THE WEARING CHARACTERISTICS OF MINERAL AGGREGATES IN HIGHWAY PAVEMENTS

by

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VIRGINIA HIGHWAY RESEARCH COUNCIL

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Virginia Highway Research Council
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SUMMARY

Fifteen asphaltic concrete and seventeen portland cement concrete pavements located in Virginia were chosen for studies of aggregate wear and related wet pavement friction. Coarse aggregates from thirteen different geologic formations and quarry sources had been utilized in construction of the pavements. Field measurements of wet friction and pavement profiles and laboratory studies of aggregate petrography and surface microtexture were emphasized.

The results of the research showed that aggregates can be classified into three categories based on their response to the wearing stresses of vehicle tires: (1) very homogeneous aggregates lacking significant zones and planes of weakness wear predominantly by abrasion; (2) aggregates marked by zones and planes of weakness wear predominantly by degradation or particle removal; and (3) aggregates of intermediate physical structure wear by a combination of abrasion and degradation. Polishing is most common with aggregates undergoing abrasion, the rate being dependent on the absolute hardness of the mineral constituents. Polishing removes micro-asperities and reduces the adhesion component of wet friction. The loss of macrotexture, or pavement relief, is common where degradation prevails. This loss, if excessive, retards water removal or drainage and adversely affects the hysteresis or tire deformation component of pavement friction. Optimum wet friction conditions are judged to prevail when a combination of abrasion and degradation creates an aggregate surface containing significant elements of both macro- and microtexture.

It is concluded that careful petrographic study of aggregate mineralogy and texture will allow a high degree of prediction of the resulting surface configuration as aggregates wear under traffic.

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INTRODUCTION

General Statement

The steady rise in the volume of traffic on modern highways, coupled with the rise in speed limits, is constantly increasing the demand for quality highway pavement surfaces. Since the wet frictional resistance of highway pavements generally decreases with wear, the frictional properties of pavement surfaces are being recognized as critical issues in highway maintenance and safety. Aggregates are the key elements in most pavement surfaces and consequently pavement surface quality hinges largely upon the aggregate type employed.

This paper deals with natural aggregates and their behavior in highway pavements exposed to high volumes of vehicular traffic. Composition and petrography, wear characteristics, contributions to pavement texture, and wet frictional resistance are considered in a general way.

The specific objects of the study were: (1) to study the wearing characteristics of various aggregates and relate these characteristics to aggregate petrography, and (2) to relate the observed wearing characteristics to wet pavement friction measurements. The successful completion of these objectives would then allow prediction of pavement skid resistance from petrographic studies of the aggregate.

Previous Research

Previous pavement slipperiness research has been voluminous and dates back to the early 1930's. The earliest investigations were primarily involved with the methods of measuring pavement slipperiness and among the earliest investigators were Moyer (1934), Klein and Brown (1939), and Shelburne and Sheppe (1948).

In the following years technology and theory advanced, but somewhat slowly considering the number of investigations conducted. Areas of investigation included tire tread design and rubber composition, surface texture of the pavement, aggregate type, pavement temperature, sliding velocity and test methods, road contamination, etc. It became evident that pavement surface texture as affected by aggregate gradation and type was of primary importance (Shelburne and Sheppe -- 1948; Moyer and Shupe -- 1951; White and Thompson -- 1958

Moyer — 1959; Marshall and Gartner — 1962). It also became apparent that wet pavement slipperiness was generally due to the polishing of aggregates, irrespective of their gradation.

Several studies related aggregate type to polishing susceptibility. Among these were the works of Stutzenberger and Havens (1958), Sherwood (1959), Gray and Goldbeck (1959), Finney and Brown (1959), Maclean and Shergold (1959), Shupe and Lounsbury (1959), Moyer and Shupe (1959), Knill (1959), Gray and Renninger (1960, 1963), and Stephens and Goetz (1961). Most of the studies conducted by these investigators involved laboratory polishing and wet friction measurements at various levels of wear. Valuable insight has been gained by these studies, particularly with regard to limestone polish-susceptibility. The variable susceptibility of limestones to polishing induced several investigators to perform petrographic and insoluble residue analyses upon these rocks. Principal investigators in this area have been Sherwood (1959), Gray and Goldbeck (1959), Gray and Renninger (1960), Burnett et al (1968) and Sherwood and Mahone (1969). These investigators found an almost direct correlation to exist between polish resistance and the acid insoluble residue contents of the carbonates.

