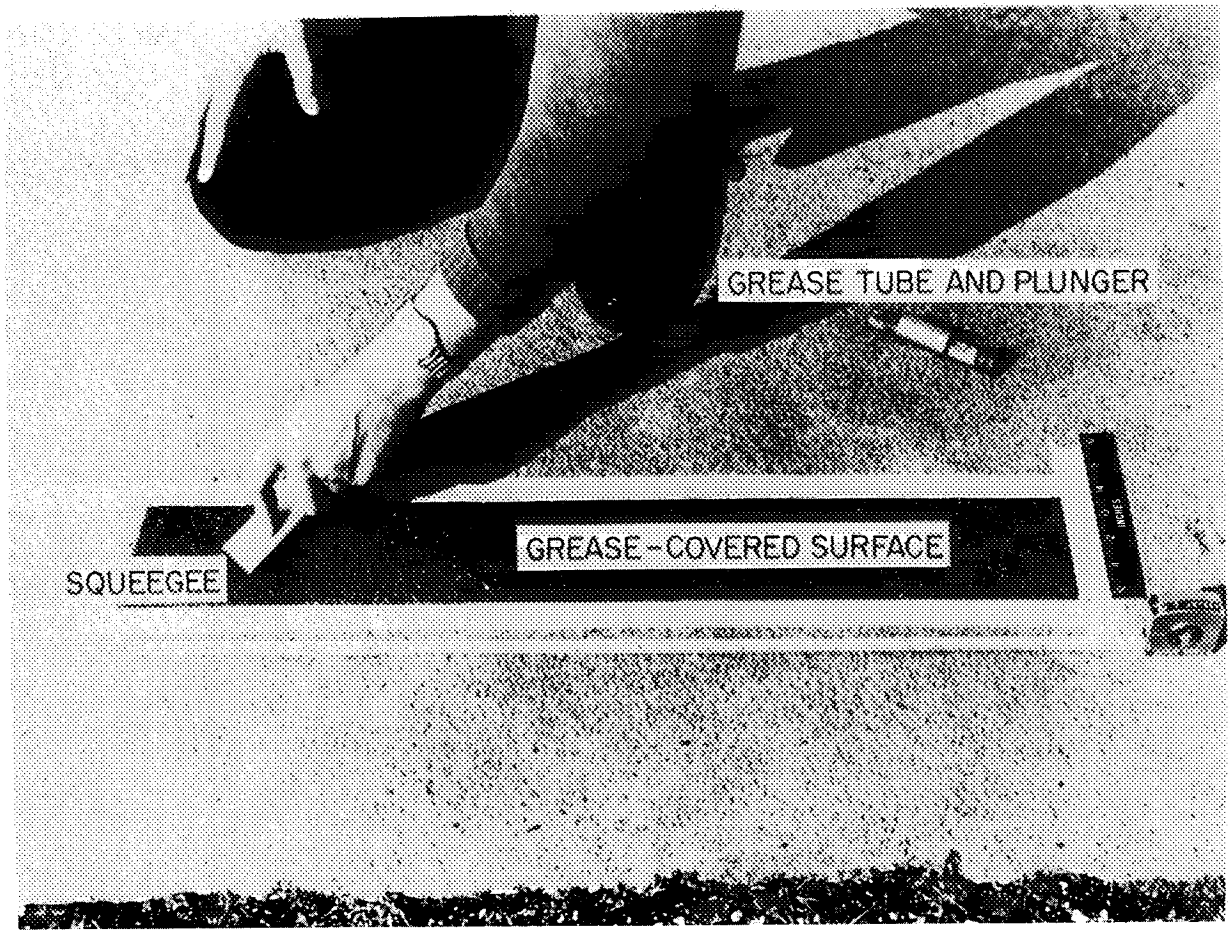


Figure 11.- Illustration of apparatus used in grease-application technique for measuring runway surface texture depth. L-67-6651

