HIGHWAY RESEARCH BOARD

Bulletin 302

Skid Testing

1961

National Academy of Sciences—
National Research Council

publication 93

HIGHWAY RESEARCH BOARD

Officers and Members of the Executive Committee

1961

N.R.C. HIGHWAY RESEARCH BOARD

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1961

Presented at the

40th ANNUAL MEETING

January 9-13, 1961

National Academy of Sciences—
National Research Council
Washington, D.C.
1961

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Effects of Aggregate Factors on Pavement Friction

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Even though the skidding resistance of pavements has been studied for many years, many questions concerning the true nature of the interaction of rubber and pavement surface remain unanswered. During field testing, the lack of control over many of the variables which are included in this problem has prevented the effective evaluation of individual factors.

For this reason certain tests were carried out by the authors on laboratory specimens which, while not greatly resembling pavements, were planned to eliminate many variables and thus aid in evaluating those which remain. Actual surface resistance measurements were made in the laboratory machine located at the Joint Highway Research Project at Purdue University.

Tests were conducted on surfaces planned in a manner to maintain a constant area of aggregate while varying the number and shape of edges. Although not exhaustive, several radically different shapes were included. For some of the specimens, the aggregate shapes used permitted controlled variation in the sharpness of aggregate edges.

A series of tests was performed in which the normal load was made the major variable. For any one specimen the aggregate area was constant. Additional specimens were tested in which the area of aggregate in contact with the test shoe was varied while the edges and test load were held constant. The rock cores used were a soft limestone and a durable sandstone.

The polishing rates of several different rocks were investigated. Skid-resistance tests were made on cores after successive polish cycles using crushed quartz as a polishing medium. The same cores also were tested after polishing with abrasive dust made from the core material.

Tests on rock cores, as polished by different sizes of abrasives, indicated that for a given rubber an optimum size of roughness existed. Graded silica sand was used to make surfaces of different degrees of roughness in order to find this optimum size of roughness or texture for the rubber test shoes used.

●IN recent years many pavement engineers have become concerned with the rapidity with which certain pavements have polished under the action of modern high-volume traffic. Several agencies have field-measurement programs under way in which skid resistance of pavements is evaluated. However, most field measurements do not aid greatly in furthering an understanding of the basic principles which contribute to this problem. Consequently, there has been a trend toward the increased use of laboratory-scale tests intended for determining the coefficient of friction or some other related property of pavement surfaces (1, 4, 5, 11, 13). Such tests, although possibly not representative of true field conditions, do have the advantages of lower cost, controlled conditions, and application to mixes not available on existing roads.

The studies presented in this paper were intended to penetrate into some of the basic factors present in skid-resistance problems. The test specimens were planned to provide information on certain factors which cannot be isolated easily in field tests. In so doing, the configuration of the aggregate pieces in the specimens necessarily departed from that in full-scale pavements.

TEST PROCEDURE

The procedure followed for these tests, consisted of three basic steps:

1. A surface specimen was mounted in a test ring from the skid-resistance machine.
2. This surface was worn or polished to a degree which fitted the series under test.
3. Measurements were made of the relative resistance value of the surface.

The second and third steps were repeated several times on some of the test surfaces, when so doing added to the information obtained.

The actual method of performing the first step was varied to accommodate the aggregate shape used. The continuous surfaces were prepared by sawing slices from 6-in. rock cores and mounting them in the test rings. The discontinuous surfaces were prepared by hand placing precut aggregate pieces in predetermined patterns and backing with mortar or bitumen. The controlled fine-textured surfaces were molded from sand-bituminous mixtures. The material was compacted into the rings to a true surface by means of a loaded vibrating plate. The first surface specimens were polished in the skid-resistance machine in a manner similar to that used by Shupe and Goetz (11) on coarse aggregate bituminous pavement specimens. This procedure consisted of holding a rubber polishing surface against the rotating specimen while water carried an abrasive between the two surfaces. The resulting polish was controlled by varying both the abrasive used and the length of the polishing cycle.

This form of polishing left a circular pattern of minute striations on the solid-core surfaces. For this reason, later surfaces were polished in the manner developed by the authors for fine bituminous surfaces (12). The equipment consisted of a turntable on which the surface specimen turned freely and a flat, tread-rubber, polishing shoe 2 in. in diameter rotated by a drill press (Fig. 1). In use, the specimen was flooded with water charged with abrasive dust. A static load on the drill-press operating level pressed the rotating shoe against the slowly turning specimen. As the axis of rotation of the turntable was offset from that of the polishing shoe, an annular area large enough to accommodate the test shoe was polished. The pressure was held constant for all specimens, but both the nature and size of the abrasive dust were varied.

The actual skid-resistance measurements were made in the laboratory skid-resistance machine developed by the Joint Highway Research Project at Purdue University (11). This machine consists of a power source arranged to rotate a flat, circular test specimen which is held in contact with a tread rubber test shoe. A schematic diagram of this equipment is shown in Figure 2. In operation, a test specimen is clamped into the powered chuck which is then rotated at a speed equivalent to 30 mph at the average radius. The test shoe is then pressed against the rotating surface by a normal force supplied through the weighted lever system. Throughout the test the surface is flooded with water. The frictional torque transferred from the driven specimen to the test shoe is measured by a cantilever arm bearing SR-4 strain gages which activate an analyzer. The values read from the resulting oscillograph are in units of torque and give a convenient relative basis for comparisons of different surfaces.

RESULTS

Several investigators have stated that friction between pavement and tire is made up of two major components (7, 8, 9). One component of the friction or skid resistance is that force required to overcome direct mechanical interference at the edges of the aggregate. This portion is affected by the hardness of the rubber, the width of the crevices between aggregate particles, and aggregate edge shapes. The second component is the friction between the surface of the aggregate and the sliding rubber surface. The magnitude of this portion of the friction is primarily a function of the nature of the two materials, speed of the relative motion, and the magnitude of the normal pressure.

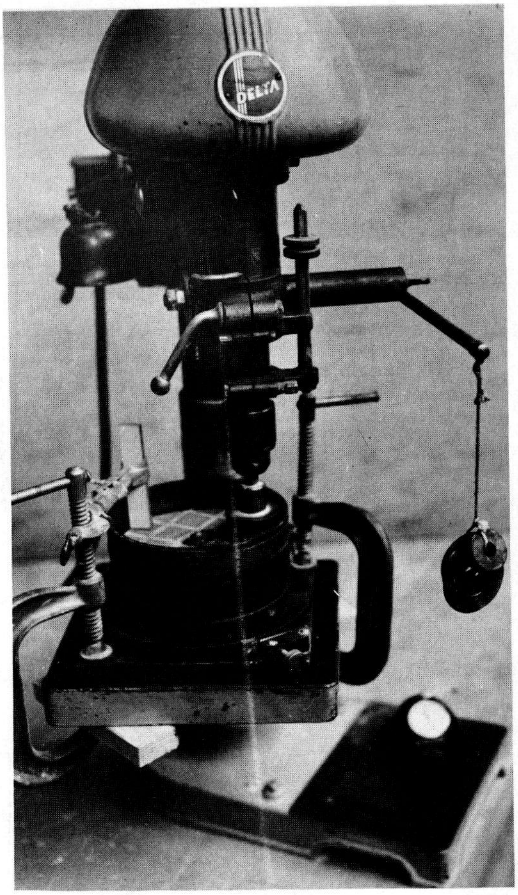

Figure 1. Drill press setup for polishing.

Effect of Aggregate Edges

To show the effect of aggregate particle edges on frictional resistance, several special specimens were prepared of similar surface aggregate area. The term "surface aggregate area" as used here refers to the total area of those faces of the aggregate which lie essentially in the plane of the pavement surface. This area can be readily determined for flat-surfaced aggregate but is somewhat indeterminate for round aggregate. It was intended to control that area of aggregate touched by the sliding rubber test shoe. The first set of specimens consisted of three limestone cores. One end of each core was squared with a diamond saw. Radial slots were cut by means of the diamond saw across two of the cores. The first received 12 slots 0.32 in. wide. The second received 24 slots one-half as wide or 0.16 in. Thus the area of the two slotted cores was the same although the number of edges for the second was twice that for the first. The slotted cores appear as RS-8 and RS-16 in Figure 3. The third core received no special treatment.

These cores were first tested in an "as sawed" condition. They were again tested after a wearing cycle in the skid machine consisting of 1 min. with No. 000 crushed quartz as abrasive, 1 min with No. 00000 crushed quartz, and 1 min with mineral filler (limestone dust). A third test was made after a polishing cycle of 1 min with mineral filler and 30 sec with water only (Table 1). The results of the last test were relative resistance values of 48 for the smooth core, 57 for RS-16, (24 slots) and 58 for RS-8 (12 slots). Thus, the creation of edges did increase the relative resistance values but the quantity of edges had little effect.

Similar solid and slotted cores were prepared from a hard sandstone obtained from Albion, New York. Table 1 shows that the relative resistance value of the solid sandstone after fine polish was 99, that of the core with 12 slots 76, and that of the core with 24 slots 72. Although the creation of edges reduced the relative resistance, the number of edges again seems unimportant. Increasing the slots from 12 to 24 did cause a further reduction in relative resistance, but not in proportion to that which resulted from the inclusion of the first 12 slots.

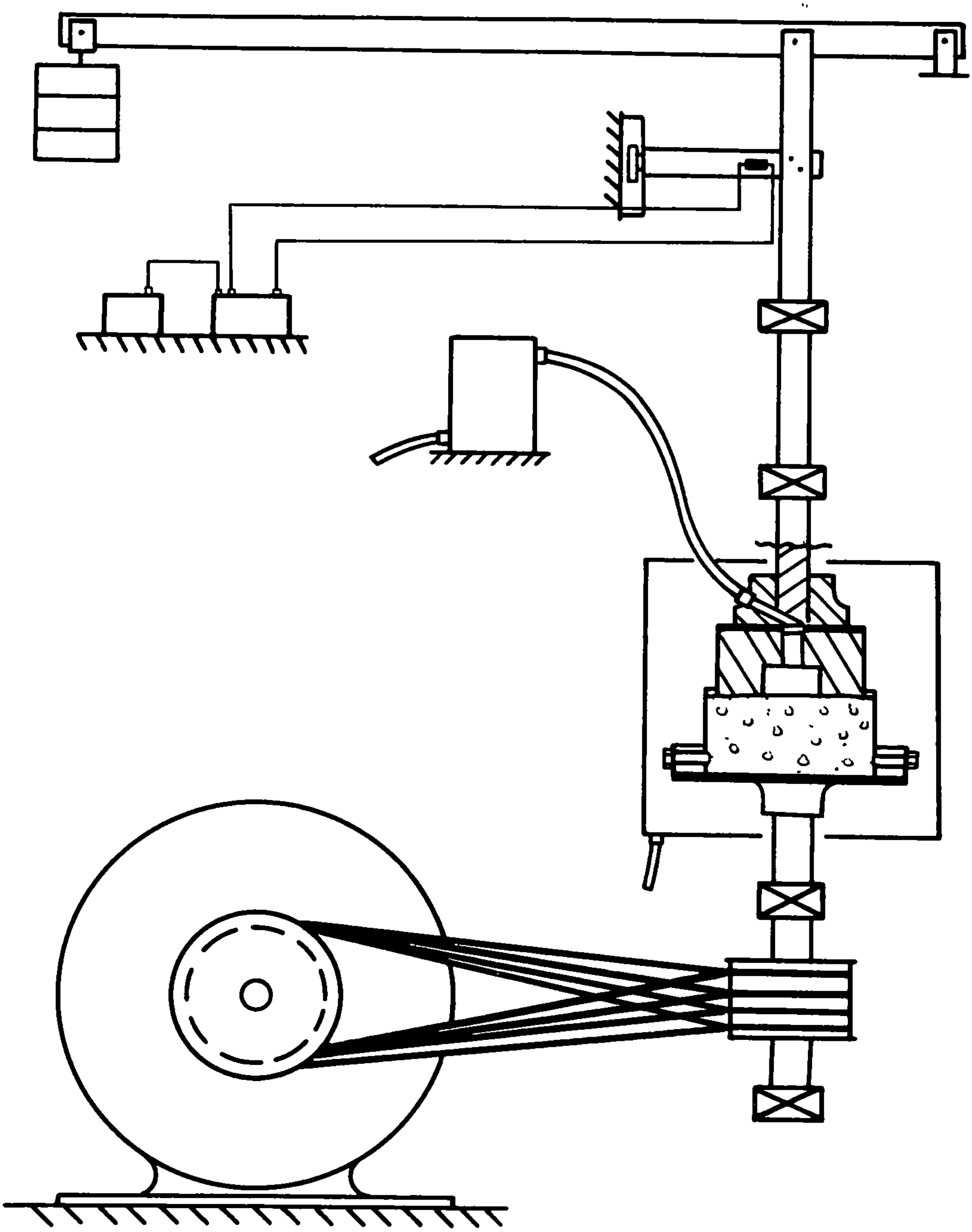

Figure 2. Schematic diagram of laboratory skid-test apparatus.