Following the First International Skid Prevention Conference hosted by the Virginia Highway Research Council in 1958, advancements in the theoretical fields of pavement slipperiness were rapid. Relationships were developed between pavement texture and the behavior of tire rubber at various sliding speeds, in the presence of variable water thicknesses and temperatures. Frictional properties of rubber in contact with wet pavements were found to be essentially due to the sum of three mechanisms (see Figure 1):

(1) Adhesion losses resulting from molecular contact between the tire rubber and pavement surface, and provided by the acuteness of surface projections, both macroscopic and microscopic;

(2) Hysteresis losses derived from the energy losses involved in deforming the tire rubber and primarily dependent upon the deformation frequency and volumes, resulting predominantly from macrotexture*, and

(3) Drainage of the pavement surface, related to the macrotexture.

Principal investigators in these areas have been Moore (1966, 1969), Kummer (1966), Kummer and Meyer (1967), and Meyer and Kummer (1969).

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*See Appendix I for glossary of terms.

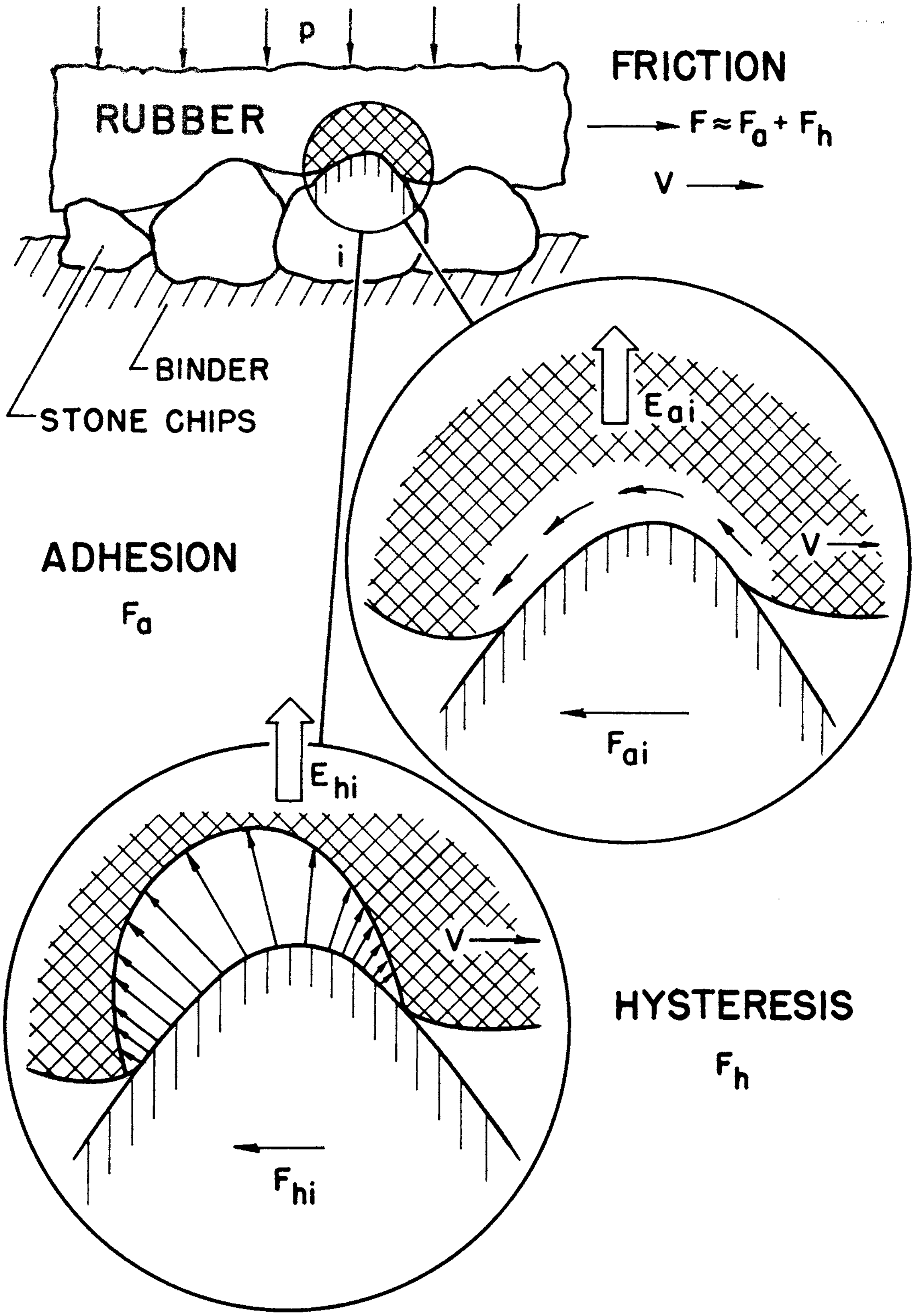


Figure 1. Principal components of rubber friction (From Kummer — 1966).