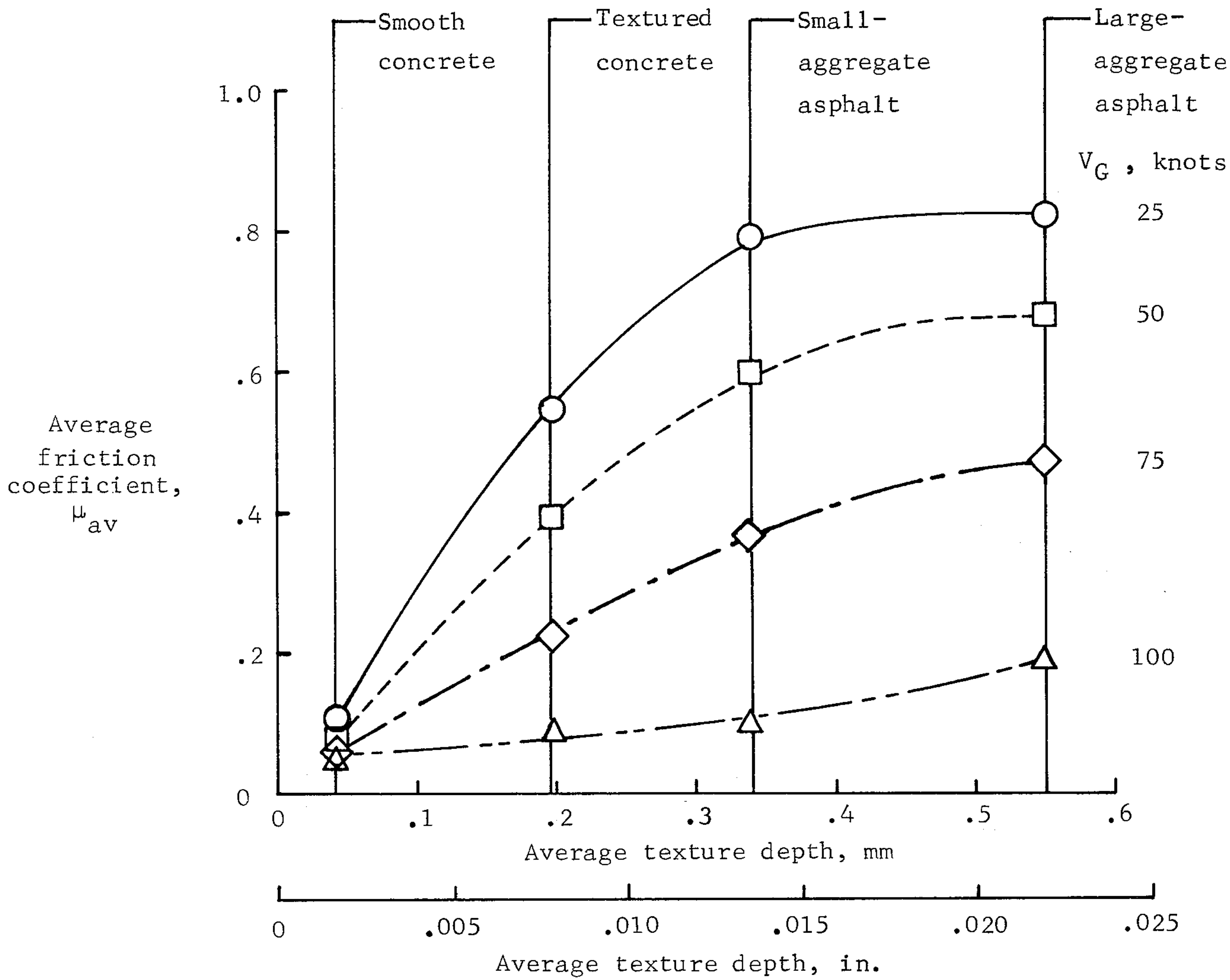


Figure 12.- Effect of measured surface roughness on average friction coefficient developed on a flooded runway. Smooth tire (tire I); vertical load, F_V = 12 000 lb (53 400 N); tire inflation pressure, p = 140 lb/in^2 (97 N/cm^2); water depth = 0.1 to 0.2 inch (0.25 to 0.51 cm).