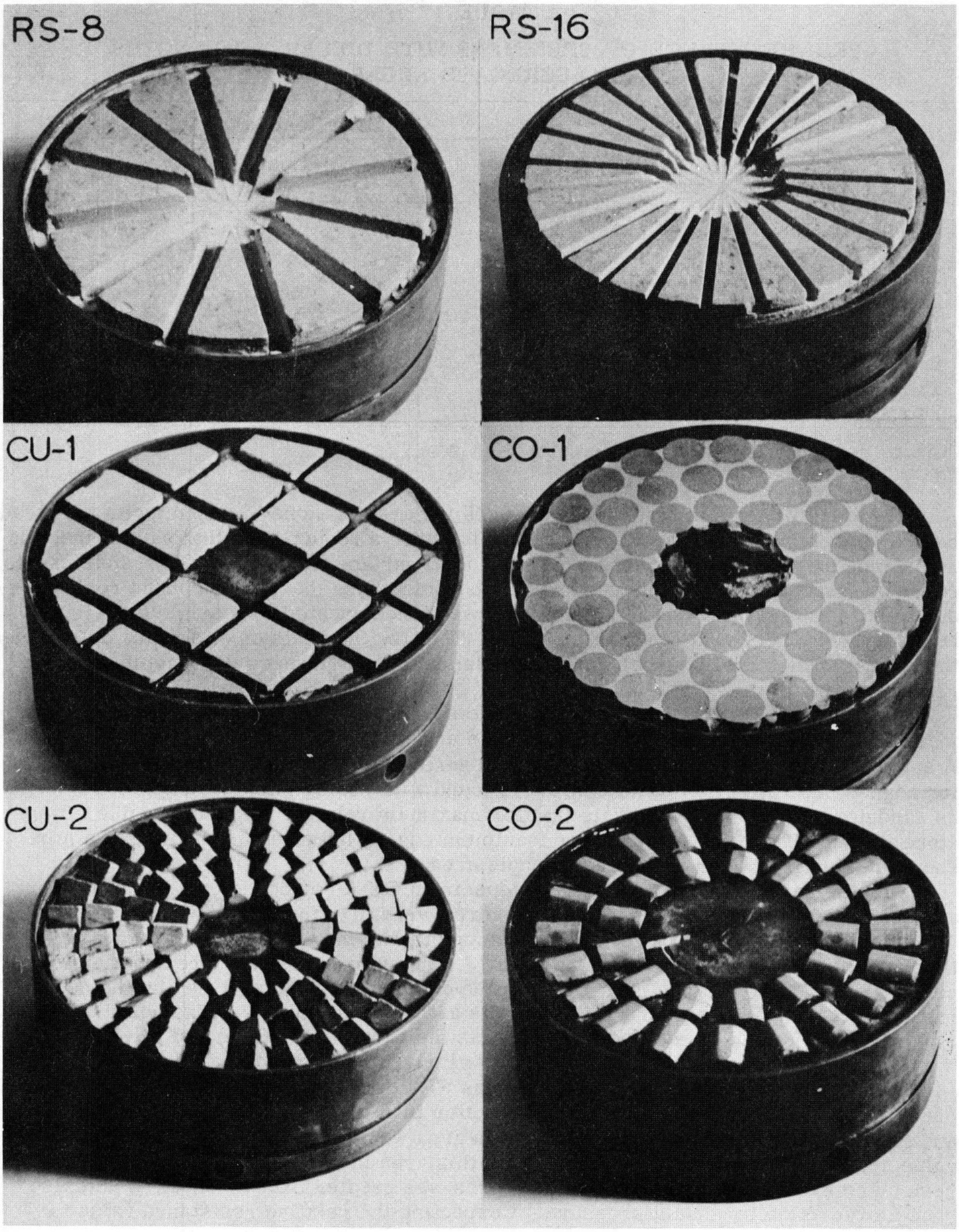

Figure 3. Specimens studied for the effects of edges and area on skid resistance.

TABLE 1

SKID RESISTANCE OF SPECIMENS WITH DIFFERENT LENGTHS OF AGGREGATE EDGES

Specimen	Relative Resistance Value		
	As Sawed	Coarse[a] Wear	Fine Polish[a]
Greencastle limestone			
Solid	46	34	48
12 radial saw cuts (0.32 in.)	60	50	57
24 radial saw cuts (0.16 in.)	55	48	58
Albion, N.Y. sandstone			
Solid	108	87	99
12 radial saw cuts (0.32 in.)	91	78	76
24 radial saw cuts (0.16 in.)	88	74	72

[a]Coarse wear and fine polish—as by Shupe and Goetz (11).

The cutting of slots in the surface reduced the area of stone in contact with the tread. Such a change in surface would be expected to cause a reduction in that part of the skid resistance or relative resistance which is due to surface friction. Cutting slots created edges or discontinuities in the surface which would cause that portion of the resistance due to edge interference to increase. The resistance created by a single edge is related to the width of void creating the edge. That is, the width of void space determines the depth to which tread rubber can penetrate and thus influences the magnitude of the resistance due to this edge.

Comparing the results from the limestone series to those from the sandstone series indicates that the effect of aggregate particle edges is related to the aggregate surface. A soft aggregate which polishes to a smooth surface is benefited by sacrificing area for edges. The directly opposite effect is found with strongly textured aggregate such as sandstone. This would indicate that for maximum relative resistance value a limestone mixture should be designed for maximum edges, but a textured-aggregate mix should be designed for maximum aggregate area.

As further verification of this effect, specimen CU-1 composed of 1-in. squares and specimen CO-1 of 0.66-in. diameter cores were prepared (Fig. 3). At this stage of the tests the method of polishing the specimens was modified to avoid polishing in the same pattern as that used during testing. The solid limestone core and the slotted cores RS-8 and RS-16 were resurfaced in the diamond saw and polished by the new method using the drill press. These results are given in Table 2. The relative resistance value for CU-1 was 50, the area was the same as for RS-8 and RS-16, and the edges were approximately those of RS-8 although not located radially.

The relative resistance value of CO-1 was 57. However, the area of stone in this specimen was approximately 15 percent greater than that in RS-8, RS-16, or CU-1 and later work indicated such an increase in area would increase the relative resistance value approximately 4 units. Adjusting for this area factor would reduce the relative resistance value to 53. The fact that the area was greater than 12 sq in. would also cause a reduction in contact pressure. Correcting the relative resistance value to terms of the same contact pressure would increase this adjusted relative resistance value to approximately 58. Thus, the more irregular voids of sample CO-1 were slightly more effective in creating resistance than the radial slots of specimens RS-8 and RS-16 and the edges of specimen CU-1.

To remove the effect of particle edges on pavement friction, the interparticle space in the specimens previously referred to (RS-16, CU-1, CO-1) were filled with plastic aluminum. (See specimen CO-1 in Fig. 3.) After the aluminum had set, the surface was repolished with the same grade abrasive as used previously and the relative

TABLE 2

SKID RESISTANCE OF SURFACES[1] COMPOSED OF CONTROLLED-SHAPE ROCK FRAGMENTS

Specimen	Shape	Length of Edges or Radial Dimension (in.)	Area of Rock Under Shoe (sq in.)	Contact Pressure (psi)	Relative Resistance Value: Aggregate Interstices Open		Relative Resistance Value: Aggregate Interstices Filled	
					As Measured	Corrected to 28 psi	As Measured	Corrected to 28 psi
CO-2	0.66-in. cores	20.64	0.0	-	28	-	-	-
	lying flat	20.95	10.69	57	46	40	-	-
CU-1	1-in. square cubes, flat, 1/4-in spacing	18.8	12.11	50	50	46	46	45
RS-16	Solid core, 24 3/16-in. radial slots	36.0	12.1	50.3	50	46	44	43
RS-8	Solid core, 12 3/8-in. radial slots	18.0	12.1	50.3	48	44	-	-
CO-1	0.66-in. cores on end	25.85	14.01	43.4	57	53	52	51
CU-2	0.5-in. cubes	30.5	0.0	-	67	-	-	-
	on edge	30.5	5.5	110	44	28	-	-
SC	Solid core	0	18.85	32.1	-	-	44	43
Aluminum cement	Solid surface	0	18.85	32.1	-	-	48	47

[1] Greencastle limestone, test load, 463.72 lb; shoe area, 14.45 sq in.; polished with No. 000 crushed quartz.

resistance value again determined. Plastic aluminum was used for this purpose as the relative resistance value for a surface of this material was 47, which was nearly the same as the limestone. Filling the interparticle spaces to eliminate edges reduced the relative resistance for all the surfaces, but the change was small. That for CO-1 fell from 57 to 52, for CU-1 from 50 to 46, and for RS-16 from 50 to 44. At the same time, the contact pressure decreased due to the greater area of contact. As shown by later tests, the small reduction in relative resistance value could easily be due to this factor (Table 2).

Effect of Aggregate Area and Contact Pressure

As area of aggregate in the contact face seemed important, an additional specimen of small, 0.66-in. diameter, limestone cores was prepared. For this specimen the cores were placed with an element of the curved surface located radially in the test specimen as shown by CO-2 in Figure 3. Located in this manner the length of edges of the cores approaching the test shoe during a test remained constant regardless of the degree of wear of the cores. The first test of this sample was made before any polishing was carried out and the value obtained probably reflected this condition. For this first test the area of contact was uncertain as the rubber shoe rested on the curved surfaces of the cores and necessarily deformed until sufficient resistance developed to support the testing load. This implies contact for an appreciable area of each core rather than zero area.

After each relative resistance value measurement, the specimen was ground by means of a rubber shoe and abrasive dust (crushed quartz) to increase the flat area on the side of each core. Figure 3 shows this specimen when the flats had been ground until approximately $^3/_{16}$ in. in width. The resulting relative resistance values presented in Table 3 have been plotted against area in Figure 4. The point on the zero area axis and possibly the next point are mislocated due to the uncertainty concerning area of contact for the cylindrical surfaces. As the area must necessarily be greater than zero, these two points should be moved to the right, possibly eliminating the reverse curve. If friction is a surface phenomena, for zero surface a relative resistance value of zero could be anticipated and for constant total load the relation between relative resistance value and area of aggregate would approach the broken curve shown.

Using a constant load for tests of different area of aggregate caused the contact pressure to vary. Tests were conducted on certain specimens to establish the relation between contact pressure and relative resistance value. The results, as given in Table 4 and shown in Figure 5, establish a rate of increase in relative resistance value with increase in contact pressure. Under dynamic test the rate of increase for limestone, whether a solid core or fragments, is nearly constant at one-third of a relative resistance value point for each pound per square inch change in contact pressure.

Applying this contact pressure factor to the data of Figure 4 modified the curve somewhat. In Figure 6, area has been plotted against relative resistance value computed for constant pressure. The curve defined by the small triangles corresponds to that in Figure 4. For the small contact area portion of this curve, the angle at which the edges of the cores met the surface was very small. It could be expected that as the corners became sharper, the relative resistance value would increase. The second

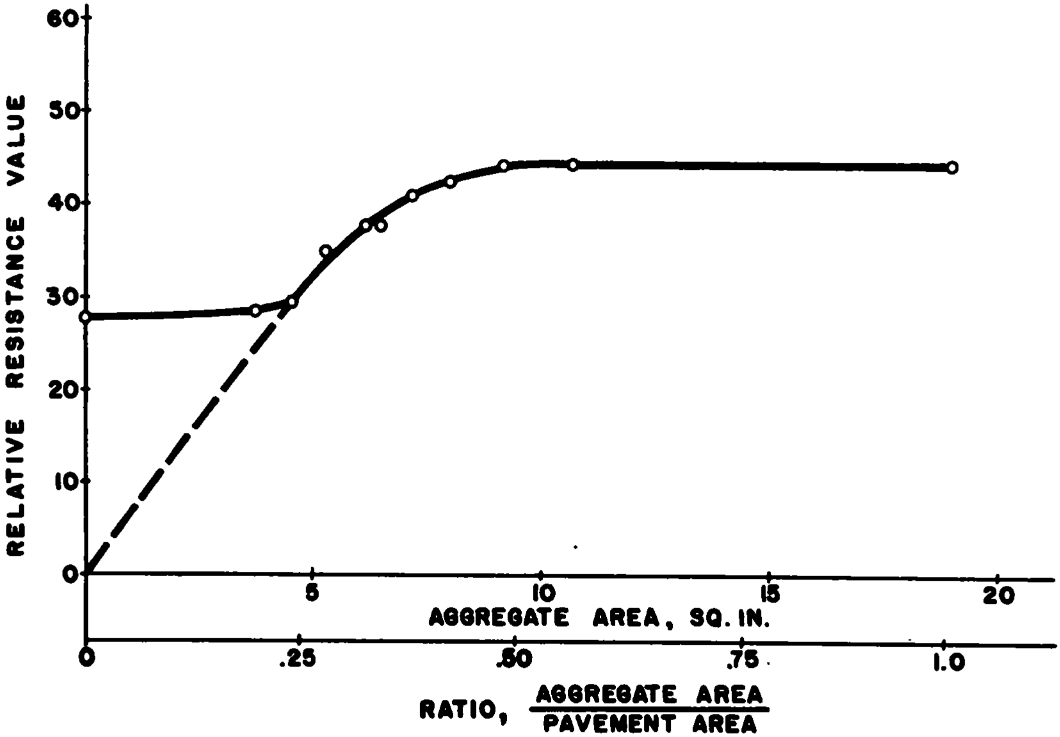

Figure 4. Variation in skid resistance with ratio of aggregate area to pavement area (constant load).

curve, defined by circles in Figure 6, shows the variation in edge angle with change in area. This angle increases slowly in the range of areas where relative resistance value increased rapidly. This nearly complete reversal of effect seems to indicate that the increased sharpness of the edges is not responsible for the increase in relative resistance value. To show that increase in area is as important as change in edges, several specimens were prepared of ½-in. cubes of limestone hand set with one edge located radially in the specimen surfaces (CU-2 in Fig. 3). Data for these tests are included in Table 3. When skid tests were made on these surfaces prior to any wear or polish, the sharp edges of the cubes bit into the rubber test shoe and shredded the surface. This extreme edge effect resulted in a relative resistance value of only 67. Grinding the surface of the specimen made from the cubes caused flat areas to develop without causing any change in the edges. The relative resistance values was obtained for only 2 deg of wear. The extreme angularity of the cubes caused excessive chatter both during the test and polishing and the cubes were pulled out of most of the specimens. The two points after wear secured for CU-2 indicate the trend which can be expected. It is interesting to note that although the extreme sharpness of the cubes decreased with wear the actual relative resistance values corrected for pressure increased.

The relative resistance values obtained for the cubes in specimen CU-2 when the worn area was 3.66 sq in. and 5.5 sq in. were essentially the same (Table 3). However, the contact pressure in the second case was only two-thirds of that for the first. After computing relative resistance values corrected to a uniform contact pressure, the two points were added to Figure 6. With no change in edges, an increase in area caused an increased relative resistance value. For the same area CU-2 gave a higher value than did CO-1. Comparisons can only be made at small areas where the angle at which the edges of CO-2 met the surface was nearly zero, yet the points plotted would project the curve for CU-2 in much the same form as that for CO-2.