FACTORS CONTRIBUTING TO WET PAVEMENT FRICTION

The measured wet friction value of a pavement surface is dependent upon the degree to which the pavement surface can contribute to the adhesion and hysteresis components of tire-pavement friction. It can also be shown that the pavement surface texture controls these mechanisms and that several textural parameters -- macrotexture, microtexture, and harshness -- contribute to the adhesion, hysteresis, and drainage mechanisms.

Macrotexture in this study is used as a general term and denotes any combination of macroscopic surface projections (macro-asperities), their heights (amplitudes), and frequencies. A macro-asperity is here considered as any asperity exceeding 0.2 mm in height. This delineation is based upon the practical limit of observation at a magnification of about 20 times. To the writer's knowledge a specific value separating macro- and microtextural components has not been offered previously.

Microtexture is similarly defined, with the prefix "micro" substituted for "macro". Micro-asperities are those less than 0.2 mm in amplitude. Microtexture is a property confined to the surface of coarse aggregate particles unless no coarse aggregate is exposed, as in a fine aggregate surface.

Harshness is used solely in reference to the acuteness of asperities, i.e., their sharpness, and denotes nothing of their amplitudes. However, since the sense of touch is generally used to evaluate harshness, and because touch is not sensitive to micro-asperities less than about 15μ, these extremely small micro-asperities are generally excluded when speaking of harshness.

Moore (1969) states that the mean wavelength and slope of individual macro-asperities of the road surface largely control the hysteresis contribution to friction at a given sliding speed. He adds that the mean wavelength should be large enough to permit rapid drainage of water from beneath the rolling or sliding tires. In addition, he relates that the adhesion component of friction can be maximized by providing a sufficiently sharp (acute) texture either on a macro- or microscopic level. Therefore, adhesion can be attained by large sharp aggregate tips, and/or large rounded aggregate tips with significant, superimposed microroughness. Moore's findings indicate that in the macrotextural range the optimum wavelength for drainage and hysteresis considerations is somewhere between 3 and 10 mm and the optimum amplitude for microroughness (microtexture) is between 10 and 100 μ.

Most new pavement surfaces are constructed in such a manner that all the textural requirements for high wet friction values are initially met. As the pavement surfaces wear, several textural changes can occur which adversely affect friction properties:

(1) Large, sharp aggregate or asperity tips become rounded,

(2) Macrotexture, resulting primarily from the relief between the large aggregate particles, and macro-asperities are reduced causing asperity slope changes, and

(3) Microtexture can be effectively reduced as a result of abrasion.

The majority of worn pavement surfaces exhibit the first two textural changes. Consequently adhesion is reduced by rounding of the particles; hysteresis is reduced by the height and associated mean wavelength changes, and drainage is inhibited. The increase in water film thickness resulting from poor drainage decreases the effectiveness of both adhesion and hysteresis. However, as long as significant microtexture can be retained, a pavement surface can provide adequate wet frictional resistance through the adhesion mechanism. This is true provided the pavement is not flooded with water, i.e., that the macrotexture and drainage characteristics are still adequate to allow the escape of water resulting from average rainy conditions. The ability of aggregates to retain textural properties that give a safe level of wet friction is of primary concern in this study. Pavements containing aggregates not possessing such properties can become critically slippery when wet and extremely hazardous to the unwary motorist.

PROCEDURES

General

In order to evaluate the wearing characteristics of a variety of aggregates, several asphaltic concrete pavement surfaces were selected. Selection was based primarily upon aggregate type, pavement age, traffic volume, expected skid resistance and field observations. A total of fifteen such pavements were studied and tested in detail. The pavements were located in the Piedmont and Valley and Ridge physiographic provinces of Virginia. Generally, the pavement sections were located in close proximity to their respective quarry sources (see Figure 2).

Pavement Cores and Thin Sections

Following selection of the field sections either two four-inch or two six-inch diameter cores were taken from each pavement. In order that the worn aggregate particles be simultaneously evaluated with respect to petrography and wearing characteristics, a special technique was used in preparing thin section specimens from the cores. This involved cutting representative surface sections from the cores. Following removal from the core the section was sawed in half perpendicular to its worn surface. The two halves, opposing one another but with a gap between, were mounted in an epoxy resin medium (see Figure 3).

When cured the prepared specimen was ground and polished well into the aggregate particle to remove disturbed edges resulting from sawing. A thin section was then prepared in normal fashion with the exception that the specimen was left slightly thicker than usual, i.e., slightly greater than 0.03 mm in thickness. This assured minimum disturbance resulting from possible wedging of the thin section edges. The final result of this procedure was a thin section profile of two halves of a worn aggregate particle with the worn surfaces opposing one another at the center of the thin section (Figure 3).

