The Skid-Resistant Properties of Carbonate Aggregates

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Pavement skid resistance is one of the major problems facing the highway engineer today. During the past fifteen years this problem has generated increased concern, and considerable time and effort have been expended seeking a solution. Unfortunately, during this same period the carbonate aggregates have become almost synonymously associated with pavement slipperiness. The data demonstrate the variability on composition and performance of the aggregates included within this broad trade classification. The skid resistant properties of the carbonate aggregates are shown to be dependent on a differential rate of wear between their constituent minerals and to vary directly with the amount of insoluble sand size material incorporated within the aggregate.

•SKID RESISTANCE has long been recognized as one of the significant properties of any highway surface. The highway engineers of 40 and 50 years ago were concerned with such problems as slippery brick, stone block, and poorly designed asphaltic surfaces. With the introduction of portland cement concrete pavements and better designed bituminous surfaces, this problem was felt to have been eliminated. However, as the volume and speed of the nation's traffic increased, even these pavement types did, in some instances, polish and become excessively slippery (1).

Some 30 years ago Moyer (2) noted that certain aggregates displayed a tendency to polish under the influence of traffic, but it has been only during the past 15 years that any real concern regarding the polishing of highway aggregate materials has been expressed. During this period it has been well substantiated that pavement skid resistance is a function of the aggregate material incorporated within the surface. It was found that some aggregates polished more readily, or to a greater degree, than others. Apparently, therefore, the polishing tendency of a given aggregate is one of its distinct physical properties and as such must be dependent on some characteristic of that material. The most obvious characteristic of an aggregate which might impart such a physical property would be its petrology, or mineral assemblage. Aggregates composed of the harder minerals might be expected to polish at a somewhat slower rate that those composed of the softer minerals. Both, however, might be expected, in time, to produce similar highly polished surfaces. Aggregates composed of minerals possessing varying degrees of hardness could be expected to display differential polishing, that is, the softer materials would polish more rapidly than the harder, leaving a somewhat rough, uneven, and possibly nonskid surface. The British (3, 4) have done some outstanding work regarding the polishing tendencies of highway aggregate materials and their related petrology. Their work has essentially verified the foregoing statements. In 1959, Maclean and Shergold (3) stated the following conclusion: "The petrological characteristics that determine whether a stone will polish or not under pneumatic tyred traffic are not yet known, but it is suggested that one important characteristic of rocks that remain rough is the presence of two minerals that have a considerable difference in their resistances to wear." This work was followed by that of Knill (4), who in 1960 conducted a rather complex investigation of the dependence of an

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aggregate's ability to resist polishing on its petrology. She broke the common highway aggregates into several petrologic groups and studied each group separately. The general conclusions of this study were that

> In the igneous rocks, those petrological features which probably affect P (polished stone coefficient) most readily are a variation in the hardness between the minerals, and the proportions of soft minerals present. Rocks in which cracks and fractures are present in the individual mineral grains generally have higher P since such grains are weak and pluck out of the matrix. Finer-grained allotriomorphic igneous rocks, provided they are reasonably fresh, present a tough, cohesive surface which polishes considerably. Sedimentary rocks are variable in their behavior. The Gritstones give a uniformly high P since hard crystals and lithic fragments pluck out of a generally soft and friable matrix. The flints being of simple mineral composition, cryptocrystalline and of uniform hardness polish and have a low P. The Limestone group has an average P of about 0.4. Higher coefficients, in this trade group, appear to be related to the presence of an insoluble residue (especially if such residue is quartz), and to the presence of coarsely crystalline patches of carbonate. The metamorphic rocks tested included members of the Quartzite and Hornfels groups. The intermediate value of P in the Quartzite group is due to the presence of altered feldspars and shattered grains of quartz and quartzite plucking out of a more resistant matrix. However, those quartzites which have recrystallized to form a voidless quartz mosaic can be expected to polish considerably. The polishing of the hornfels is possibly the result of fine grain size and the presence of a high proportion of minerals whose hardness is greater than 5 on Moh's scale, but these observations are based on only three specimens.

The matter of differential hardness seems to be emphasized in the foregoing comments and could conceivably be the controlling factor with regard to aggregate slipperiness.

Carbonate rocks, both limestones and dolomites, form the bulk of the highway aggregates used in this country. Since they are the predominant rock type in most areas, it is economically desirable to make as much use of them as possible. However, during the past 15 years carbonate aggregates have become associated with pavement slipperiness, and their use in the surface course of pavements has been either completely restricted or severely limited in many areas. That many carbonate aggregates do polish and do develop excessively slippery surfaces cannot be denied; however, there are many which have excellent nonskid properties. Limestones and dolomites encompass a wide range of individual rocks and as such might be expected to display many differences with regard to their polishing characteristics. The British investigations indicated that limestones as a group possess low to intermediate or satisfactory resistance to polishing. Investigations during the past several years at the National Crushed Stone Association's laboratory have indicated that aggregate materials bearing the general name "limestone" have developed pavement surfaces varying from excessively slippery to exceedingly nonskid. Corrective measures which will insure the maximum use of even the most polish-susceptible carbonate aggregates have been reported by Gray and Goldbeck (5) in 1959 pertaining to bituminous-concrete pavements, and by Gray and Renninger (6) in 1963 pertaining to portland cement concrete pavements. However, there still exists a need for determining before actual use, or proposed use, the probable skid resistant properties of carbonate aggregates. In 1960 Gray and Renninger (7) presented the results of a preliminary investigation pertaining to the petrological characteristics of carbonate aggregates which apparently are responsible for their behavior with regard to polishing under the action of traffic. This paper is an extension of that initial work and includes the results of that first work as well as that of subsequent investigations.

CARBONATE ROCK DEFINED

Before proceeding further it may be well to establish the meaning of the term limestone, as normally used in the mineral aggregates industry. The term is generally used to identify all carbonate aggregate materials with little, if any, distinction being made between the numerous types of true limestones and dolomites included within this broad category.

Geologically, true limestone is a sedimentary rock, the carbonate portion of which is composed essentially of the mineral calcite ($CaCO_3$) and in which the carbonate fraction exceeds the noncarbonate constituents. The term dolomite should be reserved for those carbonate rocks in which the carbonate fraction is composed primarily of the mineral dolomite ($CaMg[CO_3]_2$). Since most dolomites are postdepositional replacements of limestones, a complete series of rocks can exist between the two extreme compositions. In addition, both limestones and dolomites may contain up to 50 percent of some noncarbonate impurities. Materials such as clay, quartz, chert, chalcedony, pyrite, and feldspar may be included within the makeup of a particular carbonate aggregate. The foregoing definitions suggest the probability of the occurrence of a great number of individual carbonate rock varieties which could vary considerably in their mineral composition and relative Moh's hardness characteristics. Therefore, it is reasonable to expect these carbonates to possess significantly differing polishing characteristics.

DESCRIPTION OF TESTING PROGRAM

Since differential hardness was believed to be the controlling factor with regard to a given carbonate aggregate's susceptibility to the polishing action of rubber-tired traffic, several carbonates possessing noncarbonate fractions of widely differing amounts and of divergent mineralogies were chosen for study. During the past four years, four separate investigations have been conducted with both portland cement and bituminous concretes. Unfortunately, however, during this same period the laboratory apparatus used to measure the skid resistance of the various test surfaces underwent a gradual transition making it impossible to correlate results directly from one group of tests to another. The information obtained, though, was still relative within any given group and the factors controlling skid resistance can be expressed. For this reason, each of the four test series is described and discussed separately, but the results common to all are explained.

