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**POLISHING CHARACTERISTICS
OF
MINERAL AGGREGATES
SEPT. 1958
NO. 22**

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**Joint
Highway
Research
Project**

PURDUE UNIVERSITY
LAFAYETTE INDIANA

by

J.W. SHUPE

R.W. LOUNSBURY

TECHNICAL PAPER

POLISHING CHARACTERISTICS OF MINERAL AGGREGATES

TO: K. B. Woods, Director
Joint Highway Research Project

September 25, 1958

FROM: H. L. Michael, Assistant Director
Joint highway Research Project

File: 9-6-4
Project: C-36-53D

Attached is a technical paper entitled, "Polishing Characteristics of Mineral Aggregates." It has been prepared by J. W. Shupe and R. W. Lounsbury of the Civil Engineering staff for presentation at the First International Skid Prevention Conference held September 8-12, 1958, in Charlottesville, Virginia.

Figures 2, 3, and 6 are not included in the attached copy for economic reasons. These figures are photographs and they were included in the report by Mr. Shupe entitled, "A Laboratory Investigation of Factors Affecting the Slipperiness of Bituminous Paving Mixtures" presented to the Advisory Board on May 21, 1958. Figures 15, 16, and 20 of the referenced report are Figures 2, 3, and 6 of this report.

The report is presented for the record.

Respectfully submitted,

Harold L. Michael, Secretary

HLM:acc

Attachment

cc: A. K. Branham	R. D. Miles
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CHRONOLOGY OF THE CHINESE COMMUNIST REVOLUTION

1971	Joint Library Research Project	U. S. Navy, Director	Department of Defense
1972	Joint Library Research Project	H. L. Michael, Assistant Director	U. S. Navy, Director

47474 is a technical paper entitled "Analysis of Linear Algebraic Equations" by J. W. Daniel. It is the last paper of a series of three papers on the subject of linear algebraic equations, the other two being 47473 and 47475. The paper is published in the Journal of the Society for Industrial Mathematics, Vol. 10, No. 1, 1962, pp. 1-10. The paper is a technical paper and is not a review.

of the report received on June 2, 1947, and 1 of the report
dated to the Security Board on May 13, 1947. Figure 12, 13, and 14
show the other two slips from the "Unknown Source" file.
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Technical Paper

POLISHING CHARACTERISTICS OF MINERAL AGGREGATES

by

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and
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Joint Highway Research Project

File No: 9-c-4

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Lafayette, Indiana
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POLISHING CHARACTERISTICS OF MINERAL AGGREGATES

J. W. Shupe¹ and R. W. Lounsbury²

The majority of the highways which have been constructed recently, whether of portland cement or of bituminous materials initially have exhibited good resistance to skidding for the critical design condition, which occurs when the surface is wet. Unfortunately, for many of these pavements this initial skid resistance has been short-lived. The anti-skid properties of a well-designed pavement surface are dependent to a large degree upon the polishing characteristics of the mineral aggregate or aggregates of which the paving mixture is composed. Although the type of cementing agent, the gradation, and the openness of the surface have some effect upon the rate at which polishing progresses, the ultimate state of slipperiness is determined by the nature of wear of the pavement which, in turn, is directly related to the resistance to polishing of the surface aggregate.

If highways are to be build which possess adequate anti-skid characteristics for a reasonable period of wear under the ever-increasing polishing effect of traffic, consideration must be given to the slipperiness potential of highway materials of which paving mixtures are composed, so that adequate skid resistance may be included as a design parameter. A laboratory investigation was undertaken at Purdue University in an endeavor to contribute to a better understanding of some of the variables involved in pavement slipperiness. This paper is a report of a phase of

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the Purdue study which includes the following factors: 1. The polishing characteristics of different mineral aggregates, in both portland-cement and bituminous-concrete mixtures, and their relation to basic aggregate properties; 2. The effect of texture, as determined by gradation, on the anti-skid characteristics of bituminous mixtures; and 3. The effect of initial aggregate shape, or degree of harshness, on the skid resistance of bituminous mixtures.

BITUMINOUS CONCRETE INVESTIGATION

The standard laboratory test specimen was an open-graded asphaltic concrete in which the asphalt content was kept intentionally low in order to emphasize the effect of the aggregate. To facilitate a comparison of the different aggregates, each test specimen was composed entirely of one aggregate type. The slipperiness of each mixture was determined in the laboratory skid-test apparatus, which spun the test specimen at 2500 rpm and evaluated the skid resistance by forcing a rubber testing shoe against the wet surface of the specimen. The skid resistance was expressed as a relative resistance value (RRV), with Kentucky rock asphalt used as the reference material; i.e. a Kentucky rock asphalt test specimen gave a RRV of 1.00 when evaluated by the skid-test apparatus. A complete description of the testing equipment, as well as the wear and polish procedure which is briefly discussed in the next paragraph, is presented elsewhere in the Proceedings as a separate paper (5).

The resistance to polishing of the bituminous mixtures was determined by a laboratory accelerated wear and polish procedure. Each specimen was rolled at 140 F to accomplish initial compaction and surface particle orientation; subjected to coarse wear with quartz as the abrasive material; given a fine polish with limestone filler as the abrasive; and given a final

re in, to test the aggregate highly and similar to the actual use.
The variation in skid resistance of bituminous mixtures with wear is shown in Figure 1 for mixtures composed of these different aggregate types. The relative resistance value is plotted as the ordinate with the position in the wearing cycle indicated by the abscissa. The initial values correspond to tests performed immediately after the specimen was molded, and the other four points correspond, respectively, to tests following initial polishing, coarse wear, fine polish, and coarse wear. The results indicate a progressive decrease in skid resistance due to wear, with the sandstone exhibiting the best resistance to polishing, and the limestone the poorest, of the three aggregate types illustrated. In comparing the relative resistance to polishing of the various mixtures, the results obtained at the completion of the fine-polish procedure, which corresponds to Figure 1c, in Figure 1, are probably the most significant. At this point in the wear procedure, the test specimen had a clean, polished surface with a texture quite similar to that of a well-worn highway surface.