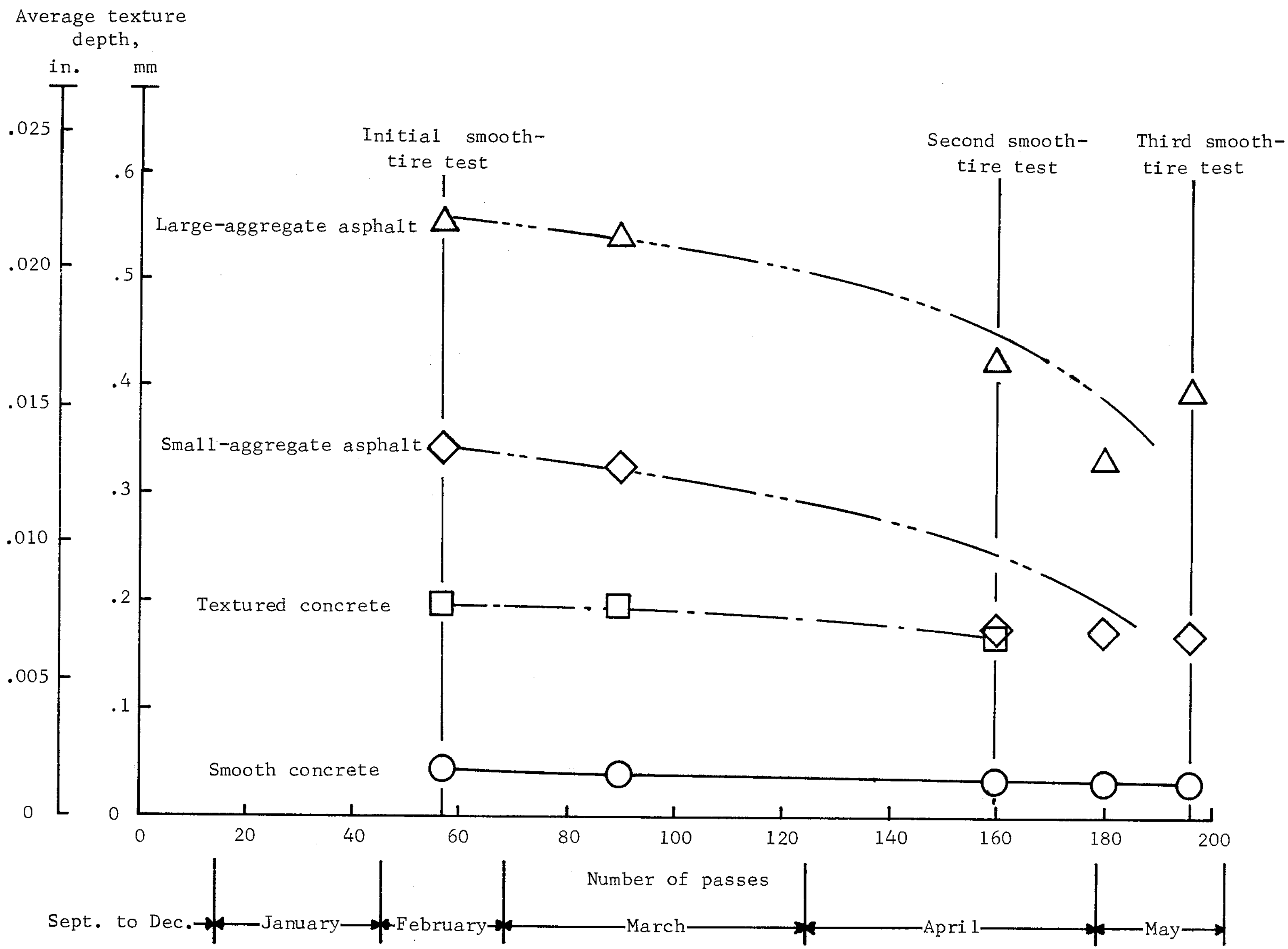
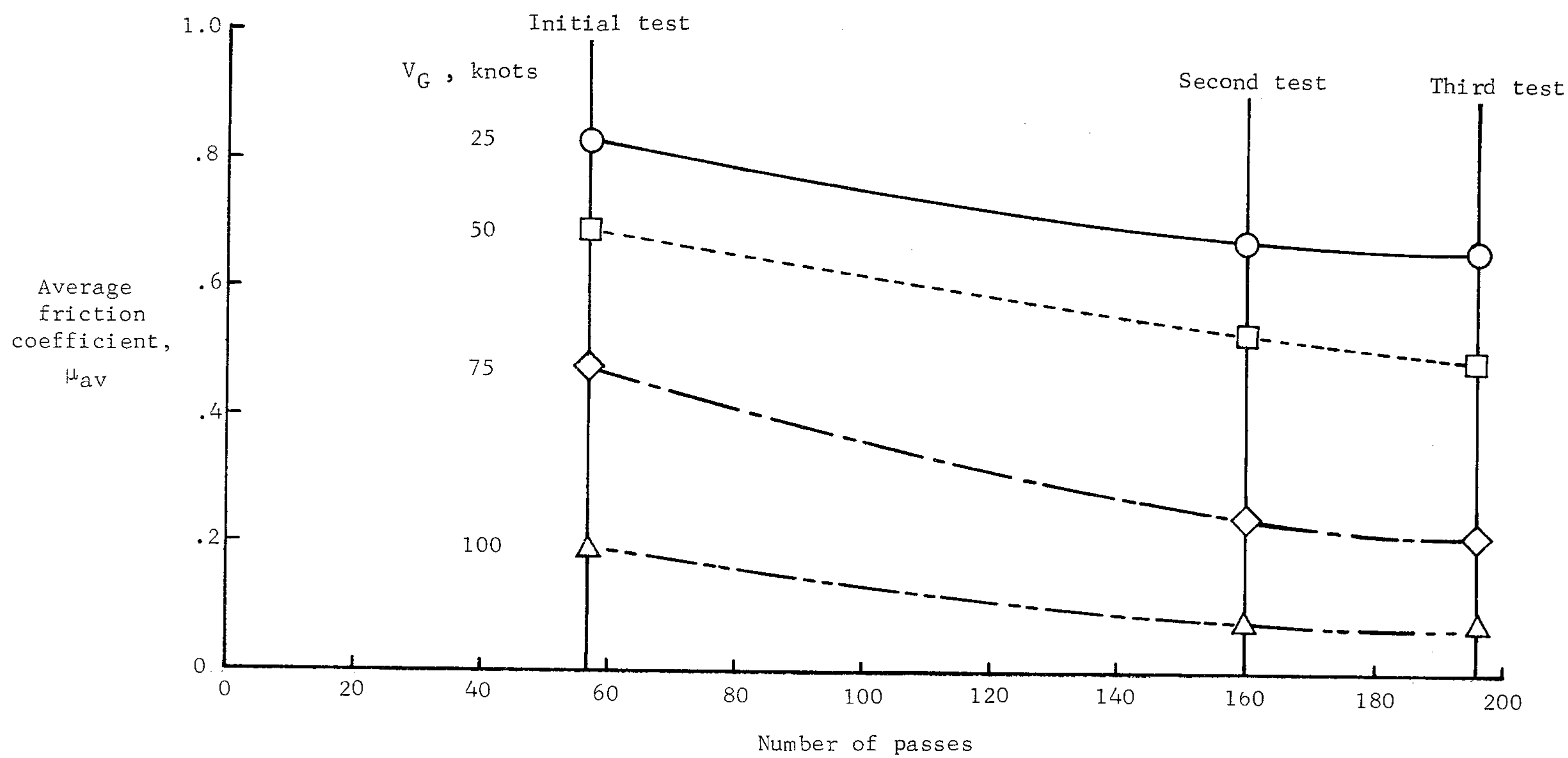