Test Series No. 1

The polishing characteristics of five dissimilar carbonate aggregates were studied in bituminous concrete surfaces. The aggregate gradations and mix compositions are given in Table 1. Each mix was designed by the Marshall procedure (ASTM D 1559) and complied with the specifications applicable to the area from which the sample was obtained. Both coarse and fine portions of the aggregates were derived from the same parent rock.

Test Series No. 2

Three carbonate aggregates in the form of manufactured stone sand were studied in portland cement mortar surfaces; the aggregate gradations are given in Table 2 and the mortar batch quantities in Table 3. Each mortar was designed to have the same properties as a mortar which would be worked to the surface during the normal finishing operations of a portland cement concrete pavement. They were designed with sufficient water and entrained air to yield, when combined with the correct amount of 2 in. to No. 4 coarse aggregate, paving concrete having 3 to 6 percent entrained air, and a slump of approximately 2 in.

Test Series No. 3

The polishing characteristics of eight carbonate aggregates in the form of manufactured stone sand were studied in portland cement mortar surfaces designed in a manner

TABLE 1

AGGREGATE GRADATION AND BITUMINOUS MIX COMPOSITION—TEST SERIES NOS. 1 AND 4

Identification	Gradation: Total Percent Passing:													Asphalt Content (%)	Slipperiness (wheel angle deg)
	½ In.	⅜ In.	¼ In.	No. 4	No. 8	No. 10	No. 20	No. 30	No. 40	No. 50	No. 80	No. 100	No. 200		
(a) Test Series No. 1															
1-A	100	99		83		64			21		11		6	6.5	52
1-B	100	90		60		42			18		9		6	5.3	51
1-C	100	90		60		42			18		9		6	5.5	79
1-D	100	95		66		46			18		11		6	6.5	39
1-E	100	95		75		50			17		10		7	6.5	89
(b) Test Series No. 4															
1-B	100	90	-	60	-	42	-	-	18	-	9	-	6	5.3	48
4-A	-	100	-	64	40	-	-	18	-	13	-	10	8	6.0	75
4-B	-	-	100	-	-	94	-	41	-	20	16	-	10	8.0	48
4-C	100	-	73	-	34	-	17	-	-	-	6	-	4	5.0	64
4-D[a]	-	-	-	100	85	-	-	29	-	16	-	10	7	8.0	57

[a]Sheet asphalt mix; aggregate less filler added to make grading here was tested in portland cement mortar.

TABLE 2

AGGREGATE GRADATION AND CERTAIN PHYSICAL PROPERTIES—TEST SERIES NOS. 2 AND 3

Identification	Gradation: Total Percent Passing:							Fineness Modulus	Specific Gravity		Absorption (%)
	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200		Bulk dry	Apparent	
(a) Test Series No. 2											
2-A	-	100	56	28	13	5	3.4	2.98	2.67	2.72	0.76
2-B	100	97	62	39	22	11	4.9	2.70	2.68	2.72	0.61
2-C	100	96	56	31	17	8	5.9	2.92	2.65	2.73	1.11
(b) Test Series No. 3											
3-A	100	83	39	20	11	6	3.1	3.41	2.60	2.77	2.44
3-B	100	98	61	37	21	10	5.0	2.74	2.58	2.72	1.87
3-C	100	91	72	37	15	8	6.1	2.77	2.63	2.72	1.29
3-D	100	99	66	31	16	9	6.7	2.81	2.74	2.82	1.00
3-E	100	92	59	34	18	8	4.0	2.89	2.68	2.72	0.63
2-A	-	100	56	28	13	5	3.4	2.98	2.67	2.72	0.76
2-C	100	96	56	31	17	8	5.9	2.92	2.65	2.73	1.11
1-D	100	75	51	32	19	8	4.8	3.15	2.68	2.74	0.76

TABLE 3

PORTLAND CEMENT MORTAR BATCH QUANTITIES—TEST SERIES NOS. 2 AND 3

Identification	Design Cement Factor (sk/cu yd of conc.)[a]	Actual Batch Proportions (lb/cu yd of conc.)[a]			Actual Cement Factor (sk/cu yd)[a]	Actual Water Content (gal/cu yd)[a,b]	Actual Water-Cement Ratio (gal/sk)[a,b]	Air Content (%)[c]	Slipperiness (wheel angle deg)
		Cement	Water[b]	Carbonate Sand					
(a) Test Series No. 2									
2-A	6.0	560	230	1,090	5.95	27.8	4.67	4.9	48
2-B	6.0	570	235	1,045	6.07	28.3	4.66	3.8	57
2-C	6.0	570	235	1,090	6.09	28.4	4.66	3.8	60
(b) Test Series No. 3									
3-A[d]	6.0	540	223	1,136	5.75	26.8	4.66	6.7	56
3-B	6.0	560	231	994	5.95	27.8	4.67	4.9	66
3-C	6.0	568	235	1,036	6.04	28.2	4.67	4.2	81
3-D	6.0	563	233	1,080	5.99	27.9	4.66	4.6	68
3-E	6.0	566	234	1,084	6.02	28.1	4.67	4.3	61
2-A	6.0	550	227	1,072	5.84	27.3	4.67	5.8	49
2-C	6.0	565	234	1,078	6.02	28.0	4.65	4.4	67
1-D[e]	6.0	569	257	1,164	6.05	30.8	5.09	2.8	40

[a]Based on paving concrete containing 2 in. -No. 4 corase aggregate.
[b]Net water content; does not include water for absorption of aggregates.
[c]Air content expressed as air content of equivalent concrete mix; calculated from measured air content of mortar.
[d]Air content too high; therefore cement factor and water content too low.
[e]Air content too low; water content too high; result of hand mixing.

identical to that previously described. The aggregate gradations are given in Table 2 and the mortar batch proportions in Table 3.

Test Series No. 4

The skid resistant properties of five carbonate aggregates were investigated. Four

TABLE 4

AGGREGATE GRADATION AND PORTLAND CEMENT MORTAR BATCH QUANTITIES

Aggregate Gradation	4-D
Total percent passing:	
No. 4	100
No. 8	81
No. 16	42
No. 30	22
No. 50	12
No. 100	7
No. 200	5.4
Fineness modulus	3.36
Specific gravity	
Bulk dry	2.63
Apparent	2.69
Absorption (%)	0.85
Portland cement mortar batch quantities	
Design cement factor (sk/cu yd of conc.)[a]	6.0
Actual batch proportions (lb/cu yd of conc.)[a]	
Cement	568
Water[b]	235
Carbonate sand	1,196
Actual cement factor (sk/cu yd)[a]	6.04
Actual water content (gal/cu yd)[a, b]	28.2
Actual water-cement ratio (gal/sk)[a,b]	4.67
Air content (%)[c]	4.2
Slipperiness (wheel angle deg)	54

[a]Based on paving concrete containing 2 in.-No. 4 coarse aggregate.
[b]Net water content; does not include water for absorption of aggregates.
[c]Air content expressed as air content of equivalent concrete mix; calculated from measured air content of mortar.

were studied in bituminous-concrete surfaces and the fifth in both a sand-asphalt and a portland cement mortar surface. The portland cement mortar surface was designed as those described previously, whereas the bituminous surfaces were designed in accordance with the specification applicable to the particular areas from which the aggregates were obtained. The aggregate gradations and bituminous mix compositions are given in Table 1, and Table 4 indicates the aggregate characteristics and batch quantities of the one aggregate tested in portland cement mortar.