Aggregate Evaluation Study

The polishing characteristics of bituminous mixtures composed of 22 mineral aggregates from five different states were determined in the aggregate evaluation study. Twelve of the aggregates were limestone, since this type of aggregate has a reputation for polishing readily, and a better complete coverage should be warranted. Only two of the aggregates were gravel, and both of these were rather uniform high-porosity aggregates. This represents a disproportionately small number of gravels when considering the tremendous quantity of this material used in bituminous paving construction throughout the United States. However, it was felt that gravels, due to

TYPE OF AGGREGATE USED IN BITUMINOUS MIXTURE

FIG.4 SKIDDING RESISTANCE OF BITUMINOUS MIXTURES AT THE COMPLETION OF THE FINE POLISH CYCLE

their law of homogeneity, would not be a well suited indicator, because of this study as uniform crushed stone sources. Although it is possible to evaluate the resistance to polishing of a given gravel, it is difficult to relate these results to any basic characteristics of the natural source aggregates.

The results of the physical tests for each of the 24 aggregates are listed in Table 1. All tests were performed in accordance with the current ASTM Standards, with the gradation of each aggregate checked separately conforming to Zone 1 grading 2.

A petrographic description of the aggregates is given in Appendix A. Included with each of the petrographic descriptions is an identification symbol (conforming to those of Table 1), a color photograph of the surface of the aggregate, and a microscopic description. The petrographic classification does not, in all cases, agree with the general classification of the aggregate listed in Table 1. This general classification is the "popular" description by which the aggregate is known to the producer and localities. Photomicrographs of thin sections of the aggregates are also illustrated in Figures 2 and 3. One of the typical aggregates is represented in Figure 2, and indicates the fine texture of the aggregate that is encountered under the general category of "granite". Figure 3 illustrates four aggregates other than "granite".

A partial chemical analysis was performed on the crushed stone samples and is reported in Table 2. Percentages of the major aggregate constituents are tabulated. Calculations for SiO_2 , FeO , CaO , MgO , and Al_2O_3 are also shown. The sum of these values are tabulated and generally total one hundred percent. There may be some minor rounding errors in the

TABLE 2

A Partial Chemical Analysis of the Twelve Limestones

Included in the Program of Research

Aggregate Identification Symbol	Calcium as CaCO_3 Percent	Magnesium as MgCO_3 Percent	Silica as SiO_2 Percent	Total of the Three Compounds Percent
L-1	94.9	0.5	3.5	98.9
L-2	58.0	38.4	4.4	100.8
L-3	60.8	34.9	2.1	97.8
L-4	54.7	39.9	4.3	98.9
L-5	66.8	24.9	5.8	97.5
L-6	83.1	5.1	4.3	92.5
L-7	93.5	1.7	2.9	98.1
L-8	74.1	8.3	7.0	89.4
L-9	54.3	27.1	3.1	84.5
L-10	86.7	4.6	5.6	96.9
L-11	98.5	0.8	1.3	100.6
L-12	95.1	0.3	3.3	98.7

FIG. 1 VARIATION IN SKID RESISTANCE OF BITUMINOUS MIXTURES WITH WEAR

or alumina, present; or portions of the tabulated constituents may exist in some other chemical form, so that the sum, as computed on the basis of the given assumptions, may total over one hundred percent.

Three replicate test specimens were made with each of the 22 aggregates and were evaluated for skid resistance after the various phases of the wear and polish procedure. The test results are tabulated in Appendix B. Only one of the test specimens of each series of three was subjected to the final rolling procedure, since it is debatable as to how realistically this operation simulates the seasonal effect. As indicated previously, the results at the completion of the fine-polish cycle are probably the most significant in comparing the polishing characteristics of the various aggregates. Figure 4 summarizes the results of the aggregate evaluation study by indicating the relative resistance values of bituminous mixtures containing each of the 22 aggregates at the completion of the fine-polish cycle. The relative resistance value is plotted as the ordinate with the type of aggregate composing the mixture listed along the abscissa.

An examination of Figure 4 leads to three conclusions, which would apply primarily to the aggregate types included in this study:

1. Limestones, as a group, do not exhibit as good resistance to polishing in bituminous mixtures as other aggregate types. Results for the 12 limestone specimens are plotted on the left of Figure 4 and indicate an average relative resistance value of 0.45, with a range of from 0.32 to 0.56. The other ten aggregates gave an average RRV of 0.63 with a range of from 0.54 to 0.88.

2. There is appreciable variability in the resistance to polishing of the various limestones. The bituminous mixture composed of limestone L - 4 exhibited 75 percent greater skid resistance than the specimen containing L - 7.

...to the ... of the ...

3. Sandstone possesses by far the best resistance to polishing of any of the aggregates evaluated in this study. Mixtures containing the two sandstones had RRV's of 0.68 and 0.75, respectively, at the completion of the fine-polish cycle, as compared to an RRV of 0.64 for the specimen with the next highest skid resistance.

The following discussion amplifies on these three conclusions and endeavors to relate the resistance to polishing of different aggregates with some of the physical or basic aggregate properties that can readily be evaluated. Unfortunately, there appears to be no relationship between any of the standard physical tests and the resistance to polishing of an aggregate in a bituminous mixture. These tests are relatively easy to perform, and a significant correlation with the percent absorption or loss on abrasion, for example, would be fortuitous. However, a comparison of the results of the physical tests in Table 1 with the relative resistance values of Appendix B fails to develop any correlation, even within a given aggregate type such as limestone. This is substantiated by the negative results obtained in Tennessee in an endeavor to relate the skid resistance, measured on 50 test sections, with the physical properties of cores removed from each of the sections (7).

The petrographic descriptions and the photomicrographs of the various aggregates provided a somewhat more fruitful source of information for relating aggregate properties and anti-skid characteristics. The photomicrographs in the left column of Figure 2 represent the three aggregates which exhibited the poorest anti-skid characteristics. At the completion of the fine polish cycle the relative resistance values for L = 1, L = 7, and L = 11 were 0.37, 0.32, and 0.34, respectively. L = 7, which gave the lowest skidding resistance of any of the 22 aggregates, was a very

uniform fine-grained limestone with the subangular calcite grains averaging less than 0.01 mm in length. These soft calcite grains wore away very readily where the unit pressure between the polishing shoe and aggregate was high, and there resulted a uniformly polished level datum which was extremely slippery when wet.