The effect of pressure was investigated further by comparing two materials, different shapes of particles, and both static and dynamic friction. Data for these tests are given in Table 4. The limestone solid core and the small limestone cylinders compared well under dynamic test. The relative resistance value has been plotted

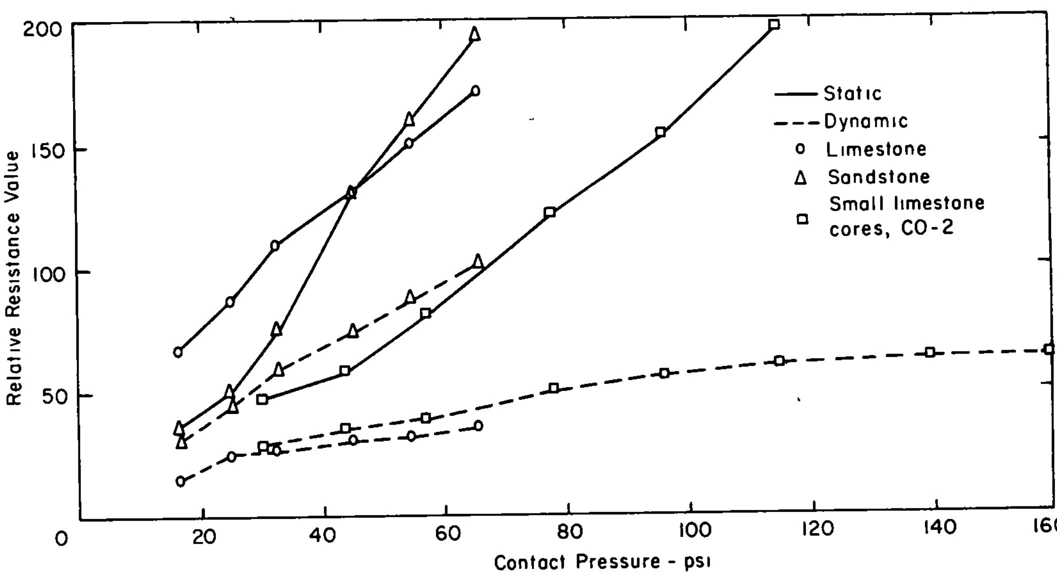

Figure 5. Variation in skid resistance with contact pressure on limestone and sandstone.

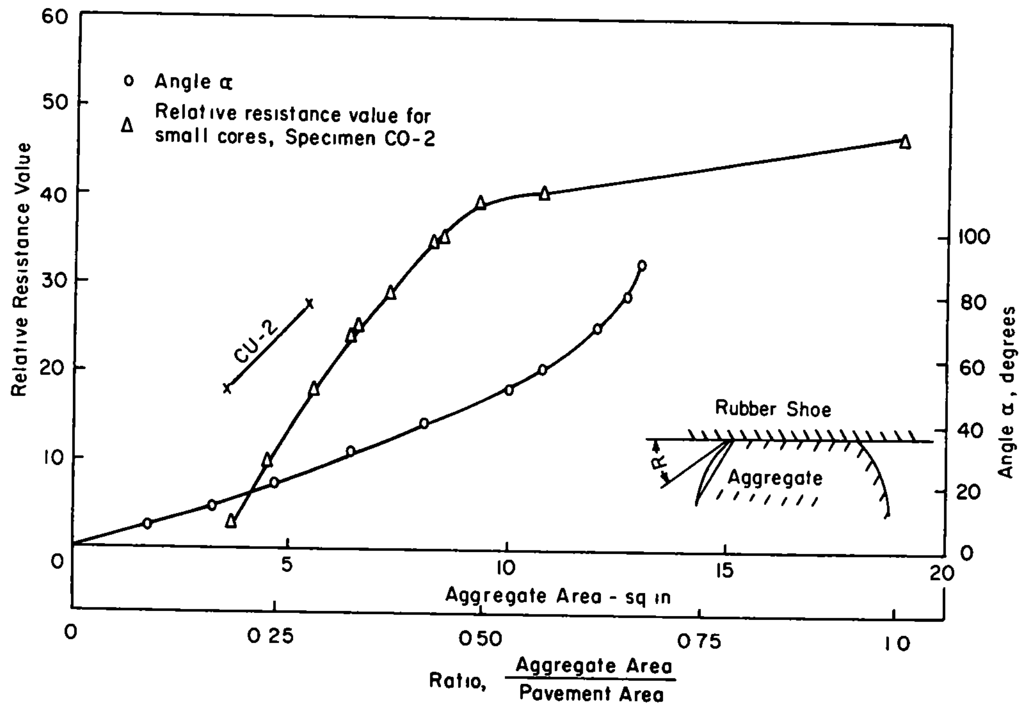

Figure 6. Variation in skid resistance with ratio of aggregate area to pavement area (constant pressure).

against contact pressure in Figure 5. At each pressure, the value for the small cores is slightly above that for the solid core and thus reflects the effect of discontinuity of the surface. Static relative resistance values for both limestone specimens are well above the dynamic values. The variation in value with pressure was a modest 0.3 units per pound per square inch change under dynamic conditions but increased to 1.8 units for static conditions.

For dynamic conditions both the actual value and the rate of increase of relative resistance are greater for the sandstone core than for the limestone. As the surface texture of the sandstone has more relief than the limestone, the greater actual value would be anticipated. The greater rate of change in relative resistance value with increased pressure can be explained by realizing that at low pressure the rubber will rub on only the tips of the texture of the sandstone surfaces; at higher pressures the rubber will deform into the texture and give increased resistance. Under static conditions the relative resistance value for sandstone increased sharply with increases in pressure. Although at low pressures the sandstone showed lower values than limestone, the rapid increase in values for sandstone made it superior at pressures above 43 psi.

The surface texture of the stone can logically explain the variations shown in the curves of Figure 5. The texture of the surface of the sandstone was deeper than that of the limestone. Under static conditions an increase in pressure caused the rubber shoe to crowd down into the texture and to increase the sliding friction. The importance or magnitude of this effect depends on the texture available to the rubber. Under dynamic corditions, the hysteresis character of the rubber prevents the full penetration of the rubber into the texture. That is, the rubber surface does not have time to rebound completely into a low texture area before being deformed upwards by the next high texture point. Therefore, the relative resistance value for dynamic conditions

TABLE 3

SKID RESISTANCE TEST RESULTS[1] FOR DIFFERENT CONTACT AREAS BETWEEN TEST SHOE AND LIMESTONE

Specimen	Area Pattern	Area of Rock Under Test Shoe (sq in.)	Pressure (psi)	Relative Resistance Value	
				Measured	Corrected to 28 psi
CO-2	0.66-in. dia. cores lying flat	No flat area	-	28	-
		3.71	164.48	30	7
		4.53	133.5	31	10
		5.24	115.0	35	18
		6.16	98.0	38	24
		6.54	92.5	38	25
		7.20	84.0	41	30
		8.10	74.7	43	35
		8.63	70.0	44	36
		9.35	64.8	46	39
		10.69	57.0	46	40
CU-2	½-in. cubes on edge	No flat area	-	67	-
		3.66	165.0	45	18
		5.5	110.0	44	28

[1]Greencastle limestone, test load 463.72 lb; shoe area, 14.45 sq in.; polished with No. 000 quartz.

TABLE 4

RELATIVE RESISTANCE VALUES AT DIFFERENT PRESSURES FOR GREENCASTLE LIMESTONE AND MEDINA SANDSTONE

Solid Limestone Core, Contact Area = 14.45 in.^{2}		Solid Sandstone Core, Contact Area = 14.45 in.^{2}		Multiple Limestone Cores, Contact Area = 8.2 in.^{2}	
Pressure (psi)	Relative Resistance Value	Pressure (psi)	Relative Resistance Value	Pressure (psi)	Relative Resistance Value
(a) Static					
16.7	67	16.7	36	29.7	47
24.6	86	24.6	50	43.3	58
32.2	110	32.3	76	56.8	80
44.5	130	44.5	128	77.5	120
54.0	150	54.0	158	95.5	152
65.0	170	65.0	192	114.5	195
(b) Dynamic (2,500 rpm)					
16.7	15	16.7	30	29.7	28
24.6	24	24.6	45	43.3	35
32.3	27	32.3	59	56.8	38
44.5	30	44.5	74	77.5	49
54.0	32	54.0	87	95.5	55
65.0	35	65.0	102	114.5	59

must always be lower than that for static conditions. The magnitude of this difference must then depend on the texture, which in reality controlled the degree to which the rubber penetrated the surface under static test.

This approach implies that for each rubber and speed of test, there is an optimum texture of surface which will give the best friction between the two. At a later point in this paper, limited tests intended to explore the possibility of finding an optimum size of crushed quartz for the rubber used are reported.

Effect of Abrasive Type

For all of the early tests of rock cores, the surfaces were polished by crushed quartz. In actuality most field pavements must be polished by traffic and abrasive dust provided by the road surface. That is, the abrasive present will be of the same character as the aggregate. Therefore, several cores were polished with the use of abrasives from the same source as the cores. The polishing cycles for each specimen started with abrasive passing a No. 30 sieve and retained on a No. 50 sieve and progressed into finer abrasives. Each cycle consisted of 15 min with one size abrasive under the compound action of the polishing shoe in the drill press. All of the cores responded to polishing with the core material in much the same manner. At first the relative

TABLE 5

RELATIVE RESISTANCE VALUES RESULTING FROM VARYING THE DEGREE OF POLISH OF STONE CORES

15-Min Polish with Each Abrasive Listed	Relative Resistance Values				
	Sandstone Medina, N. Y.	Limestone Greencastle, Ind.	Limestone Wheeling, W. Va.	Limestone Richmond, Ind.	Dolomite Bedford, Pa.
No. 2 quartz	79	55	45	68	54
No. 2 quartz	87	52	46	67	52
No. 1 quartz	87	52	37	66	53
No. 1 quartz	87	46	34	60	48
No. 00 quartz	80	46	44	60	63
No. 00 quartz	79	48	42	60	60
No. 000 quartz	80	47	45	47	62
No. 000 quartz	78	45	40	44	60
No. 00000 quartz	78	38	37	40	57
No. 00000 quartz	78	40	37	43	58
Limestone mineral filler	78	31	29	39	52
Limestone mineral filler	77	27	27	38	48
Abrasive material same as core, sieve size fractions					
No. 30-No. 50	-	48	46	65	72
No. 30-No. 50	-	43	55	70	65
No. 50-No. 100	-	47	54	65	81
No. 50-No. 100	-	49	57	65	78
No. 100-No. 200	-	53	60	65	84
No. 100-No. 200	-	51	58	63	83
No. 200-No. 270	-	50	61	55	78
No. 200-No. 270	-	35	41	41	61
No. 270-Finer	-	29	42	38	60
No. 270-Finer	-	23	46	37	58

resistance value (Table 5) appeared to increase as polishing progressed, but a definite down trend appeared with further reduction in abrasive size. All four cores represented by Figure 7 are limestones but include a wide range of crystalline structure as shown by Figure 8.

The curves can best be explained by realizing that an abrasive of the same material as the core would, in coarse sizes, tend to gouge the softer portions of the matrix and thus expose the individual particles of the structure. Polishing with particles as small or smaller than the rock structure would tend to actually wear or reduce the individual crystals. This would result in smaller but more frequent peaks in the surface texture.

In comparison, the crushed quartz abrasive when employed in a similar sequence, caused a down trend in relative resistance value throughout the series, as given in Table 5 and shown in Figure 9. The quartz was harder than any of the limestones and would reduce the surface texture for all of the sizes employed. It is notable that the quartz did not cause as rapid a decline in relative resistance value for the sandstone as for the limestones. As the quartz nearly approximates the sandstone in hardness, the curve for sandstone could be included in Figure 7.

Effect of Aggregate Texture

The outstanding performance of sandstone (Fig. 9) and the proven superiority of Kentucky rock asphalt as a full-scale pavement seemed to indicate interesting possibilities in synthesizing similar material. Also it appeared desirable to determine if an optimum size of surface texture for maximum skid resistance could be shown by this means. To take advantage of the widest range of particle sizes possible, the crushed silica originally intended for use as a polishing abrasive was selected as aggregate for one series of specimens. This gave sizes from that passing a No. 30 sieve and retained on a No. 50 to passing a No. 270 and retained in the pan. Using three adjacent

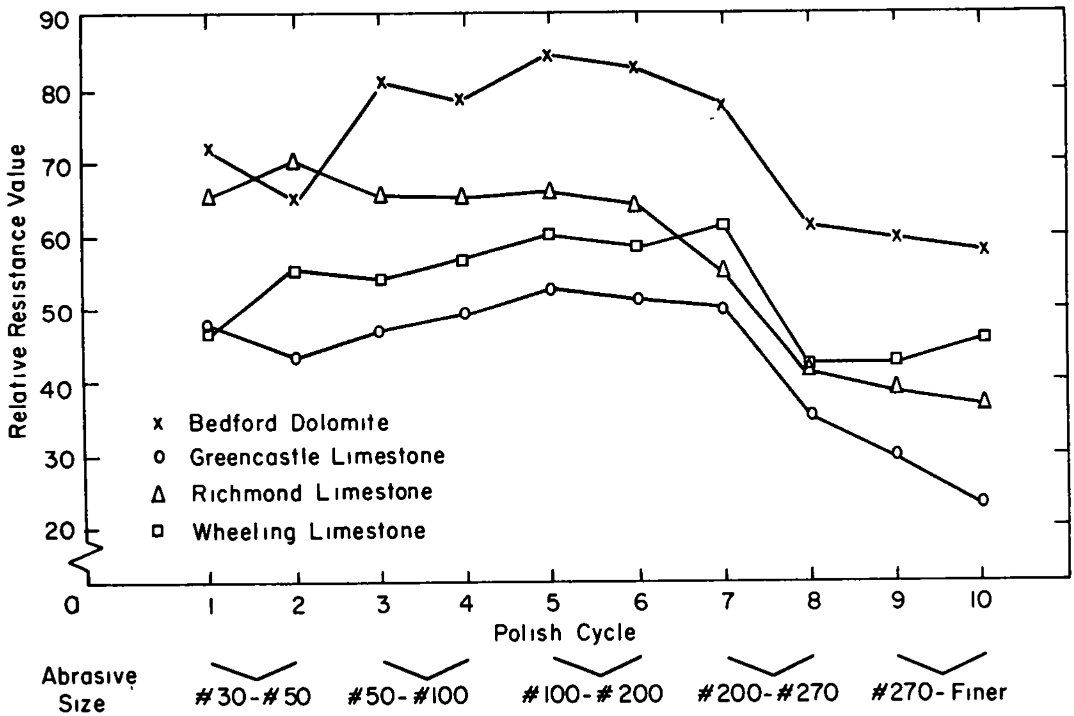

Figure 7. Variation in skid resistance with polishing cycle for rock cores (core material as abrasive).