After placement in the NCSA Circular Test Track (described in the March 1959 issue of the Crushed Stone Journal) the bituminous mixtures were initially rolled with a heavy steel roller and then with a pneumatic tire roller. The portland cement mortar surfaces were hand-finished with a wooden float and allowed to cure under a covering of damp burlap for a period of 28 days. Following this initial treatment both the bituminous and portland cement surfaces were subjected to thousands of passes of a wheel equipped with a rubber tire. Initially, water and a fine siliceous sand were placed on the test surfaces as an aid to the tire in wearing away the surface binder (either asphalt or portland cement paste) and exposing the aggregates. Once the aggregates were exposed the surfaces were cleaned and dried. To polish the exposed aggregate particles the traffic was continued using only the rubber tire.

DETERMINATION OF SLIPPERINESS

At appropriate intervals throughout the duration of each test series measurements of the skid resistance of the various test sections were made with the NCSA Slipperiness Testing Apparatus. A description of the present device and the operating procedure employed are given in the Appendix. Unfortunately, as mentioned previously, the Slipperiness Testing Apparatus underwent a period of transition during the tenure of the tests. The present apparatus was used to determine the skid resistance of those test sections comprising Test Series Nos. 2, 3, and 4. The same device, somewhat modified, was used during the conduct of Test Series No. 1. In place of the rubber strip on the present tire a portion of the original tread was left intact, the weight assembly (driving force) was somewhat heavier, and the tire rim was of a lighter design. These differences in design result in a wider spread, and generally higher values of wheel angle readings for the Test Series No. 1 surfaces. Both wheels have been found to correlate well with large-scale stopping-distance vehicles at various times; however, their measurements, due to tire wear, should be interpreted only as relative within a given series of tests. For these reasons no attempt has been made to correlate results from one test series to another. A continuous calibration of the device, during any one test series, was maintained by periodic tests on ground glass plate "standards of slipperiness."

This work was completed before the time the British Portable Skid Tester was commercially available. The British Tester which is presently employed in the NCSA laboratory has been found to correlate fairly well with the Bicycle Wheel Apparatus during any specific test series.

RATE OF POLISH

Certain carbonate aggregates polish quite rapidly with the application of very little traffic whereas others do not polish or polish very slowly during even extended periods of traffic application. This statement is amply supported by Figures 1 through 4 which depict the polishing rates of the various carbonate aggregates studied under each of the four test series. Several years ago questions were raised concerning the criteria or method needed to determine when this polishing traffic should be stopped. Ordinarily tests of this nature had been discontinued when the polishing rate curve became essentially horizontal. This normally occurred between 40,000 and 60,000 passes of the rubber tire. The assumption in the past was that at such a point a more or less static condition of slipperiness had been reached; however, this assumption had never been verified. To justify the stopping of the tests at such a point the polishing traffic applied to the surfaces constituting Test Series No. 1 was purposely continued well beyond the leveling-off point. Figure 5 shows that very little additional polishing was achieved once the leveling occurred at about 40,000 passes of the wheel. The use of the wheel angle readings obtained at the leveling-off point, 40,000 passes in this case, as a measure of the ultimate skid resistance of the various test surfaces was enhanced by the fact that these values all lay within one standard deviation of the values obtained after extending the traffic an additional 55,000 passes. The dotted bands in Figure 5 are the standard deviation limits of the readings made after 95,000 passes of the wheel for each of the test sections shown.

METHOD OF STUDYING CARBONATE ROCK CHARACTERISTICS

Since the polishing characteristics and the ultimate level of skid resistance attained by carbonate aggregates were believed to be dependent on some definite physical property or properties of the aggregate in question, a systematic procedure had to be developed to determine the basic properties of these materials. The individual samples studied were representative of stockpiles of commercially produced stone including material from the entire working face of the various quarry operations. After some exploratory tests, the following procedure was adopted:

1. Samples of each aggregate, representative of their respective gradations as used, in either the bituminous concretes or portland cement mortars, during the skid resistance studies, were selected.

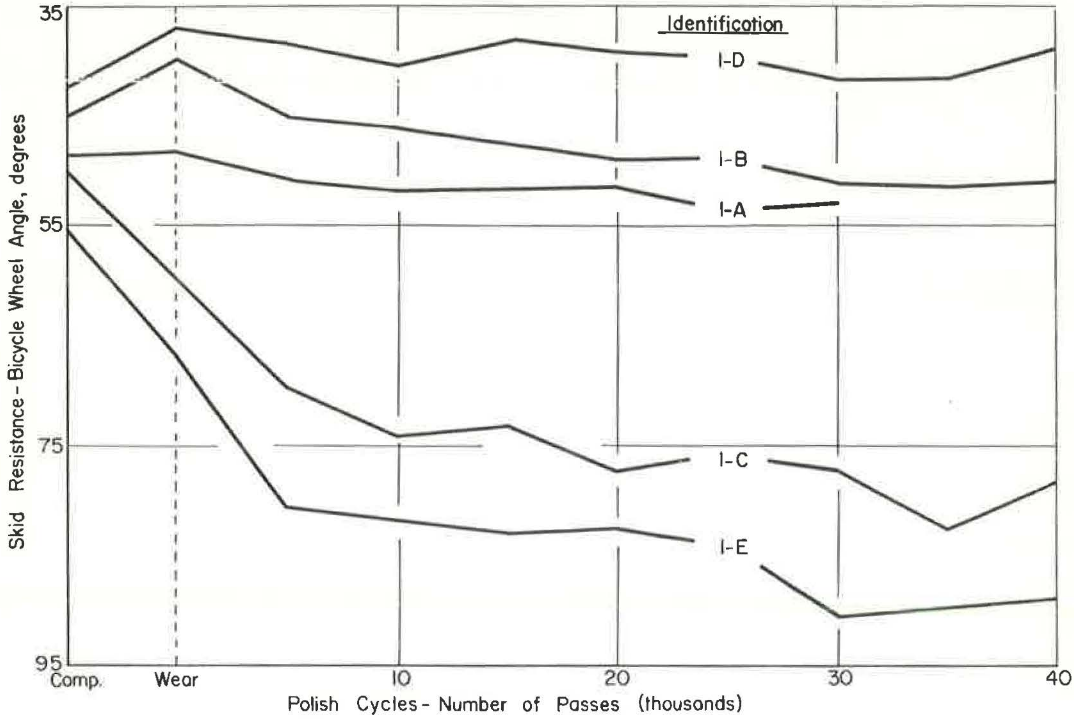

Figure 1. Rate of polish, Test Series No. 1.