The next most slippery aggregate was L - 11. As illustrated in Figure 2, the structure of this limestone is completely dissimilar to that of L - 7. It consists of large spherical to ovate oolites, averaging 0.4 to 0.5 mm in length, bound in a granular matrix of calcite. However, as there was no angularity to the individual oolites, and since the hardness of the oolites and the surrounding matrix was essentially the same, the nature of the wear was very uniform, resulting in a polished surface. To a lesser degree this same condition also existed for L - 1.

The three photomicrographs in the right column of Figure 2 represent the limestones which exhibited the best anti-skid properties. At the completion of the fine-polish cycle the relative resistance values for L - 2, L - 3, and L - 4 were 0.54, 0.51, and 0.56, respectively. L - 4, which gave the best results, was a crystalline granular limestone with interlocking grains, 0.02 to 0.06 mm in length. The granular interlock promoted greater resistance to wear, so that the initial angularity of the aggregate particles was maintained for a greater period than for limestone L - 7. The individual grains were also somewhat larger and more angular than for L - 7, so the resulting surface was not as uniformly polished. In addition, there was some porosity in L - 4 which helped to relieve the excess pressure set up in the water film, resulting in a high unit pressure between testing shoe and specimen.

Limestone L - 3 was quite similar to L - 4, as indicated by the respective photomicrographs, but it had less porosity than L - 4; and, consequently, did not possess as much skidding resistance. L - 2, on the other hand, probably owed its relatively high skidding resistance to the presence of the coarse calcite rhombs. The fine ground mass was quite similar to that of L - 7, but the larger calcite rhombs disturbed the continuity and prohibited a uniformly polished surface from existing.

The photomicrographs of Figure 3 illustrate structures common to other aggregate types. SL - 1 was a vesicular slag with a small amount of silicate microlites. The voids in the glassy structure probably relieved the excess hydraulic pressure, and eliminated an unbroken polished surface, so that the RRV at the end of the fine-polish cycle was 0.59.

The popular classification of R - 1 is a rhyolite or, as identified petrographically, a porphyritic dacite. The ground mass was very fine-grained, but the monotony of the structure was relieved by large feldspar phenocrysts. This aggregate has an RRV of 0.57 at the end of the fine-polish cycle, placing it about equal in resistance to polishing to the most resistant limestone evaluated in this study.

The dolerite, of which photomicrograph D - 1 is an example, consisted of coarse grains averaging over 1 mm in length. The resistant labradorite and augite grains maintained an appreciable amount of the initial aggregate angularity, and the RRV at the completion of the fine-polish cycle was 0.62.

The photomicrograph for the sandstone, S - 2, illustrates the type of structure that is necessary to provide permanent resistance to the polishing effects of traffic. This was a calcareous sandstone in which the quartz grains were bound in a matrix of calcite. The quartz particles were

very resistant, having a relative hardness of seven, while the cementing calcite was comparatively weak, with a hardness of three. The matrix wore away at a faster rate than the quartz grains, resulting in a high unit pressure between the sliding rubber shoe and the harsh quartz particles. In addition, the surrounding matrix eventually wore down to the point where it could no longer support each quartz particle, so rather than remaining indefinitely exposed to a polishing action, after an appreciable period of wear the particle was ejected from the surface. This continuous ejection of worn quartz grains, and the resulting exposure of fresh angular particles, caused a constant rejuvenation of the surface, resulting in excellent skid resistance. The RRV for S - 2 decreased only 0.02, from 0.77 to 0.75, during the coarse- and fine-polish cycles. The relatively high resistance to polishing of sandstone was also observed in a laboratory investigation at the University of Kentucky (6).

Other information which provided a basis of comparison of the resistance to polishing of the twelve different limestones was the chemical analysis data, listed in Table 2. There appeared to be a good correlation between the calcium carbonate content of a limestone and its susceptibility to polishing. This relationship is illustrated in Figure 5, and results in a correlation coefficient, as determined by the method of least squares, of 0.86.

There is some intuitive justification for this relationship. In considering the skidding resistance of the various aggregate types with respect to their petrographic descriptions and photomicrographs, it was noted that a lack of consistency of structure or of grain hardness appeared to be essential for good skidding resistance. The more nearly a limestone approaches to pure calcium carbonate, the more uniform and continuous would be the

FIG. 5 CORRELATION BETWEEN CdCO_3 CONTENT
AND POLISHING SUSCEPTIBILITY

structure and hardness, so that the resistance to polishing would be low.

For the twelve limestones included in this testing program the primary "impurity" was magnesium carbonate. As a result, on the basis of this study it might appear that dolomitic limestones exhibit better anti-skid characteristics than high-calcium limestones because of their high magnesium content. However, the correlation coefficient relating the percent of magnesium with the skidding resistance was 0.24, or slightly less than the correlation coefficient for calcium carbonate. Consequently, the results seem to indicate that rather than a high magnesium content contributing to anti-skid resistance, any "impurity", which tends to disturb the continuity of the pure calcium carbonate grains, results in some improvement in the resistance to polishing of the limestone.

Surface Texture Investigation

In evaluating the polishing characteristics of the 22 mineral aggregates a standard laboratory mix was selected, and an effort was made to obtain an identical surface texture, or degree of openness, for each of the test specimens. To investigate the effect of surface texture on the skid resistance of bituminous mixtures, four representative aggregates were selected for additional consideration. Two of these aggregates were limestone; one, a highly-dolomitic limestone (L = 4) that had exhibited good skid resistance, and the other, an oolitic limestone (L = 11) which had shown very little resistance to polishing. The other two aggregates were a rhyolite (R = 1) and a sandstone (S = 2).

The surface texture of the bituminous specimens was varied by adjusting both the gradation and the maximum aggregate size. The mixture compositions for the five specimens made from each of the four test aggregates

TABLE 3

Composition of Specimens for Surface Texture Study

Passing Sieve	Retained Sieve	Gradation Number				
		1	2	3	4	5
1/2 inch	3/8 inch	27.0	19.2	11.0	6.0	0
3/8 inch	No. 4	32.0	34.1	30.0	19.0	0
No. 4	8	29.2	19.1	10.0	11.0	0
8	16	4.7	6.0	11.0	11.0	15.3
16	30	1.3	7.9	13.0	10.0	16.8
30	50	3.3	7.5	11.0	10.0	13.2
50	100	0	2.6	3.0	14.0	16.2
100	200	0	2.0	2.0	10.0	15.0
200	Pan	0	2.6	2.0	11.0	11.4
		100.0	100.0	100.0	100.0	100.0
Aggregate		Approximate percent of material equal weight to mixture				
L-1 and L-23		3.5	6.0	4.5	5.0	15.0
R-1 and R-2		2.0	6.5	4.0	5.0	14.5

* Standard Test Specimen

are listed in Table 3. Gradation No. 3 corresponds to that of the standard test specimen in the aggregate evaluation study. Gradations No. 4 and 5 are progressively more dense-graded, while No. 1 and 2 are more open-graded than the standard specimen. Figure 6 represents the surface textures corresponding to gradations No. 1 and No. 5, and illustrates, respectively, the most open-graded and the most dense-graded specimens included in this investigation. These photographs were taken at the completion of the coarse-wear cycle.