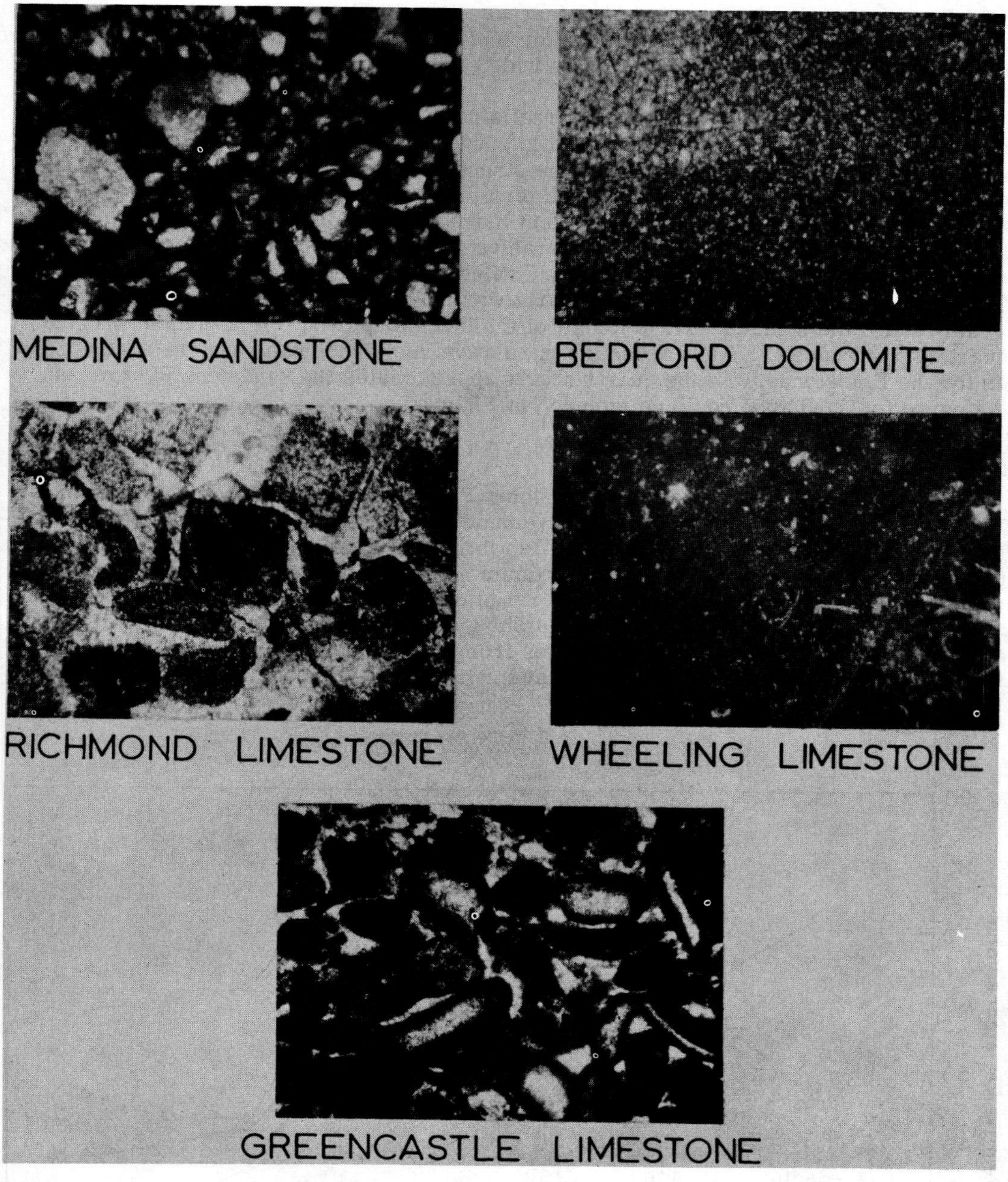

Figure 8. Photomicrographs of thin sections of rock cores (90X).

sizes of aggregates, a series of fine-textured bituminous surfaces were prepared and tested. The results are given in Table 6 and shown by solid lines in Figure 10. The different solid curves resulted from tests "as rolled" and after two different degrees of polish. The optimum relative resistance value was obtained for the mix of 70 percent—No. 30 to No. 50, 15 percent—No. 50 to No. 100, and 15 percent—No. 100 to No. 200. As the largest part of this mix would be particles approximately 0.0175 in. in diameter, the size of asperities to be expected on this surface would be 0.0088 in. high spaced at 0.0475 in.

Repeating the same procedure with naturally rounded silica sand gave a somewhat

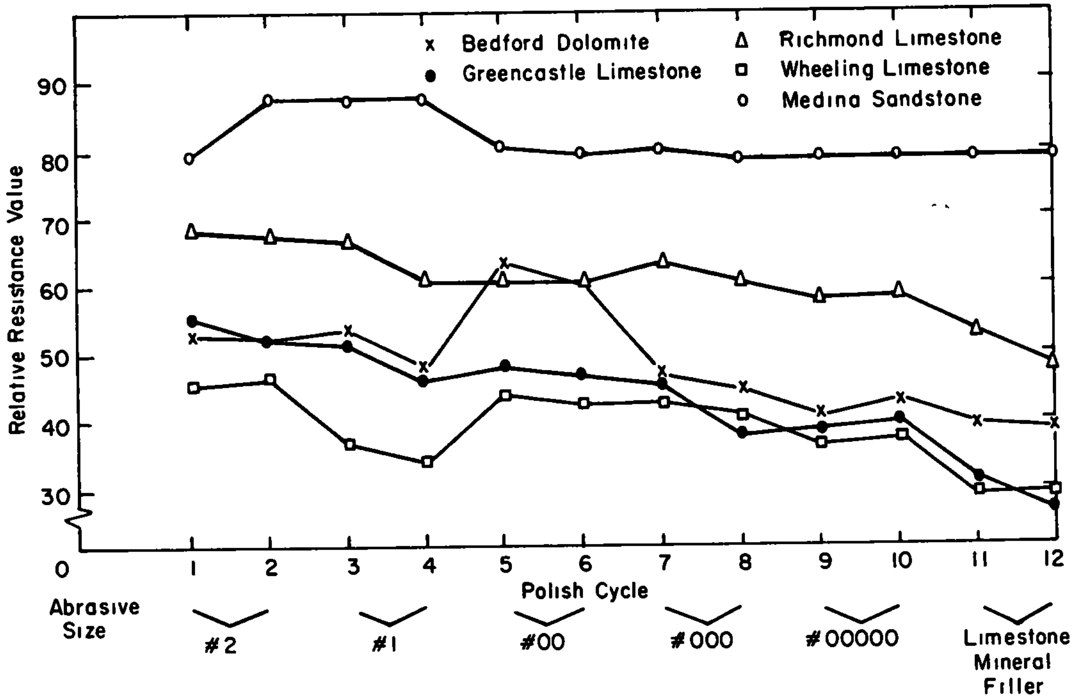

Figure 9. Variation in skid resistance with polishing cycle for rock cores (crushed quartz for abrasive).

TABLE 6

VARIATION IN RELATIVE RESISTANCE VALUE OF FINE BITUMINOUS SURFACES WITH REDUCTION IN SIZE OF AGGREGATE

Specimen	Aggregate	Shape	Gradation, % of Total Aggregate											Relative Resistance Value		
			No 4 - No. 8	No. 8 - No. 16	No. 16 - No. 30	No. 30 - No. 50	No. 50 - No. 100	No. 100 - No. 200	No. 200 - Finer	No. 000 Quartz	No. 00000 Quartz	Fineness Modulus	Asphalt, % of Aggregate	As Rolled	1 Polish	2 Polish
H-1	Silica Sand	Natural	70	15	15	-	-	-	-	-	-	5.55	6½	60	56	58
H-2	Silica Sand	Natural	-	70	15	15	-	-	-	-	-	4.55	6½	77	75	79
H-3	Silica Sand	Natural	-	-	70	15	15	-	-	-	-	3.55	6½	81	79	79
H-4	Silica Sand	Natural	-	-	-	70	15	15	-	-	-	2.55	7½	91	94	90
H-5	Silica Sand	Natural	-	-	-	-	70	15	15	-	-	1.55	8½	102	97	108
E-1	Silica Sand	Crushed	70	15	15	-	-	-	-	-	-	5.55	6	81	75	75
E-2	Silica Sand	Crushed	-	70	15	15	-	-	-	-	-	4.55	6	84	77	72
E-3	Silica Sand	Crushed	-	-	70	15	15	-	-	-	-	3.55	6½	93	79	73
E-4	Silica Sand	Crushed	-	-	-	70	15	15	-	-	-	2.55	7	102	89	79
E-5	Silica Sand	Crushed	-	-	-	-	70	15	-	15	-	1.55	7½	92	73	108
E-6	Silica Sand	Crushed	-	-	-	-	-	70	-	15	15	0.70	10	53	35	40

different result. The results obtained are shown as broken lines in Figure 10. Surprisingly, there was little spread in the results for the different degrees of polish. Also, it is interesting to note that the maximum relative resistance value obtained in this series was for the rounded aggregate. Regrettably, shortages of extremely fine round particles prevented extending the round series until an optimum had been passed. The maximum reached was for the round mixture based on 0.0088-in. diameter

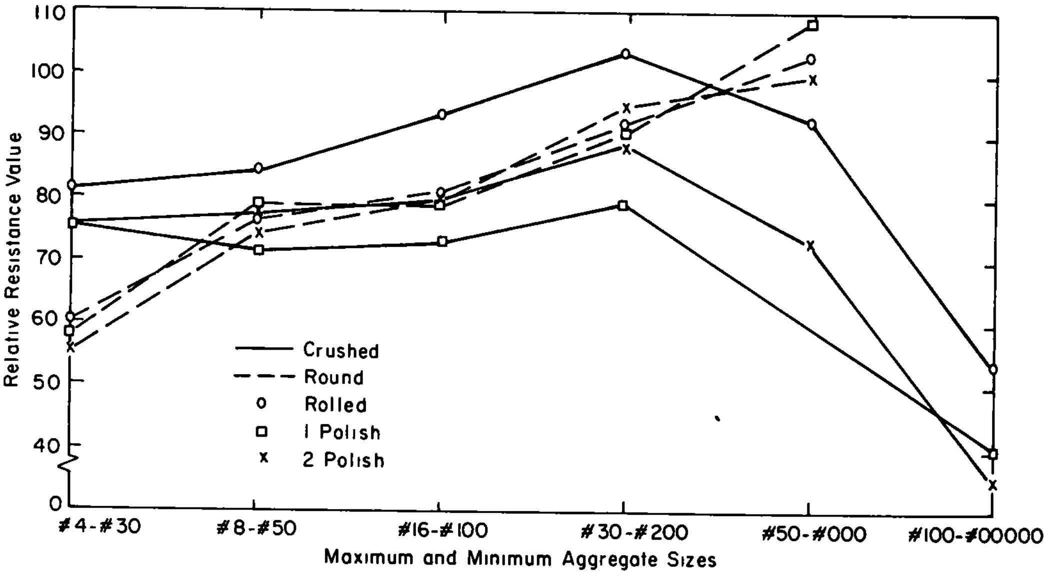

Figure 10. Variation in skid resistance with aggregate size for fine bituminous mixtures composed of round and angular silica sand.

particles. A texture of 0.0044-in. height spaced at 0.0088 in. can be expected from this size.

SUMMARY

Tests performed on surfaces of controlled-shape aggregate particles gave general indications of the relationship between the effect of particle edges and particle surfaces. The contribution of the edges to the relative resistance value of larger, smooth aggregate particles was a small increase in resistance. The creation of edges in boldly textured aggregate reduced the relative resistance value.

Area of aggregate exposed in the surface of the specimen and thus available to the rubber shoe for friction had a major effect on the relative resistance value. The greater the ratio of aggregate exposed to the total surface area, the greater the relative resistance value. The rate of this trend was strongest for low ratios, moderated as the area of aggregate approached one-half of the test surfaces, and remained nearly constant thereafter.

Several specimens tested under various pressures showed increases in relative resistance value with increased contact pressure. For coarse aggregate pavement, the rate of increase was dependent on material rather than on aggregate shape. This rate was greater for strongly-textured stone such as sandstone than for soft material such as limestone.

The use of different abrasives for polishing rock cores prior to relative resistance value tests indicated that the degree of polish attained for a given effort is a function of both the rock from which the core was cut and the abrasive used. The use of an abrasive which was harder than the cores, caused a continual reduction in relative resistance value as the size of abrasive was reduced. The use of abrasive identical with the cores established that for each material there was a definite size of similar abrasive which gave the surface a polish resulting in the highest relative resistance value. For the limestones used in this study, the abrasive size which resulted in the highest relative resistance value was that passing a No. 100 sieve and retained on a No. 200 sieve.

Bituminous mixtures using crushed and round silica sand were used to establish the size of granular surface texture which resulted in the highest relative resistance value. For crushed silica this size was 0.0175 in. in diameter. For round silica, a size below 0.0088 in. was indicated.

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Locked-Wheel Friction Tests on Wet Pavements

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The friction coefficient between a pair of locked automotive tires (running in the normal wheel tracks) and a wet highway surface was determined in an elaborate test program, using a specially constructed test trailer. This program provided data from more than 400 tested surfaces along approximately 6,500 route miles of rural sections of major transcontinental routes following the National System of Interstate and Defense Highways as nearly as possible. The data are tabulated, and cross-plots have been made to indicate the effects of age, wear (based on age and traffic volume), surface finish and aggregate composition on the friction coefficient exhibited by portland cement concrete roads. Summaries are made also for the comparative effects of age and wear on the friction coefficients of PCC and bituminous asphalt roads.