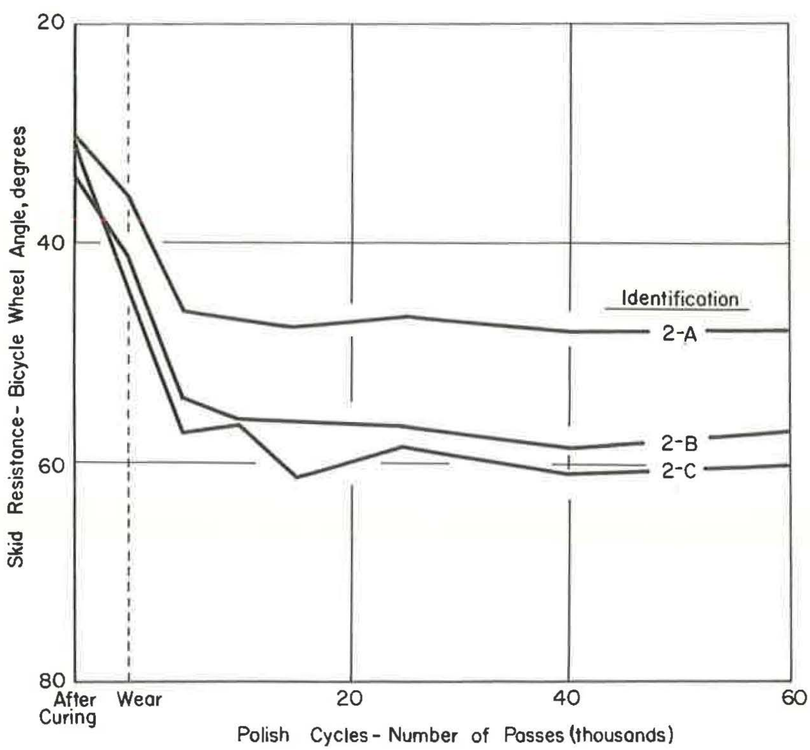

Figure 2. Rate of polish, Test Series No. 2.

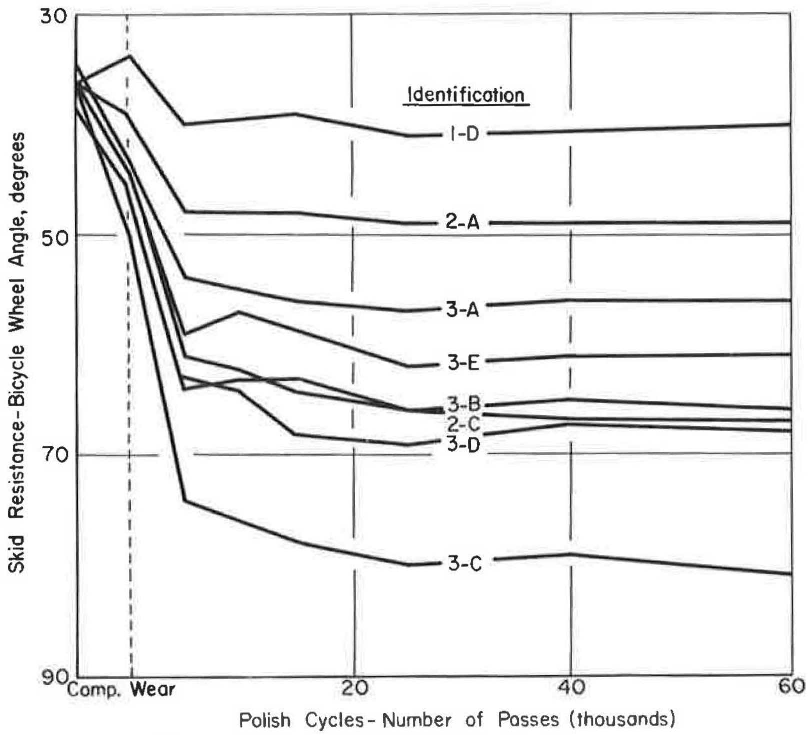

Figure 3. Rate of polish, Test Series No. 3.

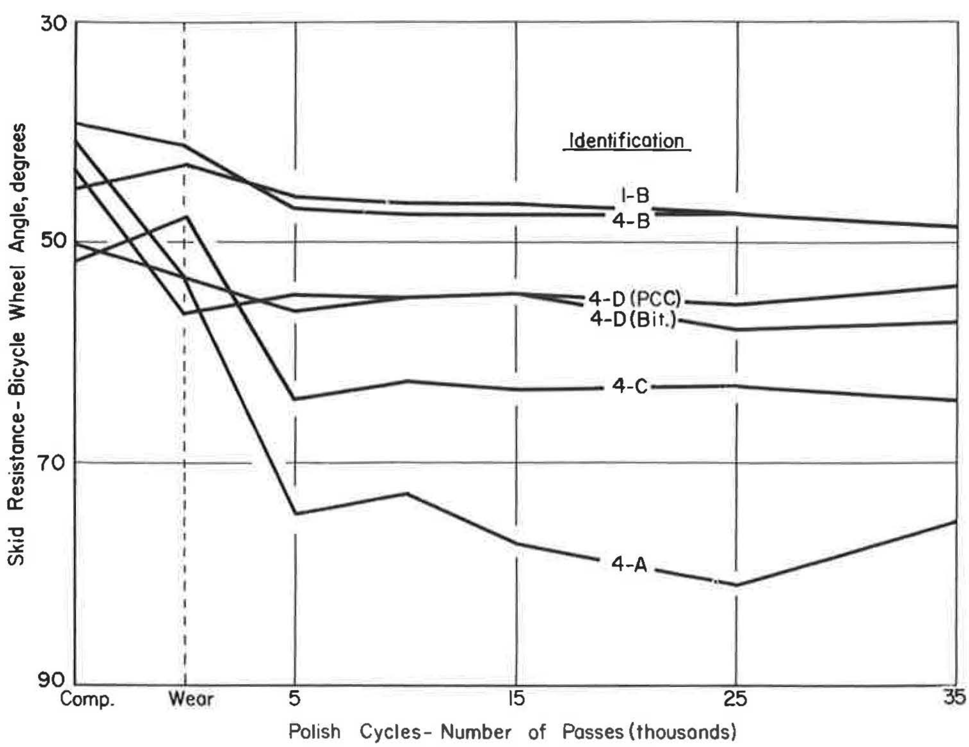

Figure 4. Rate of polish, Test Series No. 4.

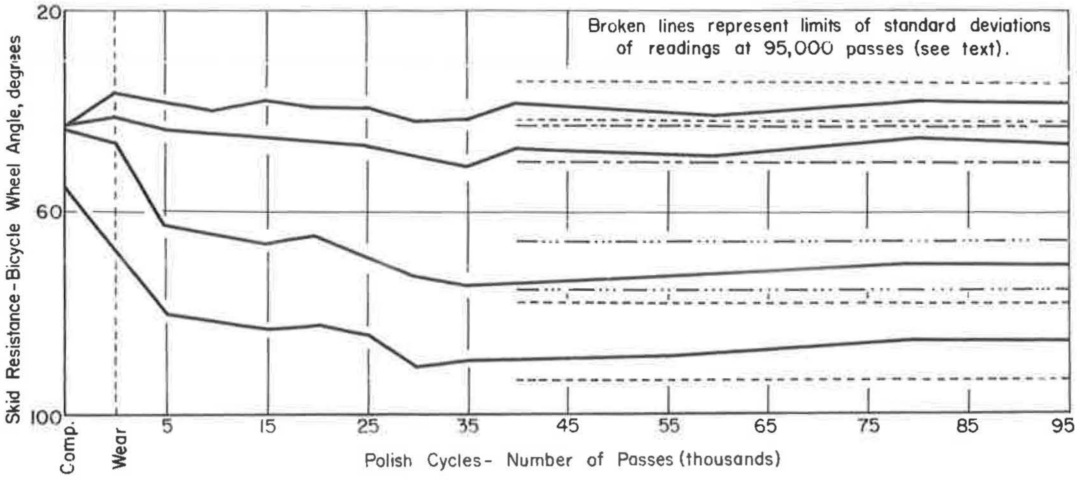

Figure 5. Effect of traffic on ultimate skid resistance.