The effect of surface texture on the polishing characteristics of bituminous mixtures is shown in Figures 7a and 7b. Relative resistance values are plotted for specimens conforming to each of the five gradations for three points in the wearing cycle; after initial rolling, after coarse wear, and after fine polish. The open-graded specimens composed of gradation No. 1 exhibited very poor durability in the wear and polish procedure, and none of the four No. 1 specimens satisfactorily completed the entire cycle without disintegrating. The point in the wearing cycle at which failure occurred is indicated on Figures 7a and 7b by an X.

Figure 7a clearly indicates that for both oolitic limestone (L - 11) and dolomitic limestone (L - 4) the dense-graded mixtures exhibit better resistance to skidding than the open-graded mixtures, with the L - 4 specimens exhibiting a somewhat greater variation due to texture than the L - 11 mixtures. The rhyolite specimens, identified as R - 1 in Figure 7b, initially showed an appreciable advantage of the dense-graded over the open-graded mixtures, but at the completion of the fine-polish cycle the difference was rather small. The dense-graded sandstone specimens (S - 2) also possessed better anti-skid characteristics than the open-graded mixtures. It is interesting to note that the wear and polish procedure actually improved

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the tenth is the fact that the

FIG. 7a EFFECT OF SURFACE TEXTURE ON THE POLISHING CHARACTERISTICS OF BITUMINOUS MIXTURES

FIG. 7b EFFECT OF SURFACE TEXTURE ON THE POLISHING CHARACTERISTICS OF BITUMINOUS MIXTURES

TYPE OF AGGREGATE USED IN BITUMINOUS MIXTURE

FIG. 8 COMPARISON OF THE RESISTANCE TO POLISHING OF DENSE AND OPEN TEXTURED BITUMINOUS MIXTURES

the skid resistance of the two most dense-graded sandstone specimens, as illustrated in Figure 7b. The wearing procedure removed the asphalt coating, which accumulation on the aggregate during mixing, and eroded away some of the fine aggregate and asphalt matrix, resulting in greater exposure of the coarse sandstone and better skid resistance than existed initially.

The results of the surface-texture investigation are summarized in Figure 8. This figure shows the relative resistance values obtained with each of the four aggregates at the completion of the fine-polish cycle, both for specimens conforming to gradation No. 5, the most dense-graded mixture, and gradation No. 2, the most open-graded mixture which satisfactorily completed the wear and polish procedure. Although the texture effect is not as significant as the difference in aggregate types, in all four cases the dense-graded specimens exhibit better skid resistance than the corresponding open-graded specimens.

Effect of Initial Aggregate Shape

To investigate the effect of the initial aggregate shape on the skidding characteristics of bituminous mixtures, the same four aggregates that were included in the texture study were used, i.e., L = 4, L = 11, R = 1, and S = 2. In the aggregate evaluation study, for which the results are listed in Appendix B, the mixtures made with each of these aggregates consisted entirely of freshly-crushed material. To provide a basis of comparison as to initial aggregate shape, a separate sample of each of these aggregates was placed in a Los Angeles abrasion machine for four hours. No steel balls were used, and the wearing action of aggregate on aggregate and

against the shell of the machine caused the individual particles to become quite rounded.

The resulting material was then sieved, batched, and mixed in accordance with the standard procedure. The finished specimen was identical to the corresponding standard specimen used in the aggregate evaluation study, except that whereas the standard specimen contained aggregate which was freshly crushed, the modified specimen consisted entirely of artificially-rounded aggregate.

The relative resistance values of the two types of specimens are plotted in Figure 9 for the four different aggregates. The initial KRV's for specimens made from all four of the aggregates were higher for the angular than for the rounded aggregate, as was to be expected. After an appreciable amount of wear, however, as represented at the completion of the fine-polish cycle (Wearing Cycle No. 3), this advantage had disappeared. For two of the aggregates the specimens made with rounded aggregate gave slightly superior final results, while the specimen containing angular aggregate showed up better than the corresponding rounded-aggregate specimen in only one case.

A possible explanation for the results indicating that the ultimate skidding resistance of a specimen made with rounded aggregate would be at least as good, and possibly better, than one made with a similar angular aggregate pertains to the relative densities of the two mixtures. In the laboratory compaction and wearing procedure, the rounded aggregate, which permitted greater workability of the mixture, resulted in higher specimen densities than was the case for the angular aggregate. This was apparent in comparing the relative heights of specimens made with equal weights of rounded and angular aggregates. This resulted in a tighter surface texture

FIG. 9 EFFECT OF AGGREGATE SHAPE ON THE POLISHING CHARACTERISTICS OF BITUMINOUS MIXTURES

for the rounded-aggregate than for the angular-aggregate specimens, with a correspondingly greater area of contact; and, as indicated in the previous section on surface texture, resulted in better anti-skid characteristics.

The sandstone specimen made with rounded aggregate exhibited the same increase in skid resistance, as wearing progressed, that was observed with the specimens included in the surface-texture study. As the surrounding asphalt and matrix eroded away, the additional coarse sandstone exposed at the surface increased the skid resistance of the specimen.

Effect of the Abrasive on Polishing of Aggregates

In the development of the standard wear and polish procedure, test specimens were subjected to a variety of polishing series and the results were observed for the purpose of selecting a method which closely simulated the polishing action of traffic. The results of such a test series, in which two asphaltic-concrete test specimens were tested, initially and after ten "polishing" cycles, are shown in Figure 10. Values for the crushed limestone specimen are plotted as squares, while results for the natural sand and gravel specimen are represented by circles. These two curves illustrate a number of pertinent factors pertaining to the phenomenon of aggregate polishing.