●THERE IS a correlation between the slipperiness of a highway and accident occurrences. The skid-resistance properties of the pavement surface are therefore vitally important in the design and construction of new highways and the refurbishing of older roads. Determination of friction coefficients along with an analysis of the road construction, material ingredients, and traffic use will indicate how the best surfaces have been attained.

In the late summer of 1959, the Vehicle Dynamics Department of Cornell Aeronautical Laboratory, Inc., undertook a program sponsored by the Portland Cement Association to determine locked-wheel friction coefficients on wet pavements. The results of this program (4) are reported herein. Data were obtained from more than 400 tested surfaces along approximately 6,500 route miles of rural sections of major transcontinental roads forming part of or closely paralleling the network known as the National System of Interstate and Defense Highways. Information was provided, therefore, on some sections of this network which have already been constructed, and on roads which will be superseded as major routes when the whole network is complete in 1970.

PROGRAM SUMMARY

The program objective was to determine the effect of surface finish and road construction on the friction forces attainable between a specific tire and various wet surfaces under steady-state nonrolling conditions.

The major pieces of equipment used in the field test part of the program consisted of a skid trailer designed, constructed, developed and proved in previous programs (1, 2) and a specially adapted tractor unit.

The route chosen and the sampling frequency for the tests are discussed later. Two months were required for the road test part of the program. This included time for tests, truck and trailer routine maintenance, minor repairs, and rest periods for the test crew of two men. The route mileage totaled 6,500 mi through 20 states, but the actual mileage covered by the truck and trailer was about 8,200 mi.

TABLE 1

DISTRIBUTION OF TESTS BY STATE

State	No. of Surfaces Tested
Arizona	12
Arkansas	34
California	11
Georgia	18
Illinois	18
Iowa	45
Kansas	58
Maryland	9
Missouri	18
New Mexico	8
New York	24
North Carolina	17
Ohio	9
Oklahoma	19
Pennsylvania	16
South Carolina	7
Tennessee	31
Texas	33
Virginia	18

At the time of each test, data acquired showed the location, basic surface material type, general description of road, ambient weather conditions, test speed (if other than 40 mph), and the average friction coefficient for the test surface. Table 1 gives the number of tests made in each state.

Subsequently, information was obtained on age, average daily traffic count, coarse and fine aggregate materials and surface finish. The portland cement concrete test sections were then divided into the various groups given in Table 2 according to the materials and surface finishes used.

TABLE 2

PORTLAND CEMENT CONCRETE SURFACE GROUPING

Group No.	Aggregate		Surface Finish	No. of Surfaces Tested
	Coarse	Fine		
1	Gravel	Nat. sand	Broom	18
2	Gravel	Nat. sand	Burlap	32
3	Gravel	Nat. sand	Belt	19
4	Limestone	Nat. sand	Broom	3
5	Limestone	Nat. sand	Burlap	41
6	Limestone	Nat. sand	Belt	4
7	Gravel and limestone	Nat. sand	Belt	2
8	Coarse grained igneous	Nat. sand	Broom	1
9	Coarse grained igneous	Nat. sand	Burlap	4
10	Coarse grained igneous	Nat. sand	Belt	10
11	Traprock	Nat. sand	Belt	1
12	Slag	Nat. sand	Burlap	6
13	Argillite	Nat. sand	Belt	2
14	Volcanic slate	Nat. sand	Belt	2
15	Serpentine rock	Nat. sand	Burlap	2
16	Limestone	Man. sand	Burlap	10
17	Slag	Man. sand	Burlap	1
18	Gravel and limestone	Mixed sand	Belt	3

Notes: Natural sand includes sand, siliceous sand, quartz sand, lake sand, concrete sand. Manufactured sand means manufactured or crushed limestone sand. Mixed sand means mixed natural and manufactured sand. Coarse grained igneous includes granite, diorite, syenite, granite gneiss.

TEST EQUIPMENT

The equipment used for road testing consisted of the test trailer and special bodied tractor shown in Figures 1 and 2.

The test trailer which has been fully described (1) consists of a two-wheel, low c.g.

unit in which the drag force acting through the two wheels into the axle is measured by strain gages mounted on aluminum cantilever beams. The trailer has a completely self-contained hydraulic brake system which in previous programs has been operated by a push-pull cable system from the towing vehicle. For this program an air-operated master cylinder was fitted to make use of the cab-controlled pneumatic trailer brake system fitted as standard on the tractor. Both trailer wheels are locked during a test run.

The direct reading friction coefficient measuring system has been improved since the trailer was built several years ago. A schematic of the system is shown in Figure 3.

The tractor used for this program was an International R-190 with 142-in. wheelbase and a gross vehicle weight of 15,840 lb. Mounted behind the cab was a 3½-in. diameter, 7½-ft long, 530-gal water tank with a 6-in. diameter filler cap on top. Behind the tank was a large wooden box with a rear opening door. The interior of the box was divided into three compartments for auxiliary equipment, spares, and crew's personal baggage. A special tow-hitch frame at the rear of the tractor matched the trailer attachment.

The auxiliary equipment included the motor-driven water pump used in previous programs, a battery box for the measuring system, and a shutoff valve operated from the cab.

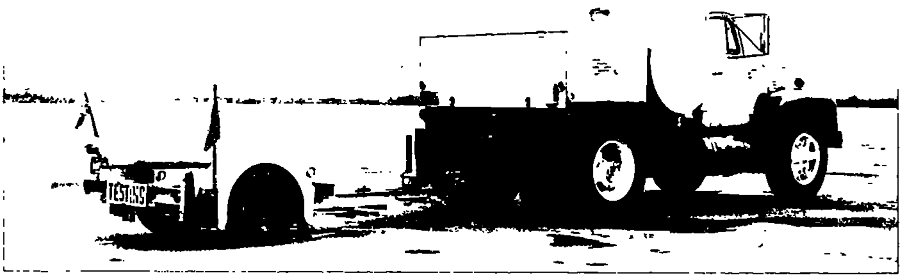

Figure 1. Tow truck and test trailer.

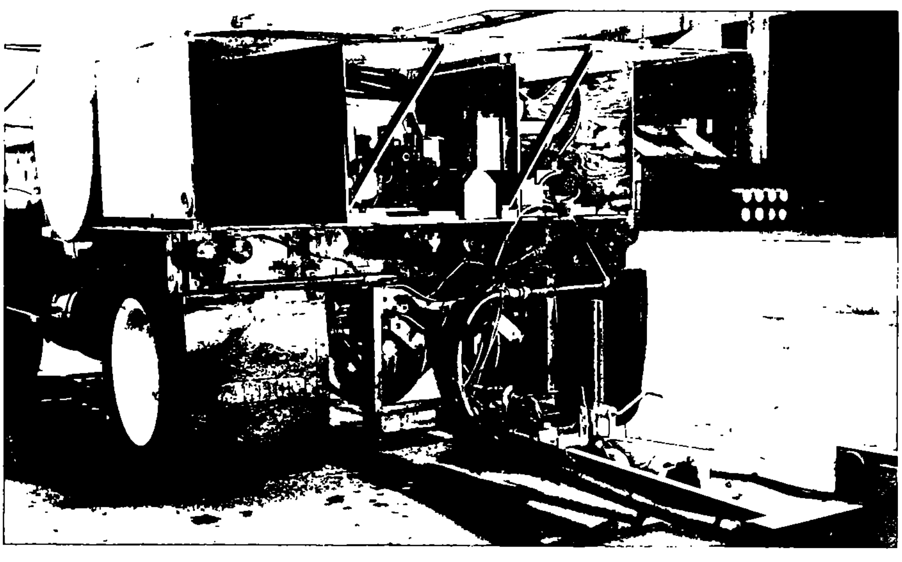

Figure 2. Rear of tow truck.

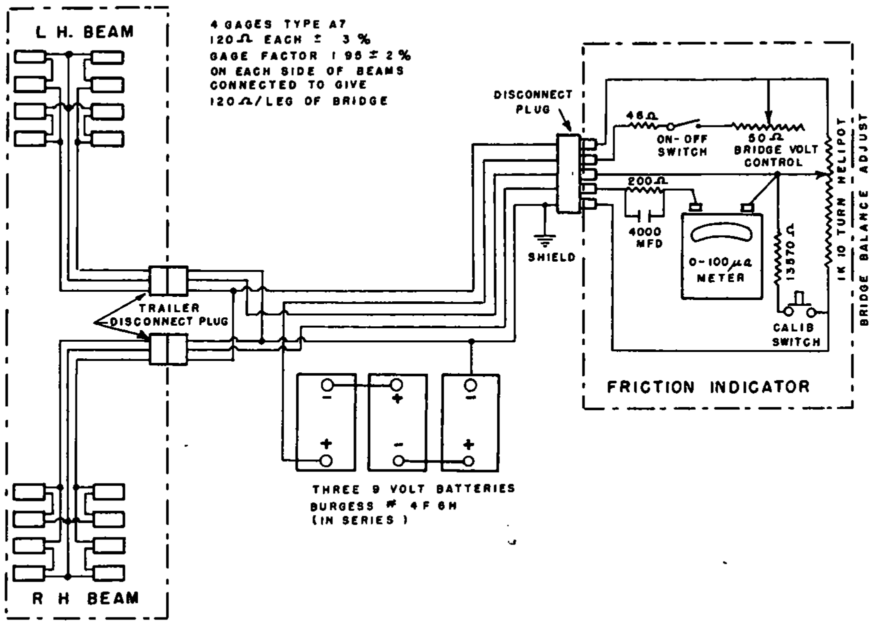

Figure 3. Schematic of friction force measuring system.

The major spares were two wheels and tires for the trailer (one being mounted on top of trailer) and an extra set of calibrated measuring beams with gages cemented in position and cables attached. A portable gas-driven water pumping unit was also carried, together with 15 ft of 1½-in. inside diameter delivery hose and 50 ft of 1-in. inside diameter suction hose. This unit was taken along as a precaution so that natural water supplies, such as creeks or ponds might be used, but was not, in fact, required at any time during the program because little difficulty was experienced in obtaining water from fire hydrants, water works, and private sources. An average of about 5 gal of water was required for each brake application test. Thus, a three-sample test required approximately 15 gal and a two-way or double-length test 25 to 30 gal.

CALIBRATION

Two sets of measuring beams, whose section sizes are slightly different and which have gages cemented in position and cables attached, are available for use on the PCA skid trailer. Both sets were calibrated before the program commenced. One set which was used for all but four test sections was recalibrated after the road test work was finished using the same calibration equipment as before. The "before" and "after" curves were virtually identical. The calibration curves for both sets of beams are shown in Figure 4.

The measuring system is calibrated by applying a horizontal load to the tongue while the trailer hitch rested on ball bearings on a weight scale platform. The trailer brake system is locked on during calibration. Inasmuch as the trailer weight is known and the load transfer to the trailer hitch equals the unloading of the trailer wheels, the normal force at the tires may be obtained. The friction coefficient between locked tires and ground is then the horizontal drag divided by the calculated normal load. It is necessary, of course, to have the trailer wheels standing on a high coefficient surface during calibration.

The accuracy of the microammeter readings is maintained by a simple procedure consisting of: (a) switching on the power, (b) adjusting the bridge balance helipot to obtain zero meter reading with no load on the trailer wheels, (c) pushing the calibration button which throws a known resistance into the circuit, and (d) adjusting the

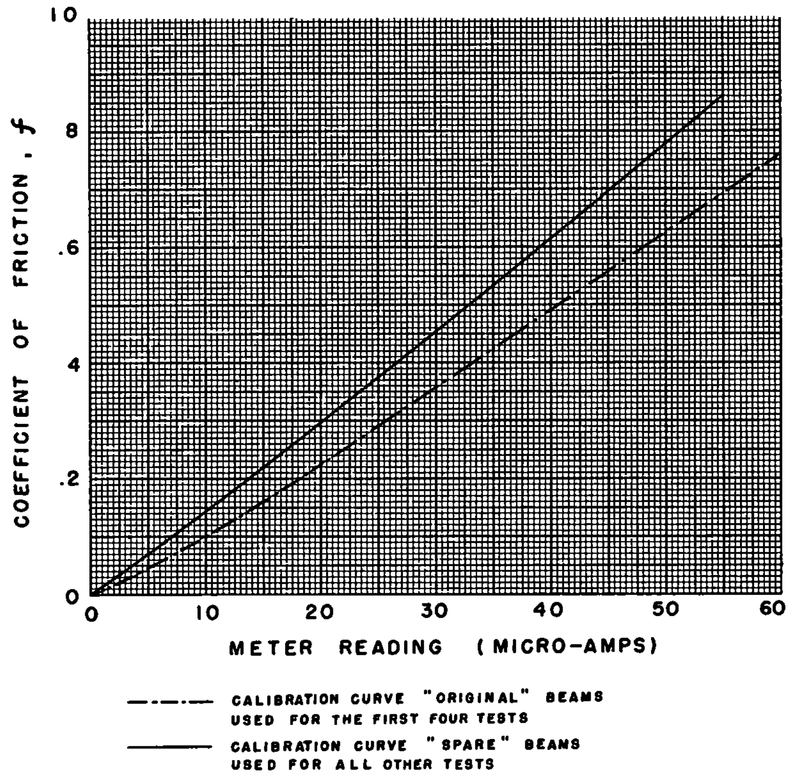

Figure 4. Calibration curve PCA skid trailer.