Code	Source	Rock Type	Code	Source	Rock Type	Code	Source	Rock Type
S41	Chemstone	Limestone	P30	Fairfax	Diabase	P31	N. Virginia	Gravel
S53	Grottoes	Gravel	P24	Charlottesville	Greenstone			
S25	Blue Ridge (1)	Dolomite	P13	Blue Ridge (2)	Calc-schist	P32	Massaponax	Gravel
S43	Riverton	Limestone	P15	Burkeville	Granite			
S42	Perry	Dol. Limestone	P20	Vulcan	Gneiss	P19	Boscobel	Granite

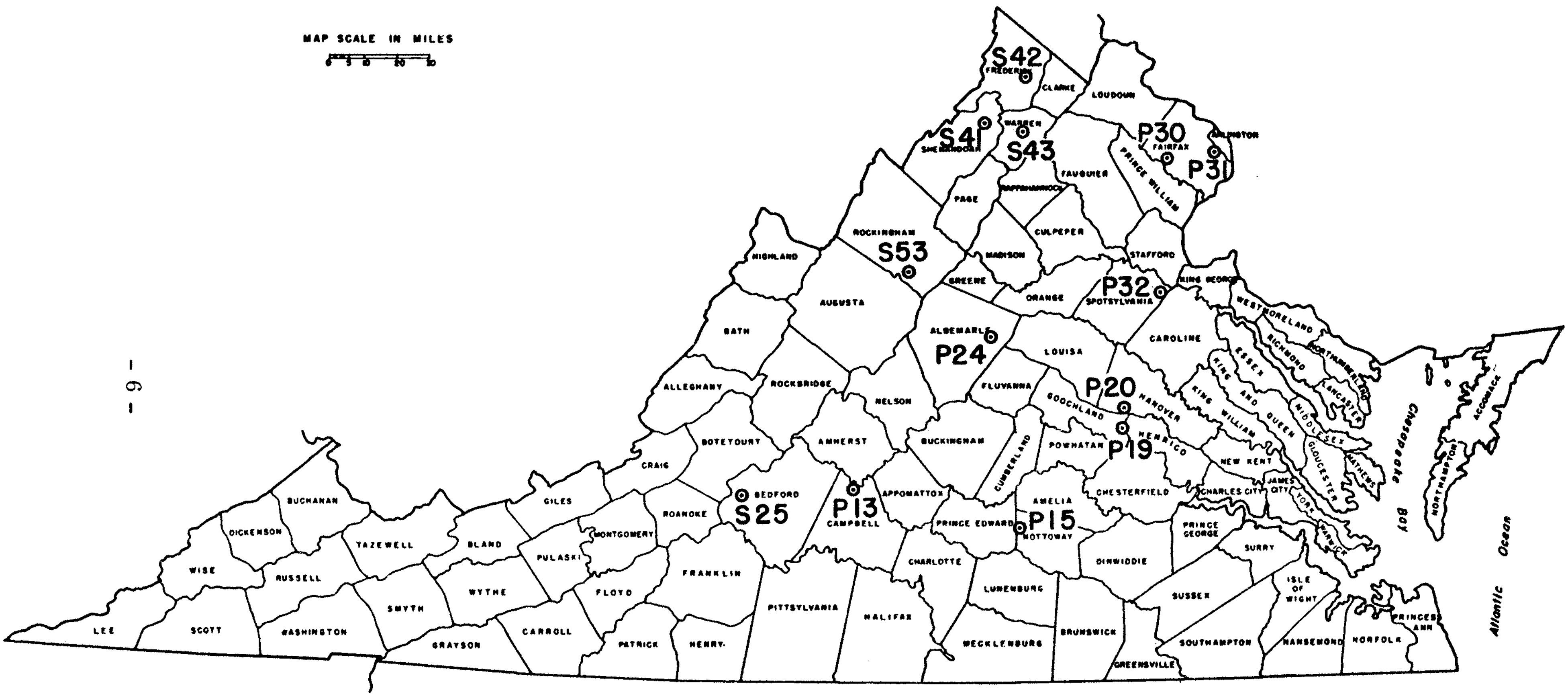
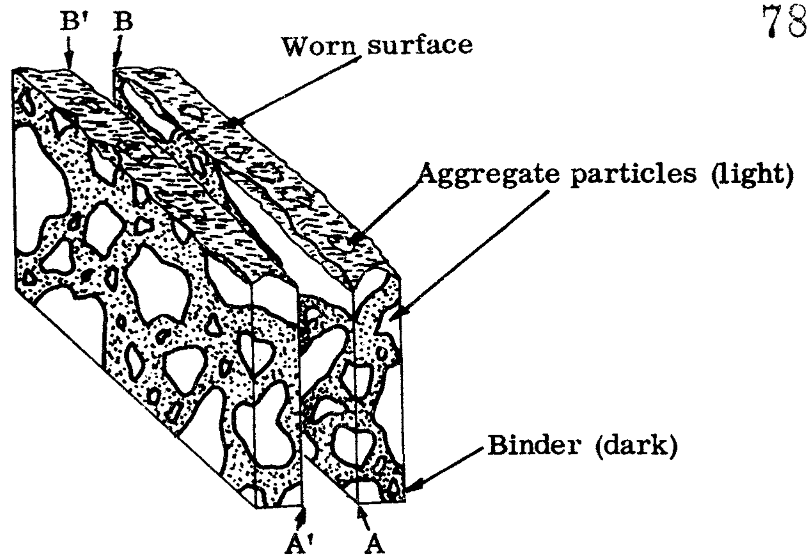
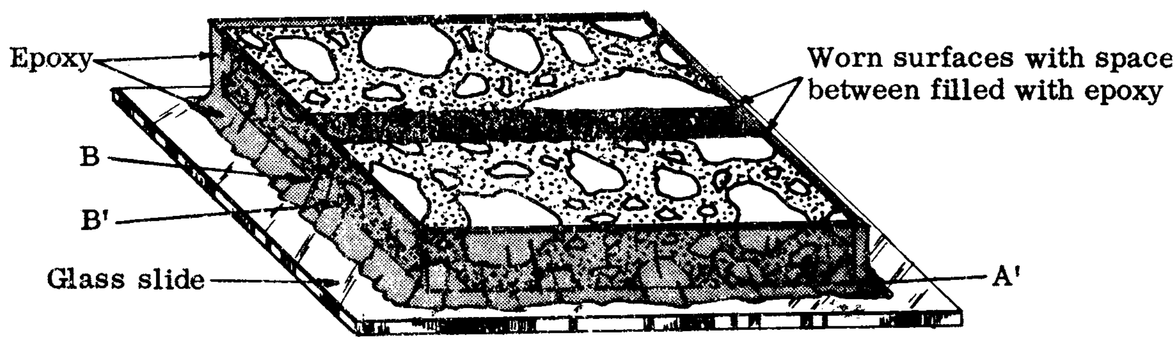