Initially the crushed limestone specimen exhibited higher resistance to skidding than the specimen composed of rounded natural gravel. During the first wear cycle, however, for which a 40- to 80- mesh sand was used as the abrasive, the skid resistance of the limestone specimen dropped appreciably while that of gravel specimen improved, so that at the completion of the first cycle, the RWV's of the two specimens were nearly identical. The wearing action of the abrasive had decreased the initial angularity of the soft limestone aggregate and lowered the original skid resistance; and, although a slight amount of this leveling action probably took place with the gravel

FIG. 10 POLISHING CHARACTERISTICS OF ASPHALTIC CONCRETE TEST SPECIMENS

specimen, the scouring effect of the sand removed the asphalt, and possibly even roughened some of the rounded-aggregate particles, resulting in an improvement over the initial skid resistance.

An 80- to 200- mesh sand was used as the abrasive in cycles No. 2, 3, and 4. Both specimens experienced a drop in skid resistance, with the gravel specimen exhibiting somewhat better resistance to polishing. By the end of cycle No. 4, it appeared that the limestone specimen was approaching the ultimate polish possible with the fine sand, so for the next three wearing cycles a limestone dust passing the No. 200 sieve was used as the abrasive. The skid resistance of the limestone specimen dropped appreciably during wear cycle No. 5, but remained unchanged during No. 6, and even showed a slight increase for No. 7. Since limestone dust was used as the abrasive in all three of these cycles, it appears that the wearing effort of cycle No. 5 was sufficient to cause the specimen to arrive at the most slippery condition possible with that particular polishing agent. Additional wear did not result in a higher degree of polish but, due to the open texture of the surface, resulted in a slight increase in contact area between the testing shoe and aggregate, with a corresponding increase in skid resistance. The skid resistance of the gravel specimen also leveled off, but at a somewhat higher level than that of the limestone specimen.

In order to investigate the effect of a coarse abrasive on a finely-polished surface, the 40- to 80- mesh sand was again used in wear cycle No. 8. This roughened and scoured the polished surface of both test specimens, resulting in a significant improvement in skid resistance. The RRV's after cycle No. 8 were only slightly less than their respective values at the completion of cycle NO. 1, in which the same abrasive material had been used. Subsequent

polishing with limestone dust during wear cycles No. 9 and 10 returned the test specimens to essentially the same polished condition that they possessed prior to the coarse-sand wear.

The polishing relationships emphasized by this test series, some of which are quite obvious, are summarized as follows:

1. For a given abrasive there is an ultimate state of polish at which each aggregate will arrive, with the finer polishing agents resulting in the higher polish.
2. Fine-grained aggregates, as typified by the limestone specimen in Figure 10, will polish more readily and to a greater degree than aggregates composed of coarse grains.
3. Polishing on a relatively-polished surface with a coarse abrasive will result in an improvement in slide resistance.

This brief summary indicates that as a "fine-grained aggregate wears it 'recrystallizes the feldspar'" by exposing a fine abrasive, which remains in the roadway and contributes to additional polishing. Conversely, the practical fine-particle wear, as exemplified by an exposure of coarse aggregates (1), results in the presence of coarse particle particles on the pavement, which may either increase and improve the anti-slip properties of polished pavements or the roadway.

These factors also are pertinent in a consideration of the mechanism of variation in slide resistance that has been observed for polished pavements. Although the "actual" frost is dependent to a large extent upon the conditions that occur during the dry season, the degree of polishing of the aggregate also contributes to this variation. During a prolonged dry period the abrasive material present on the pavement and adhering to the pavement may become finely ground and removed, so that it is possible for aggregates to

exposed aggregate to a high degree of polish. During a rainy spell, however, this fine material is washed from the surface and is replaced, both on the roadway and in the tire, with relatively coarser particles. This coarse abrasive tends to scour the polished aggregate and improve the skid resistance, as simulated by wear cycle No. 8 of Figure 10.

PORTLAND CEMENT CONCRETE INVESTIGATION

The portland cement concrete used for the standard laboratory specimen was made with a fairly well-graded aggregate, a high cement factor, and a low slump (5). As in the bituminous study, each test specimen was composed entirely of one aggregate type. The concrete was mixed for 2 minutes, placed in a circular mold, rodded 25 times, struck-off level with the top of the mold, and allowed to set for 4 hours. Each specimen was then brushed lightly with a whisk broom to give a "sandpaper" texture, allowed to moisture cure for 24 hours, removed from the mold, and placed in a 140 F water bath for 6 days. The specimen was then ready for testing in the laboratory skid-test apparatus.

The skid resistance of each test specimen was determined at three points in the wear and polish cycle. The first test was performed "prior to polishing" with the surface in the lightly-brushed condition. The second test was made after the specimen had been subjected to a wear and polish procedure similar to the total polishing effort given to the bituminous specimens, only slightly more severe. This condition is identified as the "mortar polished" cycle, since very little of the coarse aggregate was exposed by this procedure. The final step was to saw off the top quarter-inch of the specimen, and subject the fresh surface to the total wear and polish procedure, after which the specimen existed in the "aggregate polished" condition. Photographs

of specimens which have been subjected to these three procedures are shown elsewhere in the Proceedings(5). The variation in skid resistance of portland cement concrete composed of three different aggregate types is illustrated in Figure 11, with relative resistance values plotted for each of the three points in the wear and polish procedure previously discussed.

In order to compare the polishing characteristics of mineral aggregates in portland-cement and bituminous mixtures, six aggregates were selected for study. Four of the aggregates; i.e. dolomitic limestone, rhyolite, calcareous sandstone, and vesicular slag, were from the same source as that used in the 22-aggregate study. Unfortunately, it was impossible to obtain additional oolitic limestone with identical polishing properties to that of the original study, so a similar oolitic limestone from the same quarry, but which showed slightly better resistance to polishing, was used and identified as L - 11'. In addition, a supply of traprock (T - 1) had been received since the initial aggregate evaluation study, so this aggregate was also included in this phase of the investigation. It was necessary to perform complete bituminous test series with aggregates L - 11' and T - 1 to permit comparison with portland cement concrete specimens.