2. Each of the samples was reacted with a dilute solution of hydrochloric acid until the carbonate minerals had been fully digested.
3. The residue remaining after the acid leaching was filtered, washed, dried, and weighed, and the percentages of total carbonates and insoluble residue calculated.
4. The insoluble residue was then tested for grain-size distribution using ASTM D 422, Grain Size Analysis of Soils (Tentative), and for specific gravity by ASTM D 854, Specific Gravity of Soils.
5. An approximate determination of the mineral composition of each insoluble residue was made under a low power binocular microscope.

The results of the insoluble residue determinations and the grain-size analyses of those residues, Tables 5 and 6 indicate, to some extent, the heterogeneous nature of carbonate rocks as a group. A classification of the insoluble residues as percentages of the total aggregate, using a soils classification of sand size, silt size, and clay size, is also given. The insoluble residue coarser than the silt fraction, that is, greater than 0.05mm, was studied microscopically in an effort to describe the accessory mineral composition of each carbonate aggregate under study (Tables 5 and 6).

INFLUENCE OF CARBONATE ROCK CHARACTERISTICS ON SLIPPERINESS

The results obtained for the group of aggregates in Test Series No. 1 (the initial investigation previously reported by Gray and Renninger in 1960) are discussed in some detail and the results of the remaining three test series are used to substantiate the original conclusions. However, despite the fact that skid resistance is expressed as a bicycle wheel angle in each case, the interseries results should not be directly correlated with one another on that basis. As explained earlier, the NCSA Slipperiness Testing Apparatus underwent some change during the conduct of these investigations and the results are relative only within any one given series of tests.

Test Series No. 1

Carbonate aggregate 1-C which proved to be quite slippery was a siliceous carbonate containing approximately 25 percent acid insoluble residue, 40 percent of which (i. e., 10 percent of the total rock) was composed of extremely fine material, 0.05 mm or less in diameter. Carbonate aggregate 1-E, the most slippery of the five aggregates in this test series, possessed the smallest percentage of acid insoluble residue. Two-thirds of its 9 percent residue was composed of material of the silt and clay size range, i. e, less than 0.05 mm in diameter. Therefore, of the two aggregates which proved to be the most slippery in this series of tests, one had a low residue percentage, whereas the

TABLE 5

GRADATION AND SIZE CLASSIFICATION OF INSOLUBLE RESIDUE

Identification	Slipperiness (wheel angle deg)	Carbonate (%)	Acid (%)	Grain Size Tot. Percent Finer Than: ³/₈ In. (9.52 mm)	No. 4 (4.76 mm)	No. 10 (2.00 mm)	No. 40 (0.42 mm)	No. 60 (0.25 mm)	No. 80 (0.177 mm)	No. 100 (0.149 mm)	No. 200 (0.074 mm)	(0.05 mm)	(0.005 mm)	Size Classification (% of Total Aggr.) Coarse Aggr. (+2.0 mm)	Sand (0.05 to 2.0 mm)	Silt (0.005 to 0.05 mm)	Clay (-0.005 mm)	Total
(a) Test Series No. 1																		
1-A	52	58.5	41.5	100	90	78	47	39	33	-	21	14	2	9.3	26.1	5.1	1.0	41.5
1-B	51	64.2	35.8	100	94	85	63	51	42	-	25	14	2	5.4	25.2	4.3	0.9	35.8
1-C	79	74.6	25.4	100	81	69	52	48	47	-	41	40	16	7.9	7.3	6.3	3.9	25.4
1-D	39	51.9	48.1	100	100	98	94	78	64	-	18	15	8	0.9	40.1	3.5	3.6	48.1
1-E	89	90.8	9.2	100	100	94	85	81	78	-	66	60	20	0.6	3.1	3.7	1.8	9.2
(b) Test Series No. 2																		
2-A	48	85.2	14.8	-	100	100	97	77	62	-	40	34	7	0.0	9.8	4.0	1.0	14.8
2-B	57	85.0	15.0		100	97	82	76	72	-	62	55	5	0.4	6.4	7.5	0.7	15.0
2-C	60	83.7	16.3		100	100	94	91	90	-	84	79	23	0.0	3.5	9.1	3.7	16.3
(c) Test Series No. 3																		
3-A	56	94.4	5.6		100	84	60	-	50	-	44	42	5	0.9	2.3	2.1	0.3	5.6
3-B	66	97.5	2.5		100	73	56	-	45	-	30	30	14	0.7	1.1	0.4	0.3	2.5
3-C	81	95.7	4.3		100	100	96	-	91	-	84	81	50	0.0	0.8	1.3	2.2	4.3
3-D	68	96.0	4.0		100	100	95	-	90	-	84	77	14	0.0	0.9	2.5	0.6	4.0
3-E	61	84.2	15.8		100	99	83	-	71	-	59	52	7	0.2	7.3	7.2	1.1	15.8
2-A	49	85.2	14.8		100	100	97	-	62	-	40	34	7	0.0	9.8	4.0	1.0	14.8
2-C	67	83.7	16.3		100	100	94	-	90	-	84	79	23	0.0	3.5	9.1	3.7	16.3
1-D	40	51.9	48.1		100	98	94	-	64	-	18	15	8	1.0	39.9	3.4	3.8	48.1
(d) Test Series No. 4																		
4-A	75	86.2	13.8	100	100	83	67	-	59	57	51	39	-	2.4	6.0	5.4[b]		13.8
4-B	48	57.4	42.6	100	100	93	45	-	29	25	16	10	-	3.0	35.1	4.5[b]		42.6
4-C	64	92.9	7.1	100	98	91	82	-	78	76	63	46	-	0.6	3.3	3.2[b]		7.1
4-D	57	64.3	35.7	100	100	77	25	-	13	11	7	6	-	8.1	25.6	2.0[b]		35.7
4-D[a]	54	63.9	36.1	100	100	77	23	-	12	10	7	6	-	8.4	25.8	1.9[b]		36.1
1-B	48	64.2	35.8	100	94	85	63	-	42	-	25	14	-	5.4	25.2	5.1[b]		35.8

[a]Used in portland cement mortar surface. [b]Silt and clay, -0.05 mm.