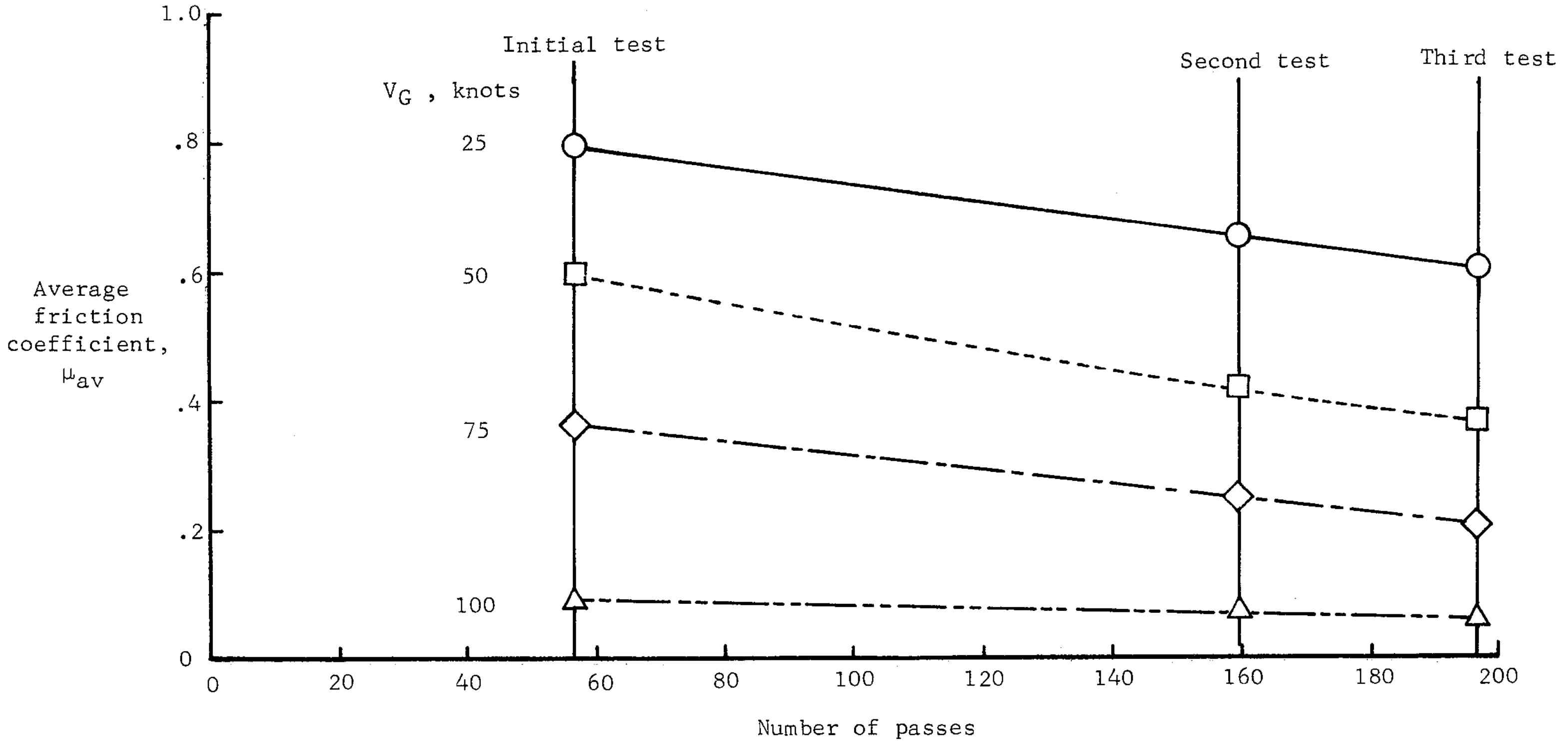