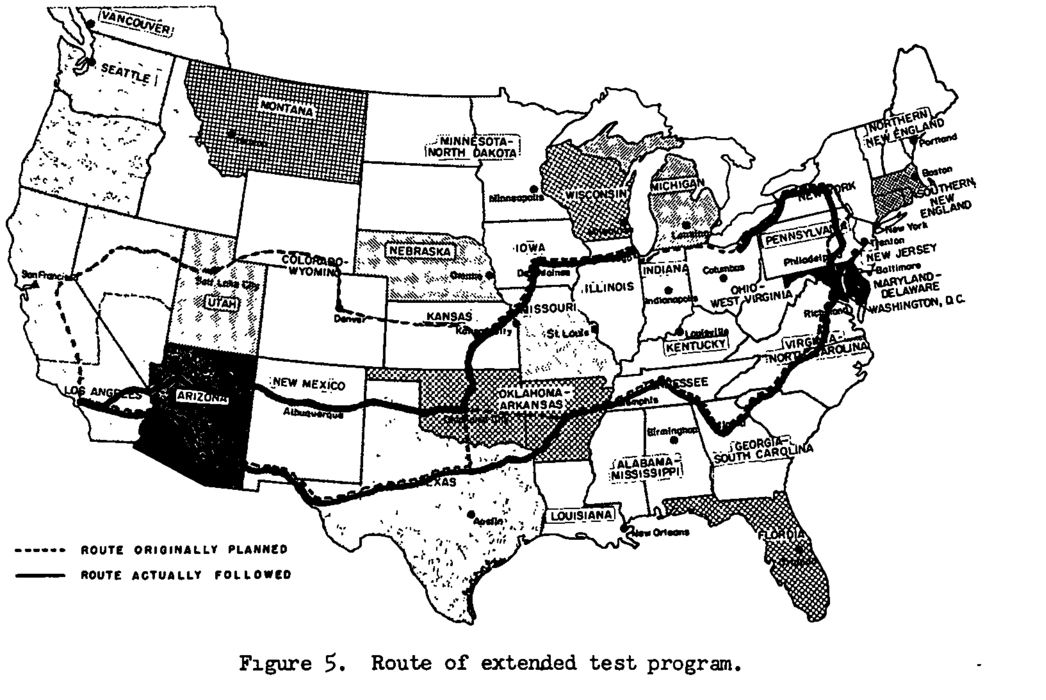

Figure 5. Route of extended test program.

bridge voltage control to read 100 microamps. This meter calibration is standardized for all tests, both calibration and road. Thus, the accuracy of the road measurements is maintained.

ROUTE AND FREQUENCY OF TESTS

The program provided approximately 40 working days of field testing. The original planned route is shown in Figure 5 and proved to be somewhat optimistic. It covered 7,156 mi through 25 states. However, by prior agreement with the sponsor, the routing could be modified during the program. The final route (Fig. 5) covered 6,500 mi through 20 states. Table 1 gives the number of surfaces tested in each state.

At the beginning of the program, tests were made every 5 mi in the rural sections. If three consecutive sample checks showed that the test surface was appreciably above or below "normal", a further three sample tests were made in the opposite direction but aligned with the first tests. If the section tested in the "normal" range, no further samples were made until five more miles were covered. Later in the program the turn-around was eliminated to save time, and if the first three sample checks showed a coefficient outside the "normal" range, a further three checks were made in the same direction.

The "normal" range is defined as that in which the friction coefficient lies between certain values (see Fig. 6). These values were varied from time to time to maintain approximately 50 percent of the tests outside the "normal" range and are given in Table 3. The frequency at which tests were made was also varied from time to time to maintain a reasonable daily mileage.

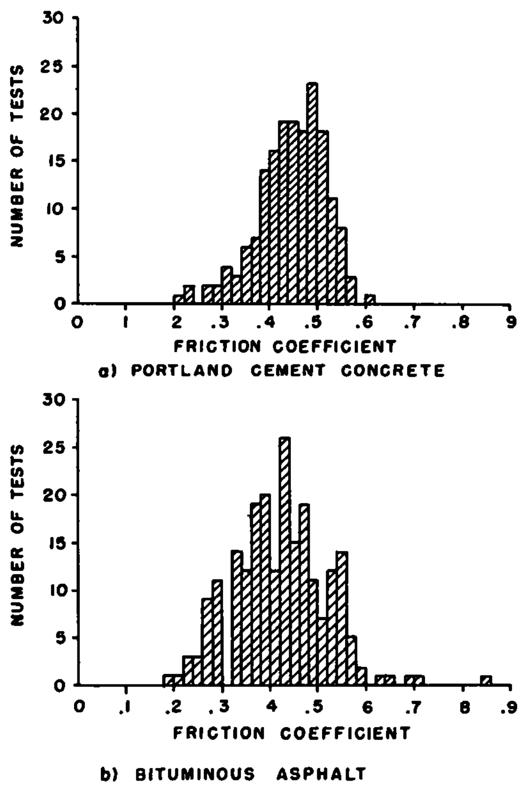

Figure 6. Distribution of tests over friction coefficient range.

TABLE 3

"NORMAL" COEFFICIENT RANGE AND FREQUENCY OF TESTS

From	To	Friction Coefficient, Normal Range	Miles Between Tests in Rural Areas	Tests Outside Normal Range (%)	Average Daily Mileage
Chicago	Oklahoma City	0.32 to 0.50	5	48.6	152.7
Oklahoma City	Dallas	0.225 to 0.54	25 plus	14.3	268
Dallas	Atlanta	0.32 to 0.50	5	41.1	190
Atlanta	Buffalo	0.32 to 0.48	5	56.3	190.2

DERIVATION OF SINGLE LINE CURVES

Close and Fabian (1) plotted the experimentally obtained friction coefficient data versus the logarithm of the Wear Index and the logarithm of road age, because the scattering of data points plotted in this form was more easily faired by a straight line. This indicated linear relationship between f and log (W) was assumed to exist for the purpose of fairing the data obtained in this series of tests. Accordingly, a straight line was fitted mathematically to the raw data by using a "least squares" or "linear regression" curve fitting procedure for the variables f, log (10W), and log (10A). At the specific request of the sponsor the resulting plots are presented here with linear scales for both friction coefficient and Wear Index or age. The resulting curves are not all-conclusive but indicative of general trends.

Figures 7 to 15 were made showing the average friction coefficient versus Wear Index. The latter is a function of age and the average daily traffic count for the lane tested. Additional plots, Figures 16 to 21, show comparisons between PCC and bituminous asphalt surfaces for friction coefficient versus age and friction coefficient versus Wear Index. Figure 22 shows the effect of surface finish.

Standard statistical analysis methods were used to derive single line curves from the masses of scattered data points. In several cases insufficient data exist for any conclusions to be drawn.

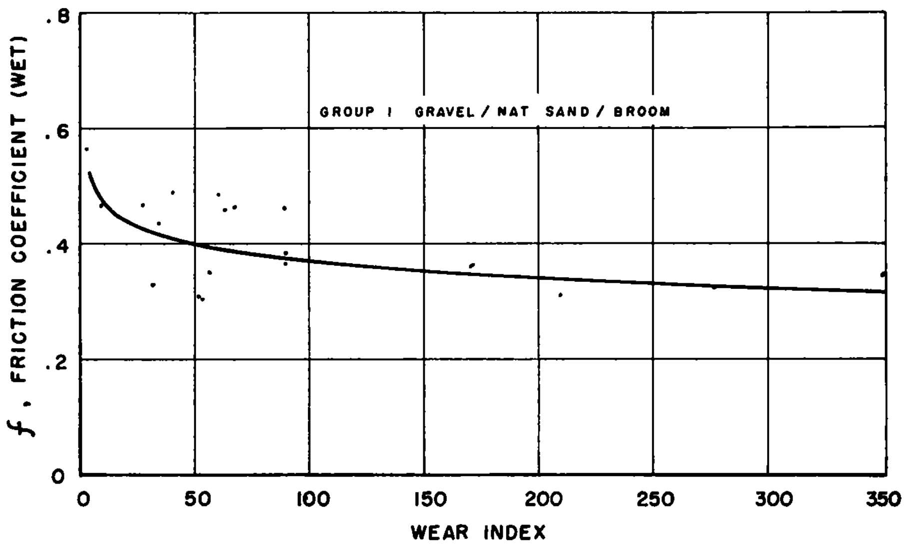

Figure 7. Effect of wear—PCC Group 1.

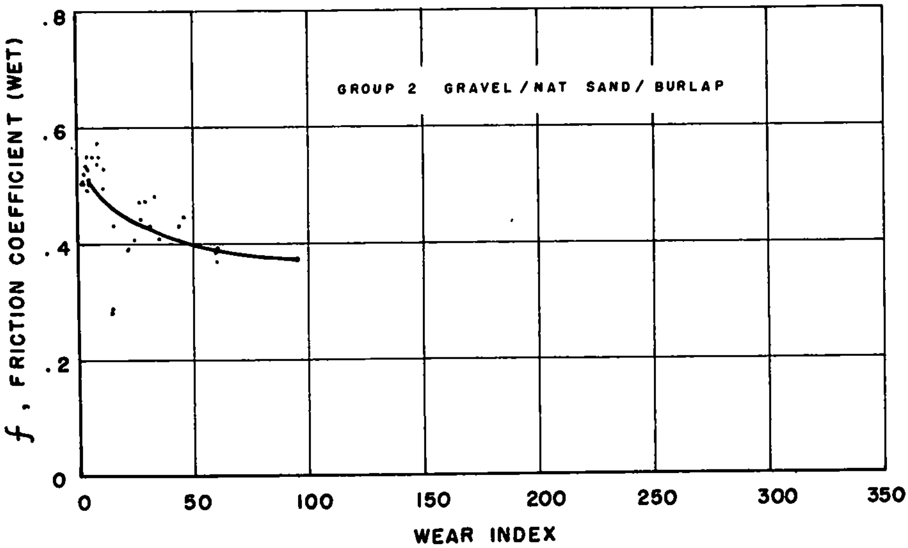

Figure 8. Effect of wear—PCC Group 2.

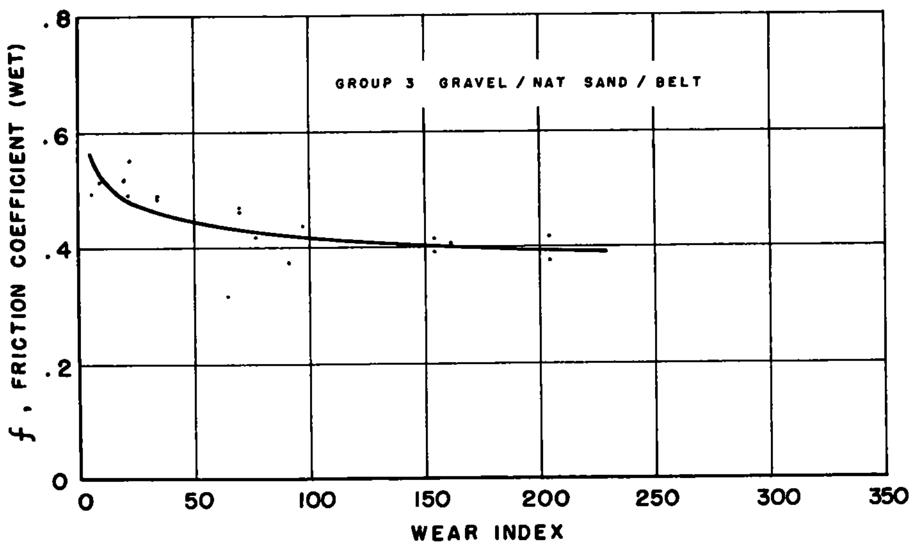

Figure 9. Effect of wear—PCC Group 3.

A total of 1,795 tests were made on 418 surfaces. However, complete data could not be obtained for a small number of surfaces and these were eliminated from the subsequent analysis.

DATA DISCUSSION

Wear Index Definition

To study the effect of wear on the surface characteristics the following Index has been used:

$$\text{Wear Index} = \frac{\text{ATL}}{1,000}$$

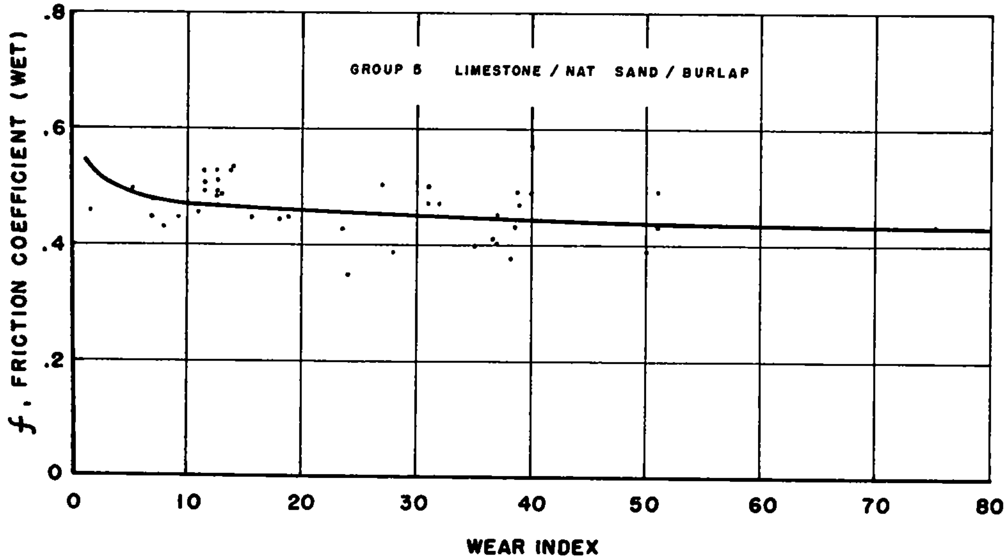

Figure 10. Effect of wear—PCC Group 5.