TABLE 6

IDENTIFICATION OF AGGREGATE BASED ON MINERAL COMPOSITION

Identification	Approximate Mineral Composition	Percent	Name
(a) Test Series No. 1			
1-A	Carbonates Quartz Mica minerals Feldspar Clay or clay-like material Carbonaceous material	58 17 11 10 4	Arenaceous carbonate
1-B	Carbonates Quartz Mica minerals Magnetite	64 10 26 Trace	Mica rich siliceous carbonate
1-C	Carbonates Quartz Mica minerals Clay or clay-like material	75 25	Grey siliceous carbonate
1-D	Carbonates Quartz Mica minerals Carbonaceous material	52 47 1	Arenaceous carbonate
1-E	Carbonates Insoluble residue (Too fine grained to distinguish under 30x)	91 9	Grey carbonate
(b) Test Series No. 2			
2-A	Carbonates Acid insoluble residue Primarily discrete particles of quartz resembling a fine beach sand, with minor amounts of clay or clay-like material and a trace amount of biotite mica.	85.2 14.8	Siliceous carbonate sand
2-B	Carbonates Acid insoluble residue Appreciable amounts of quartz, clay or clay-like material, with minor constituents including chert, pyrite, magnetite and some limonite.	85.0 15.0	Siliceous carbonate sand
2-C	Carbonates Acid insoluble residue Very small quartz particles, 30 to 40 percent clay or clay-like material, with trace amounts of mica.	83.7 16.3	Siliceous carbonate sand
(c) Test Series No. 3			
3-A	Carbonates Insoluble residue Contains a considerable amount of siliceous fossil replacements and clay or clay-like material, with discrete particles of both quartz and magnetite also evident; many particles sub- to well-rounded in shape.	94.4 5.6	Carbonate sand
3-B	Carbonates Insoluble residue Primarily sharp, angular chert particles resembling quartzite, and discrete quartz particles, with trace amounts of pyrite.	97.5 2.5	Carbonate sand
(c) Test Series No. 3 (cont'd.)			
3-C	Carbonates Insoluble residue Almost entirely finely divided quartz, and clay or clay-like material, medium to dark grey, with trace amounts of an iron-bearing mineral, probably limonite, and minor amounts of both biotite and muscovite mica.	95.7 4.3	Carbonate sa
3-D	Carbonates Insoluble residue Primarily clay or clay-like material, with minor amount of discernible quartz particles showing an iron stain; trace amounts of pyrite, mica, and an iron mineral, probably limonite.	96.0 4.0	Carbonate sa
3-E	Carbonates Insoluble residue Appreciable amounts of quartz and clay or clay-like material, with minor constituents including chert, pyrite, magnetite, and probably limonite.	84.2 15.8	Siliceous Carbonate
2-A	See 2-A, Test Series No. 2		
2-C	See 2-C, Test Series No. 2		
1-D	Carbonates Insoluble residue Almost entirely discrete quartz particles with trace amounts of both biotite and muscovite mica; resembles a fine beach sand.	51.9 48.1	Arenaceous carbonate
(d) Test Series No. 4			
4-A	Carbonates Insoluble residue Light grey, fine-grained quartz particles and a clay-like material with trace amounts of iron (limonite).	86.2 13.8	Siliceous carbonate
4-B	Carbonates Insoluble residue Light to dark grey quartz particles and what appears to be detritus from an acidic metamorphic rock containing feldspar, quartz, mica, and some dark-colored iron minerals.	57.4 42.6	Arenaceous carbonate
4-C	Carbonates Insoluble residue Dark grey, fine-grained quartz and a clay-like material, with some limonite and probably dark-colored carbonaceous material.	92.9 7.1	Carbonate
4-D	Carbonates Insoluble residue Light to medium grey chert and quartz with some minor amounts of clay, chert, occurring in coarser fractions and quartz in the finer sizes.	63.9-64.3 35.7-36.1	Cherty carbonate
1-B	See 1-B, Test Series No. 2		

second contained an appreciable amount of residue. Therefore, the residue content alone does not control the skid resistance of a carbonate aggregate. However, both of the foregoing aggregates had one factor in common. The grain-size distribution of the residues of these two aggregates (Table 5) indicates that appreciable amounts of both residues are less than 0.05 mm in diameter, i. e., both are composed essentially of silt and clay size material. These same data also serve to indicate that this very fine siliceous material does not effectively contribute to aggregate skid resistance.

Aggregates 1-A and 1-D were arenaceous carbonates and both developed surfaces possessing good skid resistance. Aggregate 1-A contained 42 percent acid insoluble

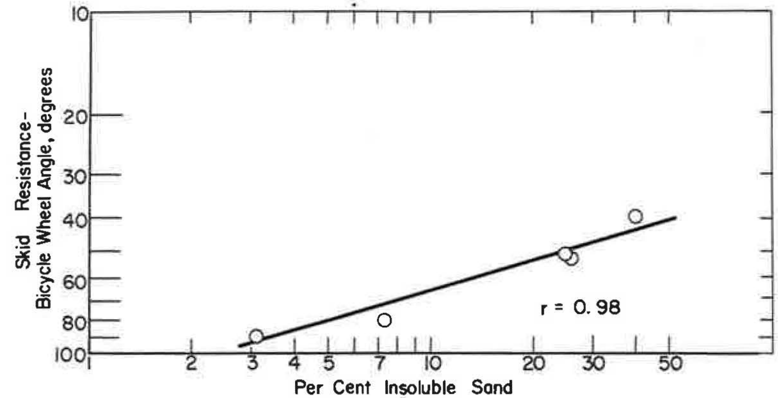

Figure 6. Relationship between skid resistance and amount of insoluble sand, Test Series No. 1.

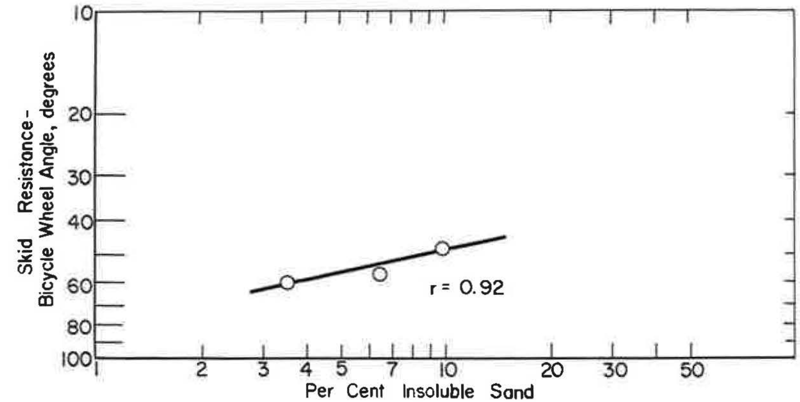

Figure 7. Relationship between skid resistance and amount of insoluble sand, Test Series No. 2.

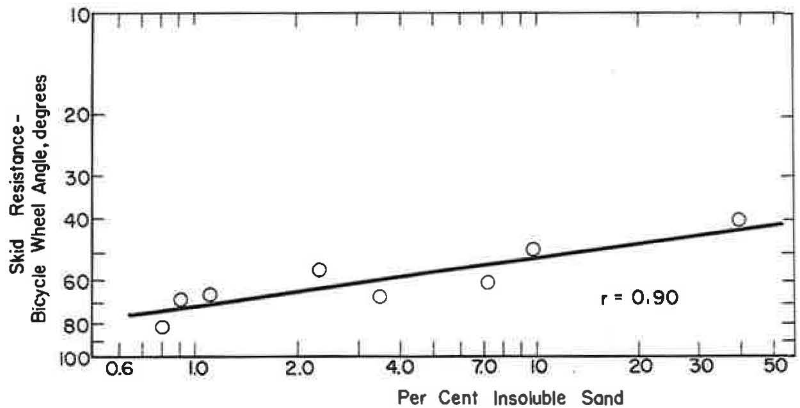

Figure 8. Relationship between skid resistance and amount of insoluble sand, Test Series No. 3.