Figure 13.- Experimental measurements of surface wear during the test program.



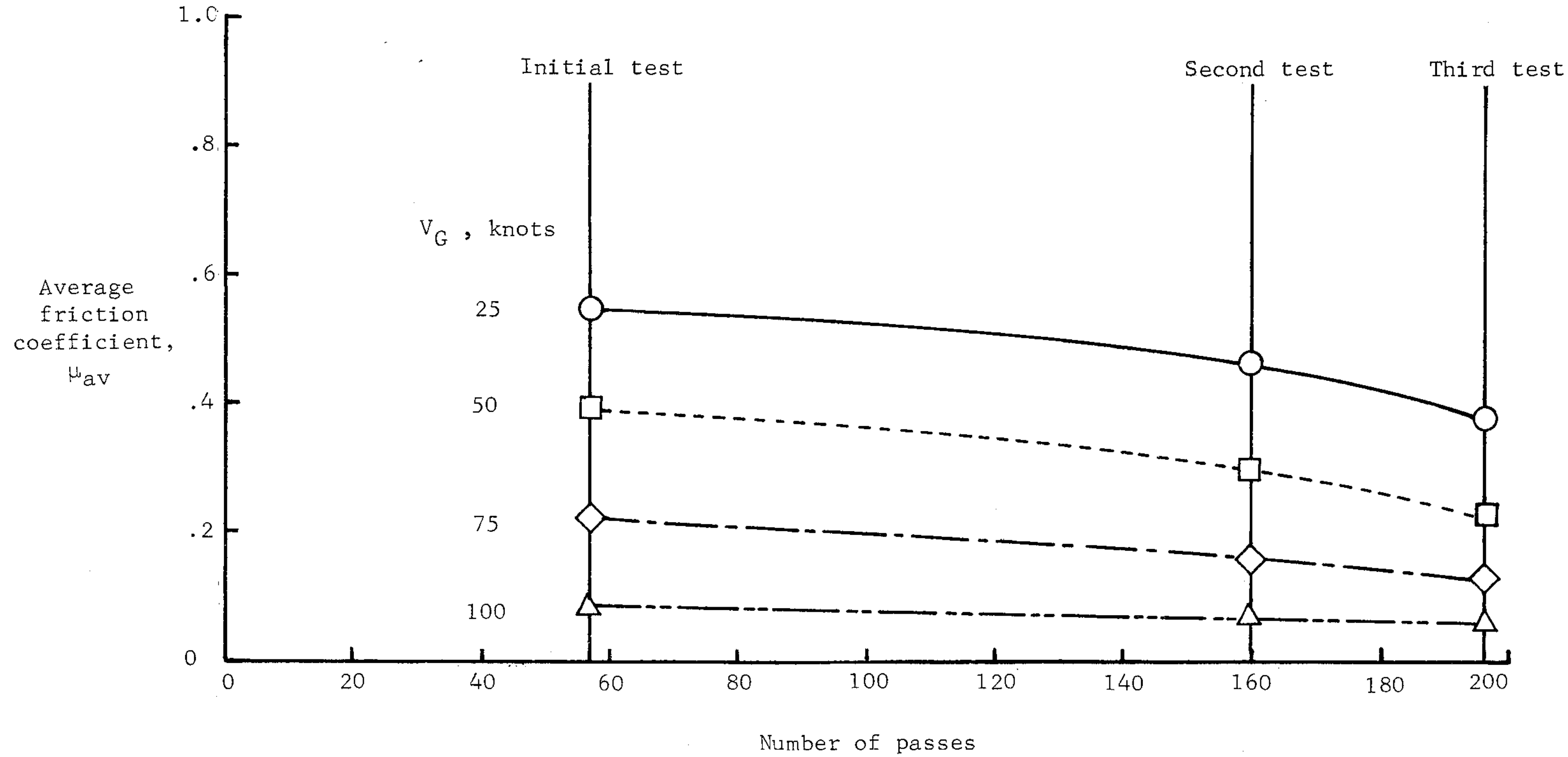
(a) Large-aggregate asphalt surface.

Figure 14.- Effect of surface wear on the friction coefficient developed on the four surfaces tested. Smooth tire (tire I); vertical load, F_V = 12 000 lb (53 400 N); tire inflation pressure, p = 140 lb/in^2 (97 N/cm^2); water depth = 0.1 to 0.2 inch (0.25 to 0.51 cm).