The polishing characteristics of portland cement concrete specimens composed of different mineral aggregates are listed in Table 4. The values obtained prior to polishing are somewhat higher than the initial values measured with the bituminous specimens, particularly for the rhyolite and the slag. During the crushing process, these materials fractured into very angular particles so that the light brushing of the finishing process resulted in a harsh "sandpaper" texture. The cement paste was sufficiently strong to hold the angular particles in place, resulting in higher resistance values than were

FIG. II POLISHING CHARACTERISTICS OF PORTLAND CEMENT CONCRETE

Table 4
Polishing of Portland Cement Concrete
Containing Different Types of Aggregate

Aggregate Identification	Specimen No.	<u>Relative Resistance Value</u>		
		Prior to Polishing	Mortar Polished	Aggregate Polished
L - 11' Oolitic Limestone	1	.76	.49	.46
	2	<u>.72</u>	<u>.50</u>	<u>.46</u>
	Avg.	.78	.50	.46
L - 4 Dolomitic Limestone	1	.87	.64	.62
	2	<u>.87</u>	<u>.68</u>	<u>.63</u>
	Avg.	.87	.66	.63
R - 1 Rhyolite	1	.95	.67	.56
	2	<u>.95</u>	<u>.62</u>	<u>.56</u>
	Avg.	.95	.68	.56
S - 2 Calcareous Sandstone	1	.87	.80	.75
	2	<u>.82</u>	<u>.83</u>	<u>.77</u>
	Avg.	.88	.82	.76
SL - 1 Vesicular Slag	1	.92	.77	.57
	2	<u>.91</u>	<u>.76</u>	<u>.55</u>
	Avg.	.92	.77	.56
T - 1 Traprock	1	.84	.72	.58
	2	<u>.82</u>	<u>.74</u>	<u>.58</u>
	Avg.	.86	.73	.58

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 UNITED STATES

No.	Name of Locality	Date	Remarks	No.	Name of Locality	Date	Remarks
1	Washburn	1872	July 1	1	Washburn	1872	July 1
2	Washburn	1872	July 2	2	Washburn	1872	July 2
3	Washburn	1872	July 3	3	Washburn	1872	July 3
4	Washburn	1872	July 4	4	Washburn	1872	July 4
5	Washburn	1872	July 5	5	Washburn	1872	July 5
6	Washburn	1872	July 6	6	Washburn	1872	July 6
7	Washburn	1872	July 7	7	Washburn	1872	July 7
8	Washburn	1872	July 8	8	Washburn	1872	July 8
9	Washburn	1872	July 9	9	Washburn	1872	July 9
10	Washburn	1872	July 10	10	Washburn	1872	July 10
11	Washburn	1872	July 11	11	Washburn	1872	July 11
12	Washburn	1872	July 12	12	Washburn	1872	July 12
13	Washburn	1872	July 13	13	Washburn	1872	July 13
14	Washburn	1872	July 14	14	Washburn	1872	July 14
15	Washburn	1872	July 15	15	Washburn	1872	July 15
16	Washburn	1872	July 16	16	Washburn	1872	July 16
17	Washburn	1872	July 17	17	Washburn	1872	July 17
18	Washburn	1872	July 18	18	Washburn	1872	July 18
19	Washburn	1872	July 19	19	Washburn	1872	July 19
20	Washburn	1872	July 20	20	Washburn	1872	July 20
21	Washburn	1872	July 21	21	Washburn	1872	July 21
22	Washburn	1872	July 22	22	Washburn	1872	July 22
23	Washburn	1872	July 23	23	Washburn	1872	July 23
24	Washburn	1872	July 24	24	Washburn	1872	July 24
25	Washburn	1872	July 25	25	Washburn	1872	July 25
26	Washburn	1872	July 26	26	Washburn	1872	July 26
27	Washburn	1872	July 27	27	Washburn	1872	July 27
28	Washburn	1872	July 28	28	Washburn	1872	July 28
29	Washburn	1872	July 29	29	Washburn	1872	July 29
30	Washburn	1872	July 30	30	Washburn	1872	July 30

obtained with bituminous specimens in which the supporting action of the matrix was not as positive as that of the cement paste. Under the high sliding pressure of the testing shoe, the bituminous matrix probably permitted some reorientation of the aggregate particles, decreasing the effective harshness of the surface. The asphalt film coating the aggregate may also have contributed to the lower initial skid resistance of the bituminous specimens.

At the completion of the mortar-polished cycle, portland-cement concrete specimens containing each of the six aggregate types exhibited better skid resistance than the corresponding bituminous specimens which had been subjected to a less severe polishing effort. However, whereas the coarse aggregate was directly exposed to the polishing action in the relatively open-graded bituminous specimens, at no point during the mortar-polish cycle was there observed an appreciable amount of exposed coarse aggregate for any of the portland-cement concrete specimens. After the portland-cement specimens had been sawed to expose the aggregate and then polished, the skid resistance of portland-cement and bituminous mixtures compared fairly closely, as illustrated in Figure 12. This figure summarizes the comparison of aggregate polishing in portland-cement and bituminous mixtures and indicates that if appreciable exposure of the coarse aggregate occurs in both and compared not only of one aggregate type, the skid resistance of the two mixtures will be similar. For three of the aggregates, the portland-cement concrete specimens exhibited somewhat better skid resistance; while for the other three aggregates, the bituminous mixtures gave the better results, but in each case the differences were small.

FIG. 12 SKID RESISTANCE OF PORTLAND CEMENT AND ASPHALTIC CONCRETE TEST SPECIMENS

short period. However, this same observation can also be made for pavements composed of such aggregates as the fine-grained basalts, chert, and high-quartz gravel. These relatively polish-resistant aggregates may retain a certain degree of their initial angularity for an appreciable period, but due to the uniform nature of wear of the fine-grained structure, can ultimately polish excessively.

7. In order for a pavement constructed with conventional highway materials to retain a non-skid surface under prolonged action of heavy traffic, some type of coarse particle-by-particle wear is necessary. This condition is typified by a paving mixture composed of sandstone or some varieties of granite, in which the highly-resistant quartz grains are dislodged from the pavement surface before they have the opportunity to polish excessively.

A similar wearing action occurs with a Kentucky rock asphalt pavement or with a silica-sand surface treatment of the type developed in Virginia (3). The continuous rejuvenation, which accompanies this particle-by-particle wear, results in excellent anti-skid characteristics during the entire life of the surface, but in so doing limits the effective life of the treatment. However, early results with the silica-sand surfaces (1, 4) indicate that this type of non-skid treatment shows excellent promise, both for use in improving the skid resistance of existing slippery pavements that are structurally adequate, and as a preventive measure in new construction when polish-susceptible aggregates occur in the mixture.