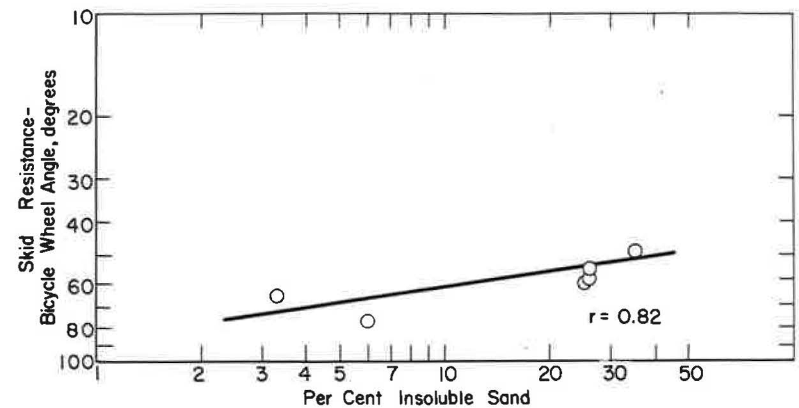

Figure 9. Relationship between skid resistance and amount of insoluble sand, Test Series, No. 4.

residue which was composed primarily of sand size (0.05 to 2.0 mm) grains of quartz, mica, and feldspar. The residue content of aggregate 1-D was 48 percent and was composed almost entirely of sand size grains of quartz. From these results, it would appear that the amount of acid insoluble residue does influence, but not control, the polishing characteristics of carbonate aggregates. There is evidence that the sand-size grains of the residue effectively contribute to the ultimate skid resistance of a carbonate aggregate. It might be expected that a carbonate aggregate having a residue content of 48 percent, most of which was sand size particles of quartz, might have the appearance of a coarse sandpaper, providing the carbonate fraction was sufficiently soft and capable of being worn away to expose the quartz particles. Actually, aggregate 1-D had just such an appearance after being subjected to the rubber tired traffic.

Aggregate 1-B, which also possessed good nonskid properties, was noticeably different from either sample 1-A or 1-D. The acid insoluble residue content of this aggregate was 36 percent but consisted primarily of the mica minerals with some quartz. The grain-size distribution of the residue was, however, quite similar to that of aggregate 1-A and the skid resistance of the bituminous-concrete surfaces containing these two aggregates was very nearly the same despite the fact that the residue of aggregate 1-B was composed essentially of the mical minerals, a rather unusual occurrence for the average carbonate rock, which is one-half to one point softer than carbonate material on the Moh scale of hardness. It would seem, therefore, that the polishing characteristics of carbonate aggregates are not indicated solely by the hardness of the minerals comprising the aggregate, but rather by a differential in the hardness of the mineral constituents. The foregoing statement made as a result of these studies finds support through the works of other investigators. The work of Maclean and Shergold (3) and that of Knill (4) have resulted in similar findings.

It is, however, questionable whether differential hardness in itself is the essential property since the results of this initial study also tend to indicate that it is a combination of differential hardness, amount of acid insoluble residue, and the grain-size distribution of that residue which seems to govern the polishing characteristics of carbonate aggregates. Certainly the presence of even appreciable quantities of hard minerals in the silt and clay size range does not impart nonskid properties to carbonate rock as evidenced by the results obtained with aggregate 1-C in which appreciable quartz is present in these sizes.

Since the results of this initial investigation seemed to define the physical properties necessary to a nonskid carbonate aggregate, and since the plot of bicycle wheel angle or degree of slipperiness vs the percent insoluble sand size material (0.05 to 2.0 mm), Figure 6, showed such a high degree of correlation it was felt some supporting data should be developed. Test series Nos. 2, 3, and 4 were conducted with this in mind.

Test Series No. 2

The three aggregates studied during this portion of the investigation were in the form of manufactured stone sands and were incorporated in portland cement mortars, the design properties of which were described earlier and are given in Table 3. The three carbonate sands contained approximately the same amounts of acid insoluble residue; however, the grain-size distribution of these residues was noticeably different (Table 6). The skid resistance of surfaces containing these particular materials varied inversely with their residue contents, further evidence that residue content alone is not the controlling factor which determines a given carbonate's nonskid properties.

The acid insoluble residue of each of the three aggregates was composed essentially of siliceous materials (Table 6), which differed primarily in their respective grain-size distributions. Figure 7 plots bicycle wheel angle or slipperiness vs the percent of insoluble sand size material. The measured skid resistance can again be seen to vary directly with this particular aggregate characteristic.

Test Series No. 3

This group of tests was essentially an extension of Test Series No. 2 and two of the aggregates included were identical to two (aggregates 2-A and 2-C) studied in that series. Aggregate 1-D, in the form of a stone sand, was also included for comparative purposes. The acid insoluble residues of the eight test aggregates again displayed a considerable variation in quantity and did not, as such, correlate with the skid resistance of the test surfaces. The grain-size distribution of the eight residues varied noticeably from fine to coarse and it was again possible to correlate the insoluble sand content of each aggregate with the skid resistance displayed by its respective test surface. Table 5 contains the pertinent information relative to the insoluble residues of the eight carbonate sands investigated and Figure 8 plots insoluble sand content vs skid resistance.

Test Series No. 4

The four carbonate aggregates (1-B, 4-A, 4-B, and 4-C) displayed the now typical variations in size distribution and amount of acid insoluble residue and skid resistance (Table 6). One aggregate, carbonate aggregate 4-D, was studied in both a sheet asphalt and a portland cement mortar surface. No appreciable difference in the level of skid resistance attained by these two surfaces was recorded (Tables 1 and 4), which may be taken to indicate that the type of binding material has little, if any effect on the ultimate skid resistance developed by a highway surface and that the aggregate comprising that surface is, in fact, the primary contributor to pavement skid resistance or pavement slipperiness. Figure 9 plots the insoluble sand content of each aggregate and the measured skid resistance of their respective test sections made without regard to binder type. The degree of correlation of the data of this test series was somewhat lower than that of the previous three. The calculated correlation coefficient for Test Series No. 4 was 0.82 as compared with 0.98, 0.92, and 0.90 for Test Series No. 1, No. 2, and No. 3, respectively.

GENERAL CONCLUSIONS

Carbonate aggregates are a rather heterogeneous group of materials and, as such, possess varied physical, mineralogical, and textural properties. These differences in turn control the various performance characteristics of the respective aggregate. Not all carbonate aggregates are expected to perform similarly in the many aggregate evaluation tests, nor are they expected to perform the same in portland cement concretes, bituminous concretes, and graded aggregate base courses. The variations present in the many types of carbonate rock determine their suitability for various uses. The rate at which carbonate aggregates polish under the application of rubber tired traffic and the ultimate level of pavement skid resistance they are capable of maintaining is a performance characteristic which varies with the particular aggregate in question and is therefore related in some way to the basic properties of that aggregate.

The data presented here have successfully related certain physical and mineralogical characteristics of carbonate rocks to their ultimate level of pavement skid resistance. The polishing rate and the ultimate skid resistance level of a given carbonate aggregate have been found to vary directly with the percentage of acid insoluble sand size material present in that aggregate. This dependence of skid resistance on insoluble sand content was displayed in each of the four test series discussed. Unfortunately, however, because of the limitations of our present laboratory methods of evaluating skid resistance, it was not possible to make an acceptable correlation from one test series to another.