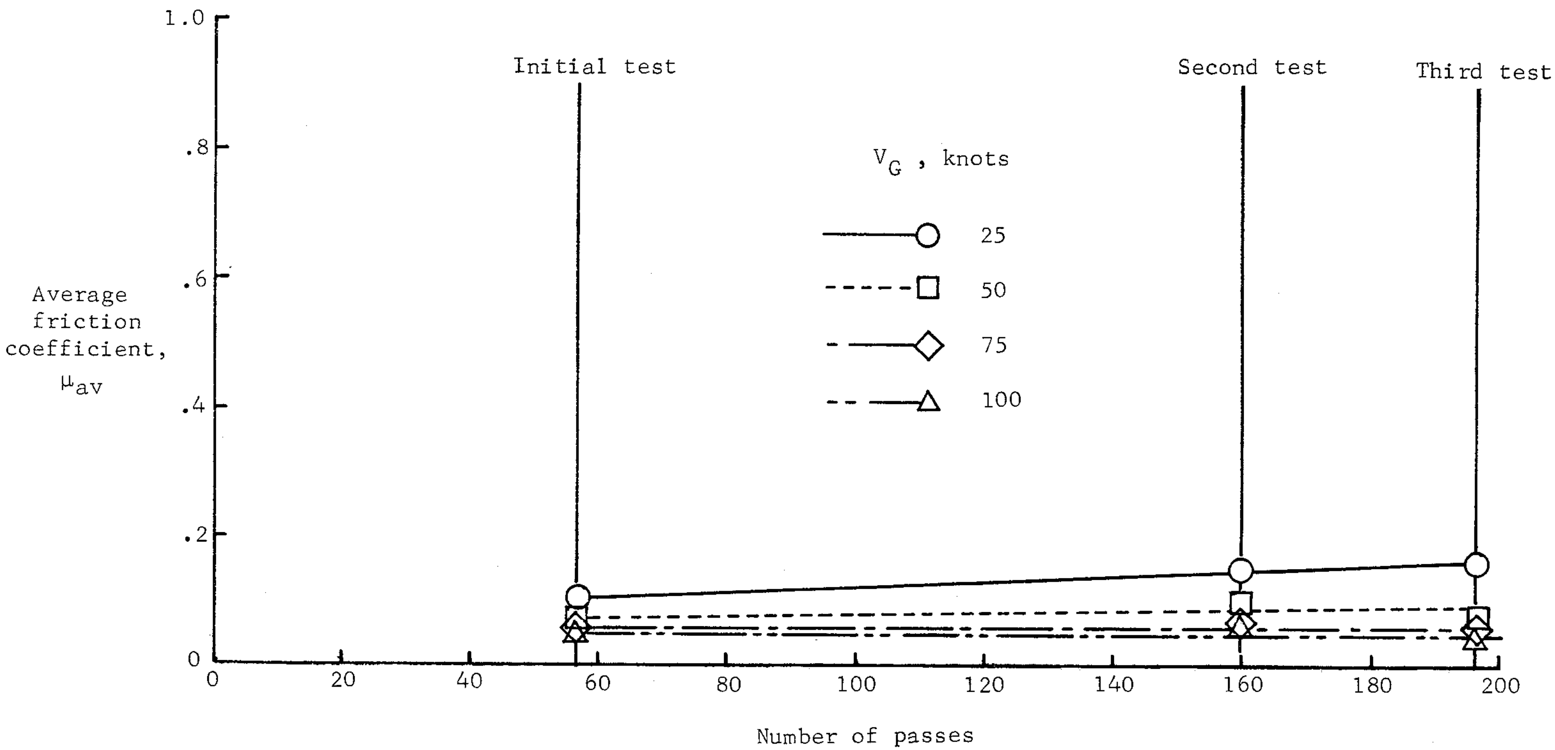
(b) Small-aggregate asphalt surface.

Figure 14.- Continued.



(c) Textured concrete surface.

Figure 14.- Continued.



(d) Smooth concrete surface.

Figure 14.- Concluded.