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APPENDIX A

A Petrographic and Megascopic Description
of the Mineral Aggregates Used in this Investigation

Information on each aggregate includes:

1. Aggregate
Identification
Symbol	2. Location
as to State	3. A Megascopic
Description
4. A Petrographic
Description		

L-1 Indiana Fine-grained, light-gray limestone

A microcoquina limestone, consisting of fossil fragments in a diagenetic matrix of calcite grains. The brachiopod, crinoid, and bryozoa fragments vary in size from 0.1 to 0.4 mm. The calcite grains in the matrix are subround to subangular in shape and average about 0.2 mm in length.

L-2 Indiana Fine-grained, light-gray limestone with visible
 bedding

A crystalline granular limestone consisting of angular interlocking calcite grains. The grain size of the primary calcite is about 0.01 mm, while the narrower beds of coarser calcite consist of rhombs approaching 0.3 mm in length.

L-3 Indiana Medium crystalline buff-gray limestone, slightly
 porous

A crystalline granular limestone consisting of angular interlocking calcite grains. The primary grains are 0.04 mm in length with occasional pockets (about 10 percent) of coarse calcite grains 1 to 2 mm in size.

There is a small amount of porosity with the voids averaging 0.1 in length.

L-4 Indiana A finely-crystalline porous brown-gray limestone

A crystalline granular limestone with interlocking grains 0.02 to 0.06 mm in length. Strongly euhedral rhombs of carbonate dominate the other angular crystals. There is a trace of subangular detrital quartz. There is also some porosity present (5 to 10 percent) in the form of voids from 0.1 to 0.2 mm in length.

L-5 Indiana Very fine-grained gray limestone

A very fine crystalline granular limestone with angular interlocking grains less than 0.01 mm in length. There is a trace of 0.1 mm quartz grains in evidence, but the primary constituent is fine-grained interlocking calcite grains.

L-6 Kansas Fine-grained, light-gray limestone with visible foraminifera tests

A fine-grained foraminiferal limestone consisting of approximately 60 percent calcite matrix and 40 percent foraminifera tests. The matrix is composed of subround to a subangular uniform grains less than .01 mm in length, while the ovate foraminifera measure 4.0 mm in their major dimension.

L-7 Virginia Fine-grained, dark-gray limestone

A very fine-grained carbonaceous limestone with a ground mass of subangular calcite grains less than 0.01 mm in length. Also present (approximately 15 percent) are mosaic "pockets" of dark carbonaceous matter and calcite grains, 0.3 to 0.4 mm in length, which appear to be fossil fragments.

L-8 Virginia "Dense" gray limestone

A crystalline granular siliceous limestone consisting of angular quartz grains bound in a matrix of angular calcite grains. The matrix, composing 60 to 70 percent of the material, is made up of calcite grains 0.05 to 0.07 mm in length with a few rhombs present. The primary detrital mineral is quartz with the grains averaging from 0.1 to 0.3 mm in length. There is also a trace of feldspar present.

L-9 Virginia Fine-grained gray limestone with visible calcite crystal faces

A crystalline granular limestone with angular interlocking grains averaging 0.03 to 0.04 mm in length. There are a few irregular rhombs, as well as coarse calcite (0.1 mm) veins present.

L-10 Virginia Fine-grained gray limestone with white calcite veins

A crystalline granular limestone composed primarily of uniform angular crystals 0.01 mm in length. Wavy irregular bedding, 0.1 to 1.0 mm wide, is present consisting of coarse (0.1 mm) calcite grains.

L-11 Indiana Light-gray visibly oolitic limestone

A uniform oolitic limestone consisting of 60 to 70 percent of elliptical and rounded oolites bound in a granular matrix of calcite. The oolites are 0.4 to 0.5 mm in the major dimension, while the calcite grains are about 0.1 to 0.3 mm in length. There are traces of fossil fragments and detrital quartz present.

L-12 Indiana Light-gray crystalline limestone with some visible oolites

An oolitic limestone consisting of 50 to 60 percent of elliptical and rounded oolites bound in a granular matrix of calcite which contains

appreciable amounts of detrital quartz and fossil fragments. The respective sizes of each of the components are as follows: colites, 0.3 to 0.4 mm; calcite grains, 0.07 mm; quartz particles, 0.1 to 0.3 mm; and foraminifera, 0.3 to 0.4 mm.

C-1 Kansas Very fine-grained gray chert

A cryptocrystalline chert consisting primarily of very fine sub-round to subangular grains, approximately 0.005 mm in length, with a few patches of coarser (0.01 mm) chert grains.

R-1 Massachusetts Fine-grained, dark-red felsite with visible feldspar phenocrysts

A fine-grained porphyritic dacite containing plagioclase and quartz phenocrysts. The ground mass, consisting of 0.01 to 0.02 mm grains, constitutes about 80 percent of the material with the remaining 20 percent composed of phenocrysts, with grain size ranging from 0.5 to 1.5 mm. In addition some quartz is present along the flow bands, probably having formed during the post crystallization period.

Q-1 Maryland White quartzite pebble with some clear quartz grains

A white quartzite pebble consisting of granoblastic quartz in which the anhedral grains vary from 1 to 3 mm in length.

Q-2 Virginia Buff-stained quartz pebble

A single quartz pebbles.

S-1 Indiana A medium-grained, buff-brown sandstone

A medium-grained friable sandstone consisting of well-sorted 0.5 to 1 mm subangular quartz grains with a small amount of limonitic cement.

S-2 Kansas Medium-grained gray limey sandstone

A calcareous sandstone in which the clastic quartz grains are bound in a matrix of calcite. The angular to subangular quartz grains are from 0.1 to 0.5 mm in length and constitute about 60 percent of the material. The remainder is primarily a calcite cement, with grains 0.1 to 0.3 mm in length, with traces of microcline, plagioclase, quartzite or chert, and dark carbonaceous matter.

D-1 Virginia A fine-grained gray dolerite with visible plagioclase

A hypidiomorphic granular dolerite with the grains, which average from 1.1 to 1.2 mm in length, forming "teepee" structure. The primary minerals are labradorite and augite with less than five percent of magnetite present. There is a slight development of epidote from the post crystallization period.