This work has been confined to the skid resistant properties of impure limestones, i.e., those not of a chemical grade. Shupe and Lounsbury (8) have shown, however, that when dealing with relatively pure carbonate aggregates the skid resistance of bituminous mixtures containing those aggregates was dependent on the calcium carbonate or calcite content. That is, as the calcite content increases, the susceptibility to polishing also increases. No attempt was made during this series of tests to make such an evaluation, nor was the degree of crystallinity considered. The effect these properties might have on the polishing characteristics of impure limestones and dolomites was not established. Indications are, however, that as the dolomite content increases, so does the aggregate's level of skid resistance, at least when considering low residue carbonates. As the residue content increases, its size distribution evidently overshadows these other characteristics, and is the primary skid resistance controlling property.

These data are presented with the hope that specifying agencies will consider some of the many basic differences which result in the varying performance characteristics of carbonate aggregates. Blanket rejections of limestones for skid resistance purposes solely because they belong to this heterogeneous trade name group may result, in many cases, in the refusal to consider perfectly adequate materials.

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Appendix

DESCRIPTION OF PRESENT NCSA SLIPPERINESS TESTING APPARATUS

The essential parts of the NCSA Slipperiness Testing Apparatus (Fig. 10) consist of a flexible outer frame which supports a rigid inner frame by means of a loose fitting adjusting screw. The axle of the bicycle wheel rests in slotted supports which are a part of the inner frame and permit free vertical motion of the axle. The wheel is a heavy duty bicycle front wheel equipped with a 26 × 2.125 tire with its normal tread removed by a belt sander. A strip of rubber 1 in. wide by ¼ in. thick is cemented over half the circumference of the tire. The leading edge of this rubber strip which, during operation of the wheel, first comes in contact with the road surface, is tapered from full thickness to zero thickness over a distance of approximately 5 deg. Tire inflation pressure is 22 psi.

Motive force for the operation of the wheel is provided by a weight consisting of two sections of ¾-in. i. d. copper tubing about 8 in. long filled with lead and bent to an outside radius of 10¾ in. to fit the shape of the tire rim. The weight assembly is secured by two small bolts that extend through the two sections and press them tightly against the spoke nipples. The entire weight assembly weighs 1,663 g and is centered approximately 50 deg from the leading edge of the rubber strip.

In operation, initial adjustment is made so that when the rubber strip and the weight assembly are in a downward position the rubber strip is barely in contact with the pavement but the wheel is still supported by the axle. The wheel is then rotated 180 deg so that the rubber strip and the weight assembly are in their uppermost position. The wheel is locked in this position and it and the inner frame assembly are lowered $1/12$ in. by means of the adjusting screw. The wheel is then unlocked and rotates freely until

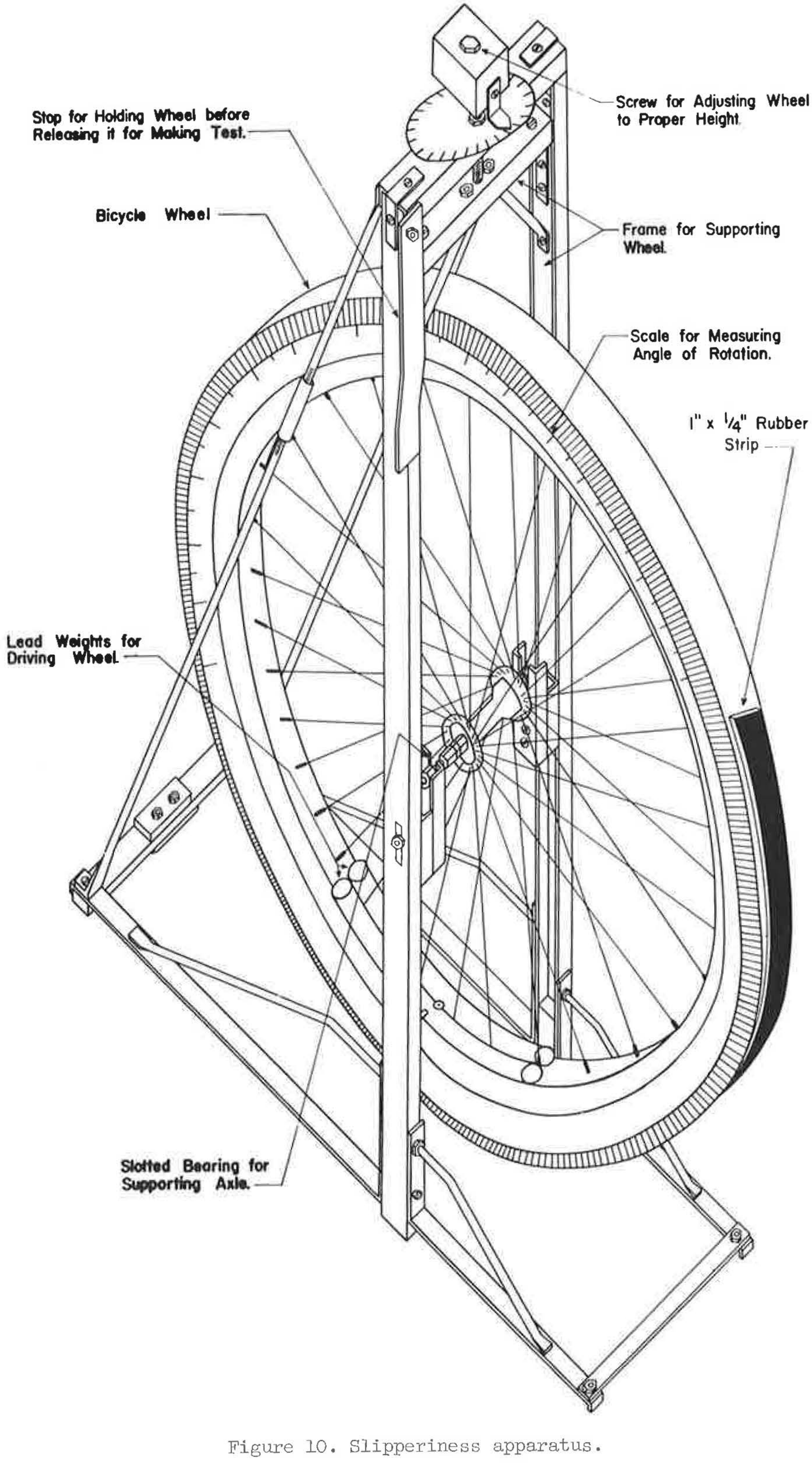

Figure 10. Slipperiness apparatus.

the rubber strip attached to the tire comes in contact with the pavement surface, thus raising the axle off its supports and permitting the tire to slide on the pavement surface until it is brought to rest by the forces of friction.

For any repetition of tests, the angular momentum of the wheel at the instant of contact between tire and pavement surface is the same and the energy expended is reflected in the angular distance through which the wheel turns after striking the pavement surface. Thus, the angle through which the wheel rotates while the tire is in contact with a surface serves as a measure of its skid resistance. The wheel angle readings increase as the skid resistance of the surface decreases. Usually an average of 24 readings in different positions on the road surface is obtained.