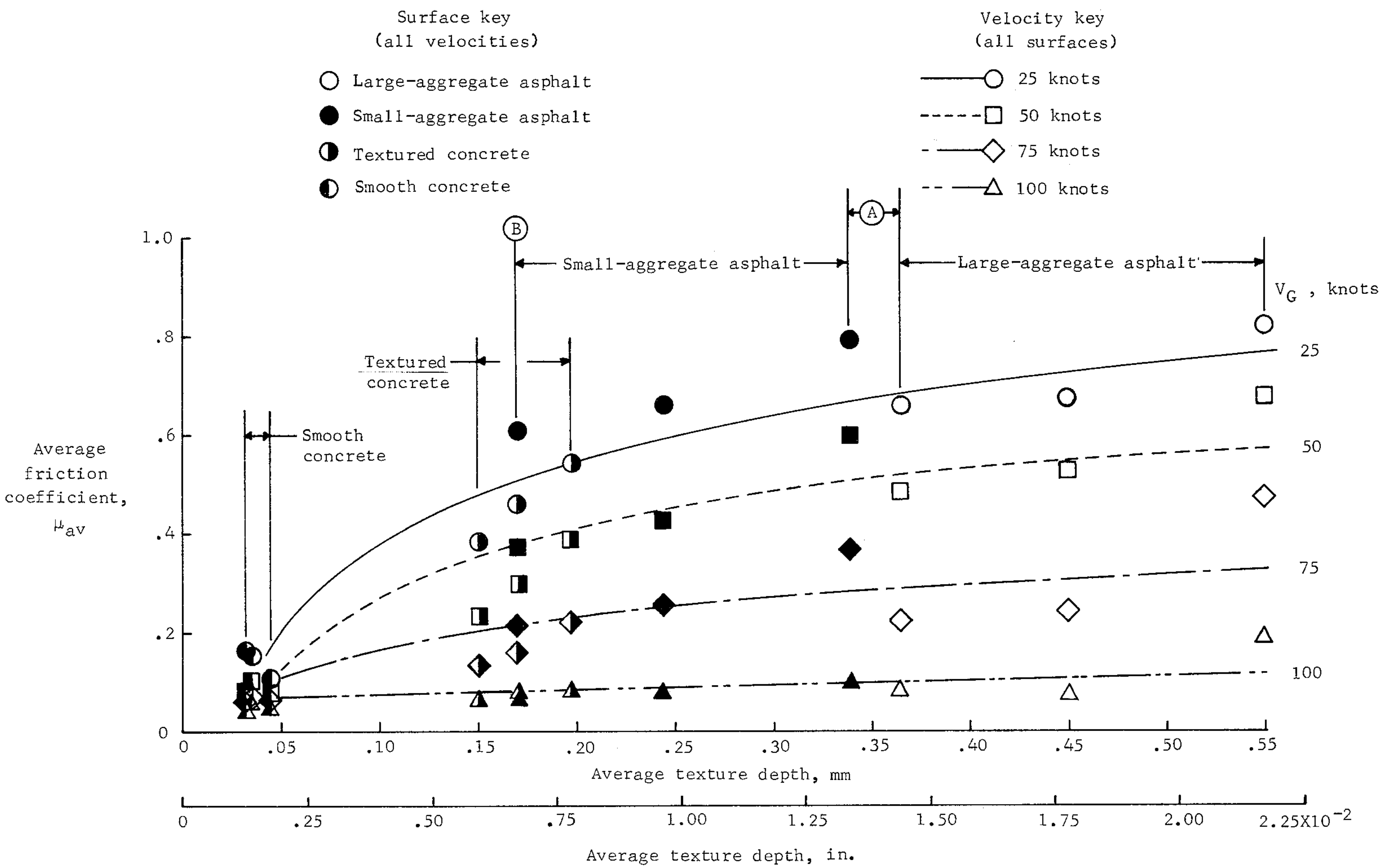


Figure 15.- Effect of measured surface roughness on average friction coefficient developed on a flooded runway. Smooth tire (tire I); vertical load, F_V = 12 000 lb (53 400 N); tire inflation pressure, p = 140 lb/in^2 (97 N/cm^2); water depth = 0.1 to 0.2 inch (0.25 to 0.51 cm).

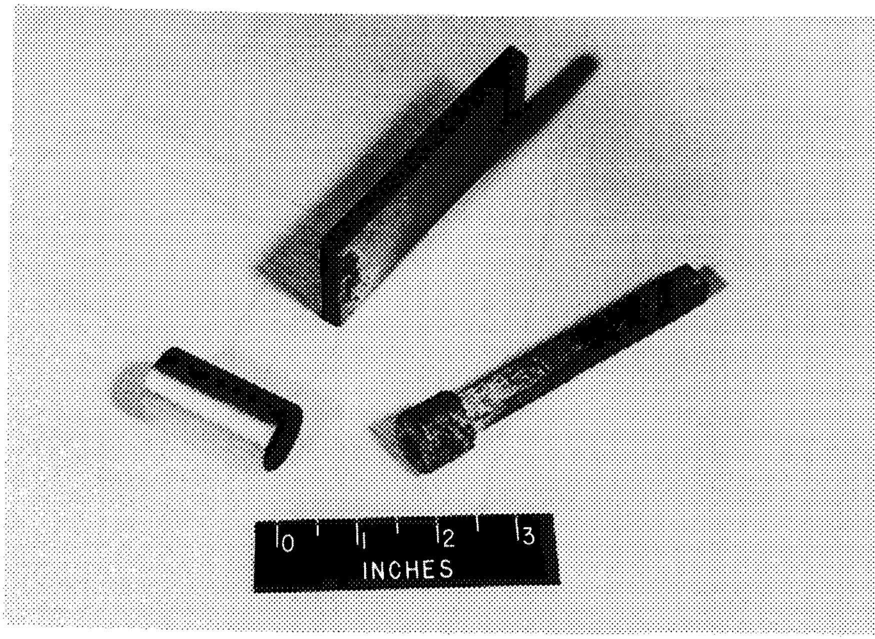


Figure 16.- Grease-volume measuring tube, plunger, and rubber squeegee. L-65-1868