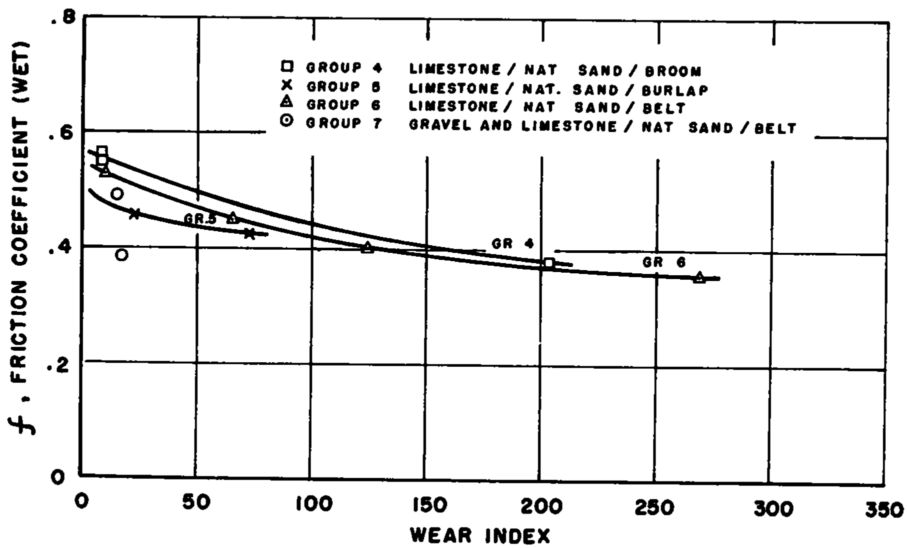

Figure 11. Effect of wear—PCC Groups 4, 5, 6, 7.

in which

A = age of pavement surface in years,
T = average total daily traffic count, and
L = correction factor for traffic distribution in lane tested.

A and T are derived from State Highway Authority data, and L is discussed in the next paragraph.

Traffic Distribution in Various Lanes

Where there are more than two lanes, observation shows that they will not all carry equal amounts of traffic. A few traffic counts have been made which show the traffic volume in various lanes but these data are somewhat scarce. Figures are given in Reference 3 for the percentage of vehicles using the right-hand lanes in a four-lane highway. These percentages vary with the total traffic volume.

A certain traffic distribution pattern was assumed as satisfactory for use in this program. The assumed distribution pattern is given in the text table on page 28.

For the Wear Index, the correction factor L is 2/100 of the percentage of the total traffic estimate for the appropriate lane in which testing was performed; for example, for a six-lane highway outside lane $L = \frac{2}{100} \times 20 = 0.4$.

The total traffic volume figures used in this report are based on recent traffic counts

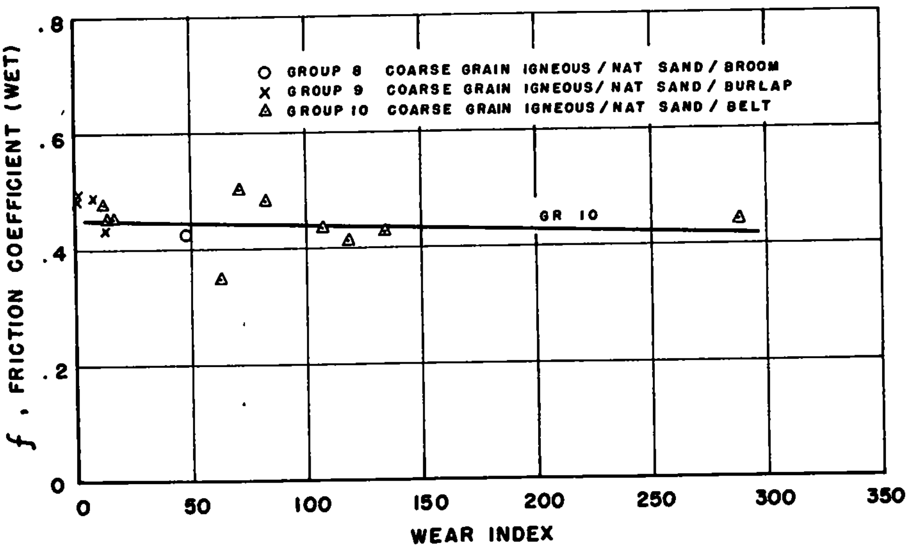

Figure 12. Effect of wear—PCC Groups 8, 9, 10.

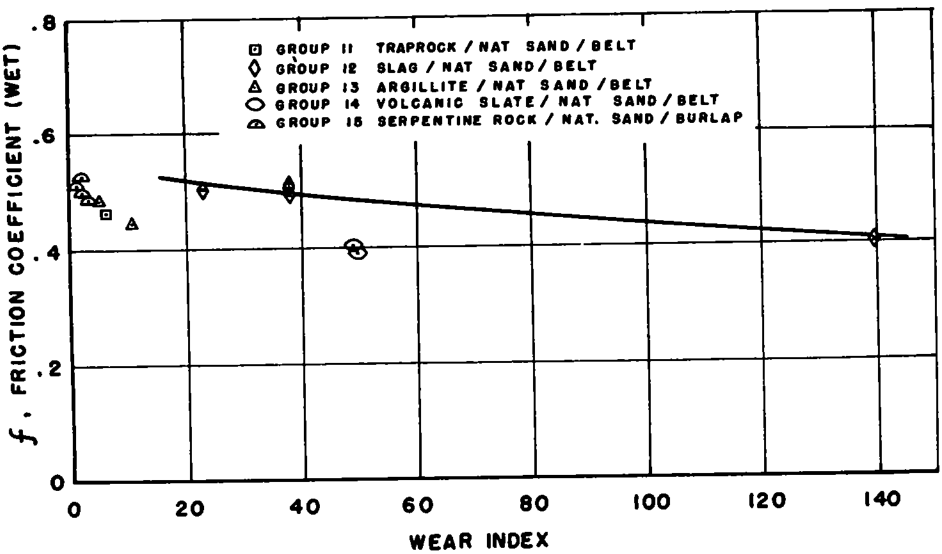

Figure 13. Effect of wear—PCC Groups 11 to 15.

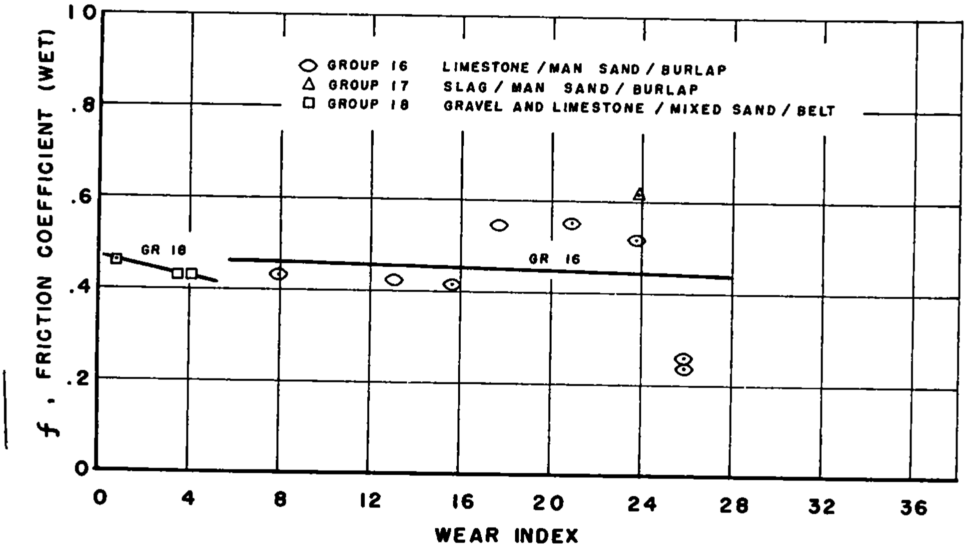

Figure 14. Effect of wear—PCC Groups 16 to 18.

No. of Lanes	Distribution per Lane (%)
2	50, 50
3	40, 20, 40
4	40, 10, 10, 40
6	20, 20, 10, 10, 20, 20
8	15, 15, 10, 10, 10, 10, 15, 15

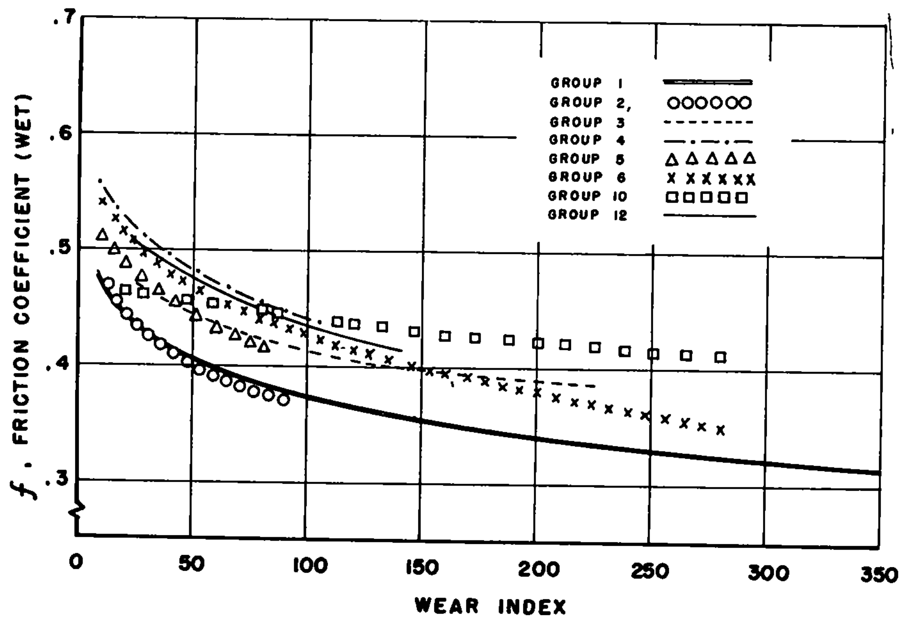

Figure 15. Effect of wear—PCC various groups.

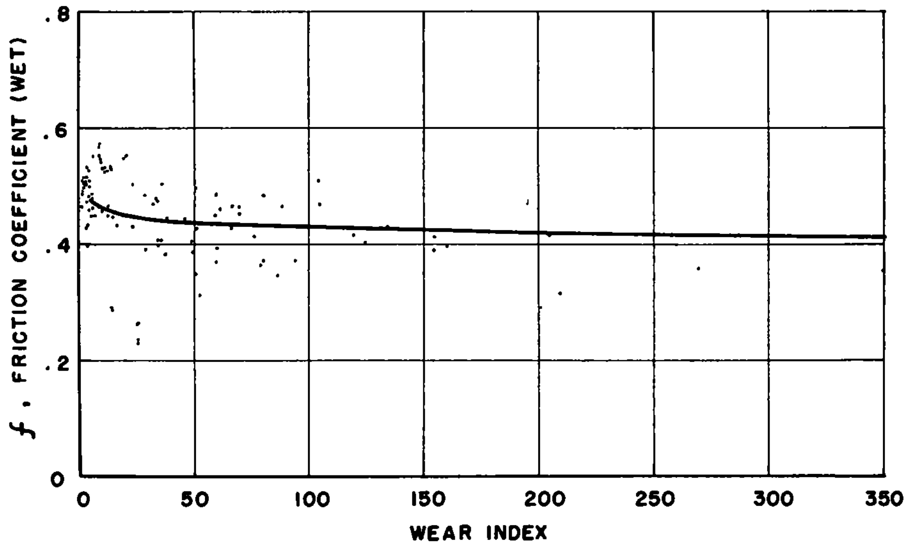

Figure 16. Effect of wear—PCC.

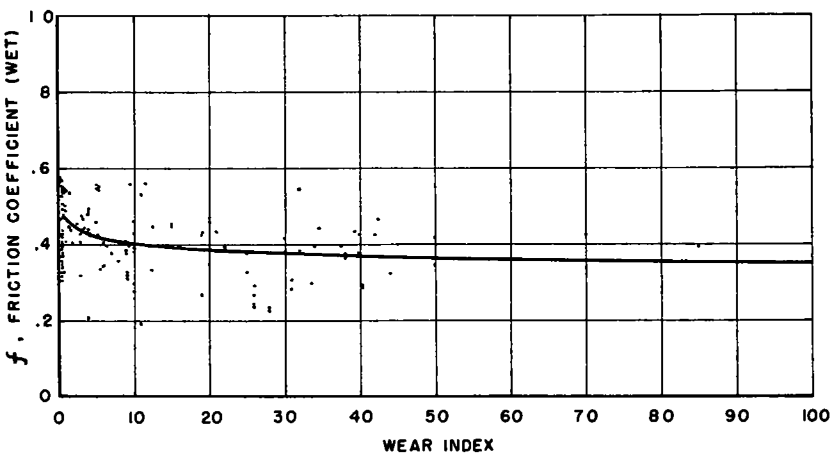

Figure 17. Effect of wear—asphalt.

over short periods. Because it is logical to assume traffic increases over the years, these traffic volume figures may give higher totals for the older pavements than is probably true. But there is no accurate way to correct these figures.

Tire Standard

The program was designed primarily to evaluate the variation in friction coefficient due to road surface alone. However, because measurements were being made of the friction coefficient between road surface and automotive tires, it was necessary that a "standard" tire be used for all tests.

The standard tires adopted for this program were similar to those used in the First International Skid Conference Correlation Study tests conducted in Virginia, August 1958. These tires (specially made by the Goodyear Tire and Rubber Company), are described fully in the Proceedings of the First International Skid Prevention Conference (2, p. 387).

Tire Wear Effects

Inasmuch as standard tires were used in all tests it might appear that the only source of major variation in the friction coefficient would be due to the road surface. However, it is recognized that tread wear is a factor influencing skid resistance of a tire (2, p. 159). In a test program of the long-distance type reported here, tire wear might have had some effect on the friction coefficient values measured. Two sets of standard tires were used, the first set covered 4,500 mi and the second set 3,700 mi. Although comparative tests were made on the same surface, when the former had 4,500 mi and the latter less than 100 mi, the variation measured was less than the known accuracy of the test trailer. No valid conclusion can therefore be drawn inasmuch as the two sets were

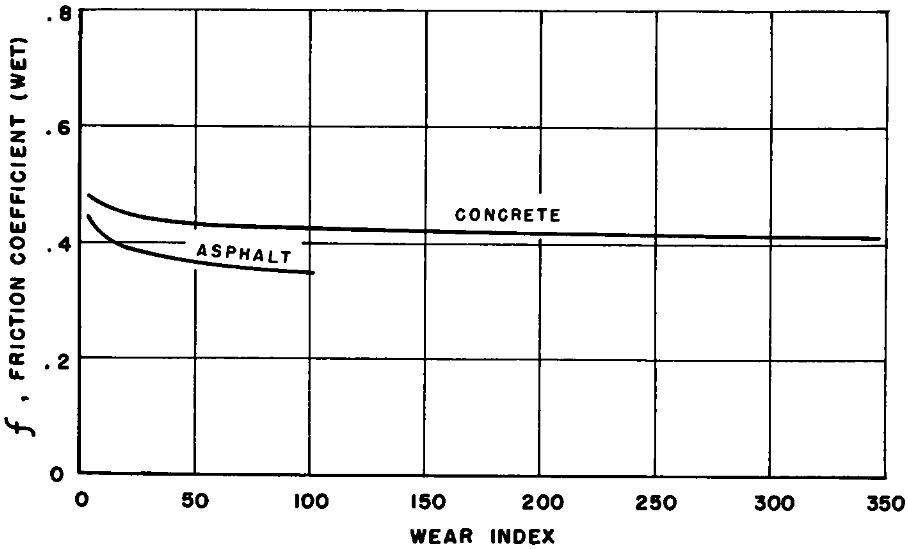

Figure 18. Effect of wear—comparison of PCC and asphalt.