Figure 2. Quarry locations for aggregates studied.



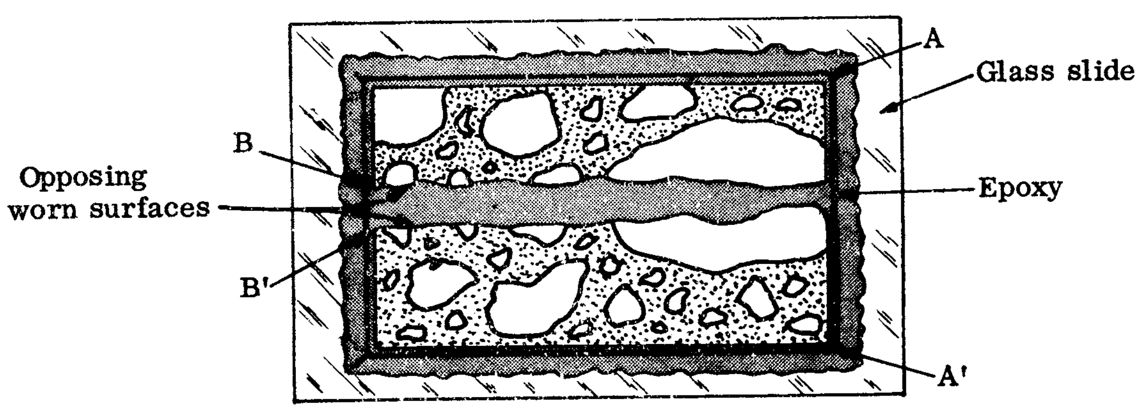
Step A

Section cut from core and vertically split



Step B

Section coated with epoxy, polished and mounted on glass slide.



Step C

Plan view of completed section, ground to appropriate thickness.

Figure 3. Preparation procedure for thin sections of pavement surfaces.

By observing these worn surfaces together with the petrographic properties of the aggregate, reasons for the variable wearing characteristics of the surfaces could be determined. Depending upon the homogeneity of the material, between 20mm and 80mm of worn aggregate surface was evaluated. Approximately eighty thin sections were studied.