D-2 Virginia Dark fine-grained dolerite

A hypidiomorphic granular dolerite with the grains, which average from 0.07 to 0.14 mm in length, forming "teepee" structure. The ground mass consists of interlocking crystals of labradorite and augite, with occasional plagioclase phenocrysts 0.7 mm in length. There are traces of olivine, apatite, magnetite, and chlorite.

G-1 Virginia A fine-grained, gray-green granite with visible quartz and mica

A hypidiomorphic granular biotite-granite with some parallel arrangement of large mica crystals averaging 1.4 mm in length and a small amount of recrystallized grains 0.05 mm in length concentrated along the shear lines. The mineral composition consists of 50 to 60 percent microcline with 25 percent quartz, 10 to 15 percent biotite, and traces of apatite, zircon, epidote, and muscovite.

SL-1 Indiana Light-gray vesicular glass (slag)

A vitrophyric glass with a small amount of silicate microlites. There is a vesicular structure with the circular vesicles, which constitute from 10 to 20 percent of the material, varying from 0.1 to 0.5 mm in diameter.

APPENDIX B

Summary of Results on the Polishing of Bituminous Mixtures
Containing Different Types of Aggregate

Aggregate Identification Symbol	Specimen No.	RRV at the Completion of:			
		Initial Rolling	Coarse Wear	Fine Polish	Final Rolling
L-1	1	.53	.43	.35	.33
	2	.54	.44	.37	
	3	<u>.55</u>	<u>.45</u>	<u>.38</u>	
	Avg.	.54	.44	.37	
L-2	1	.69	.57	.53	.47
	2	.72	.62	.54	
	3	<u>.70</u>	<u>.60</u>	<u>.54</u>	
	Avg.	.70	.60	.54	
L-3	1	.70	.58	.52	.46
	2	.70	.59	.50	
	3	<u>.71</u>	<u>.60</u>	<u>.51</u>	
	Avg.	.70	.59	.51	
L-4	1	.75	.64	.56	.50
	2	.74	.63	.56	
	3	<u>.76</u>	<u>.62</u>	<u>.56</u>	
	Avg.	.75	.63	.56	
L-5	1	.72	.59	.51	.41
	2	.72	.59	.51	
	3	<u>.68</u>	<u>.57</u>	<u>.49</u>	
	Avg.	.71	.58	.50	
L-6	1	.61	.50	.45	.41
	2	.59	.50	.44	
	3	<u>.59</u>	<u>.50</u>	<u>.45</u>	
	Avg.	.60	.50	.45	
L-7	1	.51	.44	.30	.30
	2	.49	.44	.32	
	3	<u>.50</u>	<u>.43</u>	<u>.33</u>	
	Avg.	.50	.44	.32	
L-8	1	.56	.49	.45	.37
	2	.56	.50	.47	
	3	<u>.56</u>	<u>.50</u>	<u>.47</u>	
	Avg.	.56	.50	.46	
L-9	1	.58	.52	.50	.39
	2	.57	.50	.48	
	3	<u>.58</u>	<u>.50</u>	<u>.47</u>	
	Avg.	.58	.51	.48	

APPENDIX B (continued)

Aggregate	Specimen	Initial Rolling	Coarse Wear	Fine Polish	Final Rolling
L-10	1	.56	.46	.42	.39
	2	.56	.47	.43	
	3	<u>.56</u>	<u>.48</u>	<u>.44</u>	
	Avg.	.56	.47	.43	
L-11	1	.55	.41	.34	.29
	2	.54	.42	.35	
	3	<u>.53</u>	<u>.40</u>	<u>.33</u>	
	Avg.	.54	.41	.34	
L-12	1	.56	.48	.46	.38
	2	.57	.49	.45	
	3	<u>.58</u>	<u>.49</u>	<u>.46</u>	
	Avg.	.57	.49	.46	
C-1	1	.73	.63	.55	.48
	2	.73	.63	.55	
	3	<u>.72</u>	<u>.62</u>	<u>.55</u>	
	Avg.	.73	.63	.55	
R-1	1	.68	.59	.55	.48
	2	.68	.60	.56	
	3	<u>.70</u>	<u>.62</u>	<u>.59</u>	
	Avg.	.69	.60	.57	
Q-1	1	.72	.64	.62	.57
	2	.69	.66	.63	
	3	<u>.70</u>	<u>.66</u>	<u>.63</u>	
	Avg.	.70	.65	.63	
Q-2	1	.57	.53	.52	.47
	2	.56	.53	.52	
	3	<u>.60</u>	<u>.57</u>	<u>.53</u>	
	Avg.	.58	.54	.52	
S-1	1	.94	.88	.88	.85
	2	.95	.90	.88	
	3	<u>.98</u>	<u>.90</u>	<u>.89</u>	
	Avg.	.96	.89	.88	
S-2	1	.79	.76	.74	.67
	2	.76	.76	.74	
	3	<u>.75</u>	<u>.76</u>	<u>.76</u>	
	Avg.	.77	.76	.75	
D-1	1	.81	.66	.62	.51
	2	.79	.67	.63	
	3	<u>.77</u>	<u>.64</u>	<u>.62</u>	
	Avg.	.79	.66	.62	

APPENDIX B (continued)

Aggregate	Specimen	Initial Rolling	Coarse Wear	Fine Polish	Final Rolling
S-2	1	.79	.76	.74	.67
	2	.76	.76	.74	
	3	<u>.75</u>	<u>.76</u>	<u>.76</u>	
	Avg.	.77	.76	.75	
D-1	1	.81	.66	.62	.51
	2	.79	.67	.63	
	3	<u>.77</u>	<u>.64</u>	<u>.62</u>	
	Avg.	.79	.66	.62	
D-2	1	.84	.68	.59	.50
	2	.80	.67	.58	
	3	<u>.80</u>	<u>.64</u>	<u>.58</u>	
	Avg.	.81	.66	.58	
G-1	1	.68	.63	.65	.56
	2	.69	.62	.63	
	3	<u>.70</u>	<u>.62</u>	<u>.65</u>	
	Avg.	.69	.62	.64	
SL-1	1	.82	.67	.60	.54
	2	.78	.64	.59	
	3	<u>.80</u>	<u>.66</u>	<u>.59</u>	
	Avg.	.80	.66	.59	