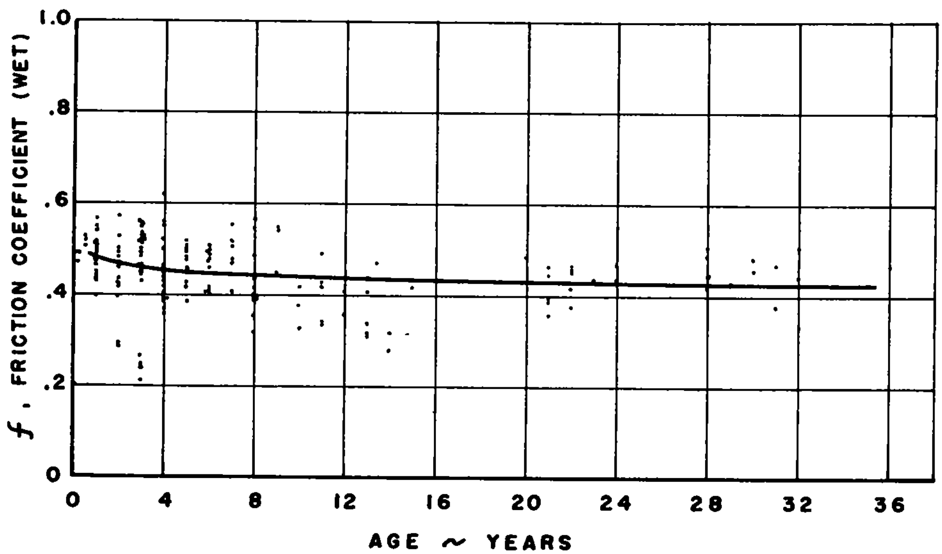

Figure 19. Effect of age—PCC.

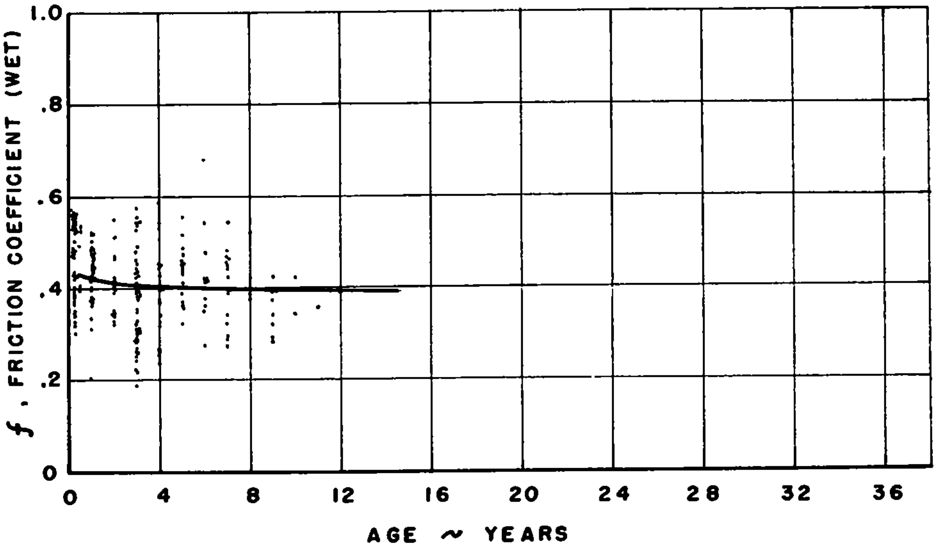

Figure 20. Effect of age—asphalt.

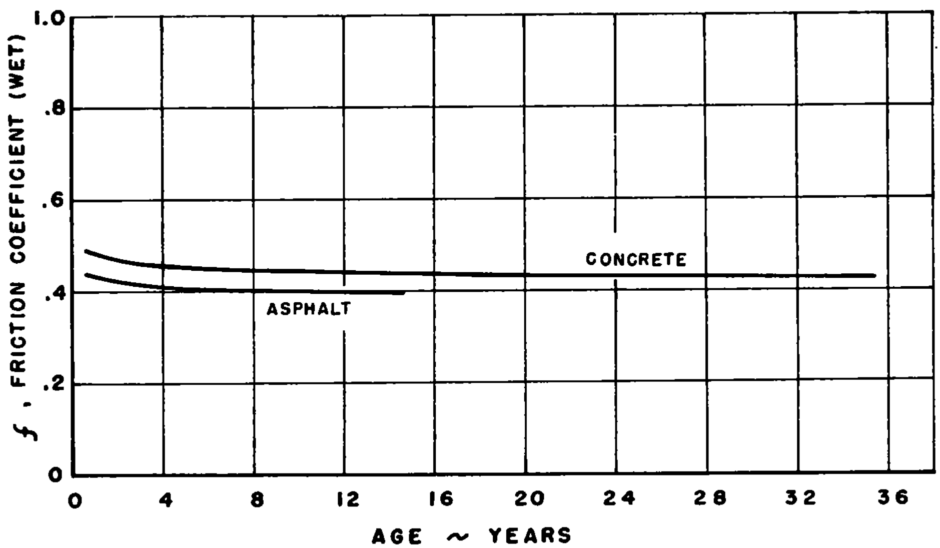

Figure 21. Effect of age—comparison of PCC and asphalt.

not tested on the same surface when all tires had almost zero mileage. It is possible that much greater mileages are required to demonstrate authentic measurable differences.

Effect of Grade

It was necessary to eliminate two-way runs early in the road testing, and accordingly, the effect of road grade on the accuracy of the measurement has to be assessed. An error is introduced when the trailer is stationary on a grade because the combined weight of the tires, wheels, axle, and springs has a small component (equal to the sine of the grade angle) which is "read" by the measuring system.

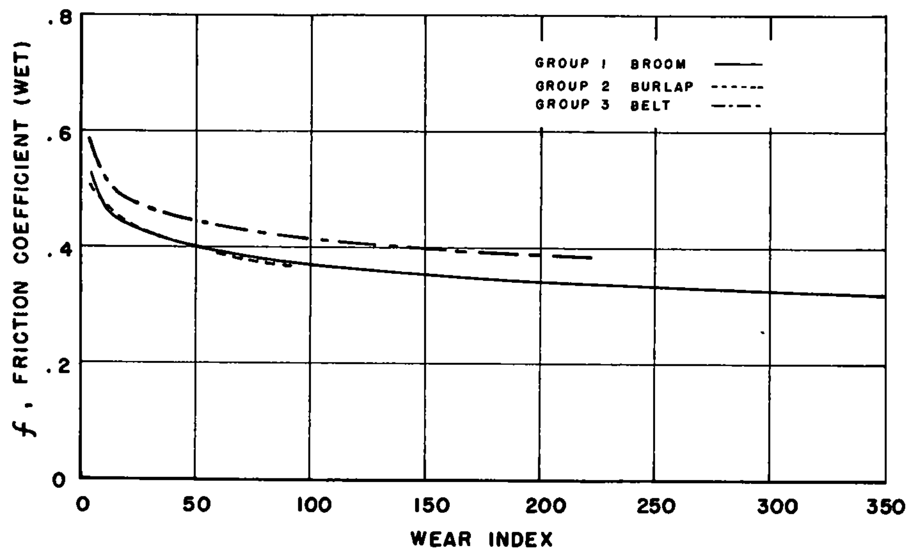

Figure 22. Effect of surface finish—PCC Groups 1, 2, 3.

Weight of tires, wheels, axle, springs	= 300 lb
Static load on tires (level road)	= 1,855 lb
Steepest grade tested	= 4 deg 30 min
Component force due to grade	= 300 x sine 4 deg 30 min
	= 23.5 lb
Tire load normal to road (4½ deg grade)	= 1,855 - (1,855 x sine 4 deg 30 min) = 1,709.3
∴ maximum theoretical error in friction coefficient	$= \pm \frac{23.5}{1,709.3} = \pm 0.0137$

The measured error is actually less because of friction in the spring support link bearings. Tests show that on a 5-deg slope the actual reading in the measuring system is less than 1 microamp which is equivalent to a friction coefficient of 0.01.

Effect of Speed

The effects of speed shown in Figure 23 are derived from test runs made on a four-lane, asphalt-surfaced road in the vicinity of Lancaster, N.Y., at speeds of 30, 35, 40, 45, and 50 mph. It is interesting to compare these results with tests made at 20, 30, 40, and 50 mph on the New York State Thruway in November 1957, using the same equipment (1). The shape of the curve is identical in the speed range common to both.

Except in a very few cases, all tests in the program were run at a standard speed of 40 mph. Friction coefficients for these few cases have been corrected to 40-mph equivalent, using a calibration factor derived from the curves shown in Figure 23.

Apparatus Repeatability

A series of runs were made to show the repeatability accuracy of the measuring system. As reported in the original test result sheets, each set of four runs was made on the same piece of surface in the same direction, at the same speed on the same day. The over-all average for 16 runs gave a value of f = 0.322 and the individual tests average 0.313, 0.331, 0.320, and 0.324, giving deviations of -0.009, +0.009, -0.002, and +0.002. This demonstrates the claimed average friction coefficient accuracy of the PCA test trailer as being ± 0.01.

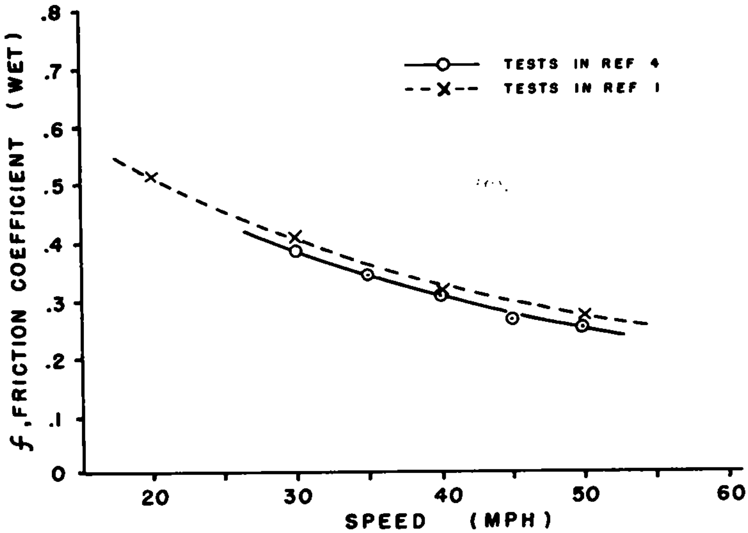

Figure 23. Effect of speed (locked wheels on wet surface).

Effect of Wear

A comparison of the effect of wear on the various groups of portland cement concrete surfaces is shown in Figure 15. This indicates that, of all the various groups measured in this program, the belt-finished, coarse-grained igneous/natural sand combination has the highest friction coefficient when the Wear Index exceeds 100, even though it is inferior to most of the other groups when first laid. It can be seen also that the belt-finished, gravel/natural sand combination and the belt-finished, limestone/natural sand combination are both superior to the broom-finished, gravel/natural sand group at all times.

The graphs shown in Figures 16 and 17 are combined in Figure 18 and show that on the average the PCC surfaces tested gave a higher initial friction coefficient which decreased less with wear than that of the asphalt surfaces tested in this program.

Effect of Age

Figures 19 and 20 show the effect of age on PCC and asphalt surfaces, respectively, whereas Figure 21 combines these graphs to give a direct comparison. The average age and friction coefficient for the 177 PCC surfaces tested in this program are 8.508 years and 0.45, respectively. For the 230 asphalt surfaces tested, the figures are 3.289 years and 0.42, respectively. In comparing PCC and asphalt-surfaced roads, it is interesting to note that only three asphalt surfaces tested in the program were more than 10 yr old. Of the PCC surfaces, 46 were more than 10 yr old and 31 were more than 20 yr old, with the oldest section being 36 yr.

Effect of Surface Finish

A comparison of broom-, burlap- and belt-type finishes on a gravel/natural sand combination is shown in Figure 22. It can be seen that although broom and burlap are virtually similar in effect, they are both inferior to a belt finish in maintaining a good friction coefficient. Figure 5 provides some comparison between broom, burlap and belt finishes on a limestone/natural sand combination. In this case, broom and belt give similar results with burlap slightly inferior. However, it is questionable whether there are sufficient data points for the broom and belt finishes for a reliable trend to be deduced.

RECOMMENDATIONS

More data are required for many aggregate combinations and surface finishes tested in this program. Only groups 1, 2, 3, and 5 have sufficient data points with groups 10 and 16 being marginal in this regard.

Examination of the remaining groups shows that further testing in the States of Arkansas, Georgia, Iowa, Maryland, North Caroline, Ohio, Oklahoma, Pennsylvania, South Carolina, Tennessee, and Texas is required to establish valid trends.

In this paper, all bituminous surfaces have been grouped together because of lack of information about materials used and fabrication methods. It would be desirable to have such information so that these surfaces can be analyzed in the same manner as the PCC surfaces.

For future studies that use Wear Index as a measure of surface wear, more accurate estimates of average daily traffic counts over periods of several years are required. Better data on traffic distribution in various lanes of wide highways is also required.

ACKNOWLEDGMENTS

The research on which this paper is based was sponsored by the Portland Cement Association under Contract Number CC-93, with the Cornell Aeronautical Laboratory, Inc.

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