Laboratory Evaluation of Microtexture and Wet Friction

Many of the pavements studied possessed appreciable macrotexture, so they were omitted from the quantitative evaluations of the effect of microtexture upon wet friction properties. Two types of samples were used to evaluate microtexture:

(1) Samples of worn pavements wherein the aggregates possessed a minimum of macrotexture, and

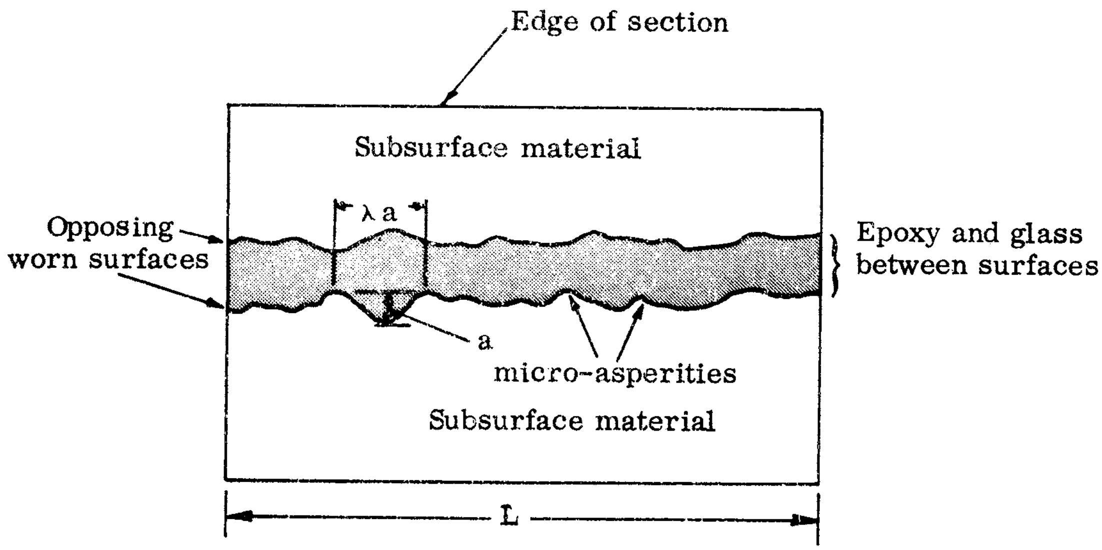
(2) Laboratory samples polished with 75μ, 22 μ, 12μ, and 5 μ abrasives as outlined in Appendix II.

The laboratory polished specimens were prepared for microscopic studies of their worn surfaces in the manner described in the previous section.

Microtexture was evaluated as shown in Figure 4, and micro-asperities as small as 3μ amplitude were included in the final analyses. Microtexture measurements were correlated with laboratory wet friction values obtained on the same surfaces.

As noted by Kummer (1966), "the attempt to obtain a clear picture of the friction process in the tire contact area through field tests alone is futile in most cases, because other factors partly or completely mask the effects one is looking for." These factors, especially when relating microtexture to wet friction values obtained in the field, include temperature, contamination and macrotexture.

For these reasons it was decided to evaluate the effect of microtexture on wet friction by using controlled laboratory tests. In order to accomplish this, surfaces devoid of appreciable macrotexture were chosen. A British pendulum tester was used and the wet friction values obtained are reported as BPN's in this report. A detailed description of the pendulum and the test methods used are given in Appendix III.



Where:

o* $_a$	=	amplitude of micro-asperity
λa	=	wavelength of micro-asperity(s) of amplitude "a"
L	=	length of section
N_a	=	number of micro-asperities of amplitude "a"
o $\bar{\lambda}_a$	=	L/N_a = mean wavelength of micro-asperity(s) of amplitude "a"

Assuming the surface is isotropically microtextured then,

$1/\bar{\lambda}_a = f_a$ = frequency of micro-asperities of amplitude "a" per unit length

and,

* $(f_a)^2$ = micro-asperity density or number of micro-asperities of amplitude "a" per unit area.

* Principal components of microtexture used.

o Principal components of macrotexture used.

Figure 4. Nomenclature and symbols used to describe microtexture. Usage is similar for macrotexture.

Profile-o-Meter Evaluation of Pavement Macrotexture

Macrotexture measurements were made on all test sections using a profile-o-meter designed and built specifically for this study (see Figure 5 A). The nomenclature used in describing and evaluating macrotexture is similar to that used for microtexture (see Figure 4). A typical worn pavement surface profile is seen in Figure 5 (B). Six such profiles were usually made on each pavement section, two each at three separate test sites.

Two factors hindered the quantitative assessments of macrotextures, both related to the nature of the profile-o-meter used:

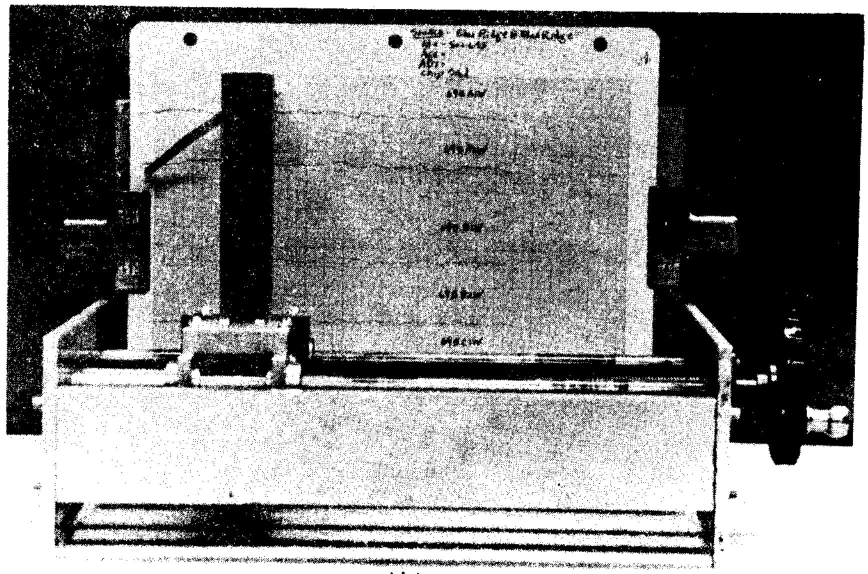
(1) The profile-o-meter was usually not sensitive to macro-asperities less than 1 mm in amplitude due to the weight on the tracer point which resulted in scratching or digging into the surfaces, and

(2) There was no amplification of the reproduced surface profiles making the analyses of small macrotextural features (less than $\frac{1}{2}$ mm amplitude) very difficult.

For these reasons macro-asperities less than 1 mm amplitude were excluded from the quantitative evaluation of macrotextures. However, some general conclusions were possible, based upon the coarser macrotextural values and observed harshness (acuteness) of the macro-asperities.

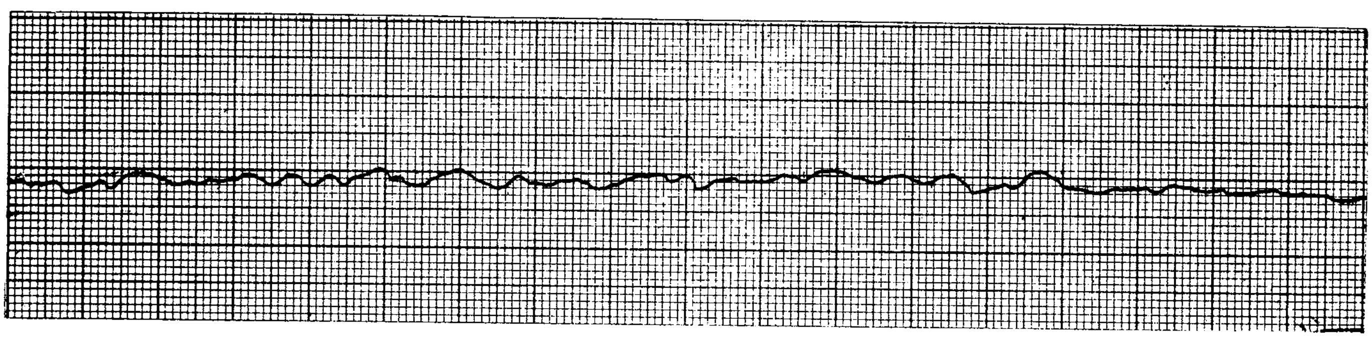
Field Wet Friction Tests

The Virginia Highway Research Council skid trailer was used to obtain wet friction values in the field. Whenever possible, tests were taken at speeds of 20 mph and 40 mph in order to determine friction-velocity gradients for correlation with macrotextures. An average of fifteen measurements per test speed were performed upon each surface and the average values are used in the text. The skid trailer values reported in this paper are corrected to stopping distance numbers, or SDN's, SDN values were originally determined by skidding an automobile on wet pavements and measuring the stopping distance. A given SDN is subscripted with the test speed at which the value was obtained.



(A)

Profile-o-meter



(B)

Typical Profile, Scale 1:1
(1 division = 1mm)

Figure 5. Profile-o-meter and a typical worn pavement surface profile.

AGGREGATES SELECTED FOR STUDY

A broad range of rock types which had, in the past, exhibited a wide range in wet skid resistance values were chosen for study. Included were carbonates, granites, diabase, siliceous gravels, and a greenstone or meta-basalt, (see Figure 2).

With the above rock types considered desirable for study it was decided to choose a number of individual aggregates of each type so that a range in petrographic properties would be represented. It was reasoned that not only variation between rock types but variations within a specific rock type could well affect wear, texture, and skid performance.

Of the carbonate rocks studied three were chosen which were relatively high in total insoluble residue contents. These were S25, the Elbrook formation of Cambrian age containing 23% average total insoluble residue; S42, the Connococheaque formation of Cambrian age containing 17% average total insoluble residue; and P13, the Arch Marble, a calcareous Schist of Cambrian age containing 38% average total insoluble residue (all insoluble residue analyses conducted by Sherwood — 1959). Two carbonates known to polish were chosen. These were: S41, the Mosheim limestone of Ordovician age, $< 2\%$ total insoluble residue content; and S43, from the Beekmantown of Ordovician age, $< 3\%$ total insoluble residue content (Sherwood and Mahone — 1969).