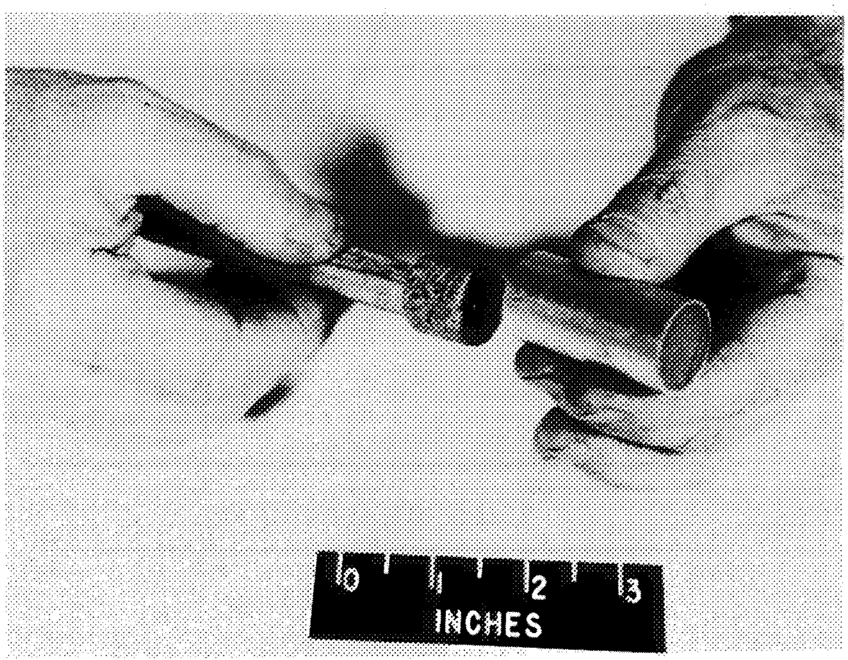


Figure 17.- Measuring tube filled with grease. L-65-1869

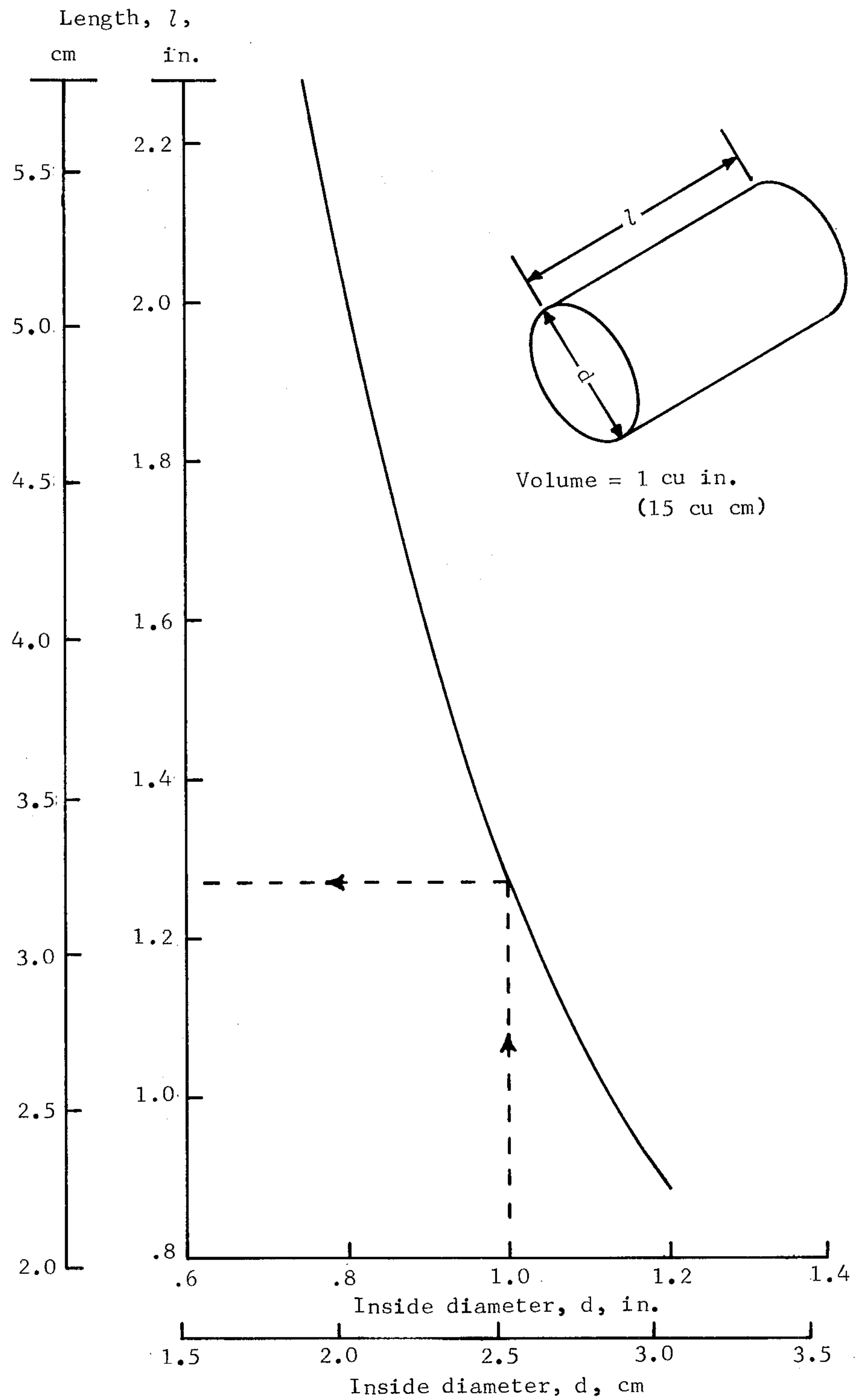


Figure 18.- Measuring-tube dimensions to measure 1 cubic inch or 15 cubic centimeters of grease.

NASA-Langley, 1967 —— 27 L-5106

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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