The three granites studied are quarried from the complex crystallines of the Virginia Piedmont. P15 was chosen as a typical, fine-grained, biotite granite. P20 and P19 were selected because of their generally coarse textures and mineralogical dissimilarities. P20 is composed principally of microcline feldspar and quartz and P19 of microcline feldspar with minor sericite included in some fractures and joints.

The only diabase studied was P30 and it was considered to be representative of most of the very homogeneous diabase sources in the Triassic of Northern Virginia.

The siliceous gravels, all of recent of Pleistocene age, includes sources S53, P31 and P32. S53 consists predominantly of sedimentary, siliceous sandstone fragments. In contrast, P32 consists of predominantly vein quartz, and meta- and orthoquartzite particles. P31 consists of approximately equal amounts of quartzite and sub-friable to non-friable sedimentary siliceous sandstone particles.

The greenstone (P24), an epidotized meta-basalt from the Catoctin formation, was included in the study because of its widespread use and its marked petrographic dissimilarity from any of the other rocks studied.

RESULTS AND DISCUSSION

Mechanisms of Rock Wear

General

Due to the extreme differences in mineralogy and texture among the common mineral aggregates, significant differences in their reaction to the impact and scrubbing action of rubber tired traffic would be expected. On the basis of the results of studies of the petrographic properties and the traffic worn surfaces of the aggregates examined, the following mechanisms of traffic wear are proposed:

(1) Wear primarily in response to vertical traffic stresses,

(2) Wear primarily in response to tangential traffic stresses, and

(3) Wear primarily as a result of a combination of both vertical and tangential stresses.

It is realized that, because both types of stresses are always present to some degree upon pavement surfaces, aggregates must wear in response to both in the strictest sense. However, upon evaluating worn aggregate surface textures, it becomes obvious in most cases that these textures are the manifestation of wear by either (1), (2), or (3) above.

As shown below, petrographic properties determine the manner in which an aggregate will respond to traffic stresses. A representative of each class will be discussed in detail, and a summarization of the other aggregates wearing similarly will be given.

Aggregates Wearing in Response to Vertical Stresses

Aggregates possessing gross physical weaknesses will degrade under the vertical component of traffic stresses. This degradation results in the removal of discreet mineral grains or fragments from the individual aggregate particles. A constantly renewed surface results. The petrographic properties causing these physical weaknesses are:

(1) Weak mineral grain-bonds, or weak minerals such as mica, and

(2) Structural weaknesses in the form(s) of weak planar elements, i.e., schistosity, fissility, fractures, joints, bedding planes, etc.

The dominant worn texture of the rock will reflect the collective particle loss and the size of the particles, and significant changes in both macrotexture and microtexture can result from this process. For descriptive purposes, asperities developed on individual aggregate particles are termed intraparticulate textures.

796 One example of an aggregate wearing principally by degradation in response to vertical stresses is that from the Arch marble formation, which, as studied, is a quartz and mica-rich, calcareous-schist. The samples studied were quarried by the Blue Ridge Stone Company near Lynchburg, Virginia (P-13, Figure 2). The rock possesses weak minerals in the form of crystalline calcite and mica and well-developed schistosity imparts additional planar weaknesses to the rock. Approximately 60%-80% of the total rock is calcite with 10%-25% each of quartz and mica and a few minor mineral components being present. Grain size of the minerals is generally between 0.1 and 0.2 mm. An insoluble residue analysis of this formation conducted by Sherwood (1959) shows an average of 38%-40% insoluble constituents, chiefly quartz and mica.

The rock degrades at a relatively rapid rate by fracturing and grain-loss. Macrotexture, initially resulting from the voids between individual aggregate particles (interparticulate texture), is reduced by wear until the pavement surface displays only the texture corresponding to the level of dominant wear, i.e., microtexture. Figures 6, 7 and 8 illustrate the textures displayed by highly worn Arch Marble surfaces.

The average SDN_{40} was 46 for the surface containing this aggregate and the average SDN_{20} was 57.* Using an SDN_{40} of 40 as the minimum acceptable, it is seen that the microtexture of the Arch Marble is adequate for wet skid resistance at 40 mph and less.

Though none of the other aggregates studied were considered to wear primarily by degradation, there are others, not studied, which would fall into this category. Friable sandstones would be typical of such rocks.

Figure 6. Close-up of a worn particle of Arch Marble illustrating the effectiveness of schistosity in producing a microtextured surface. Scale: 1 division = 1 mm.

*Data for all samples are tabulated in Appendix IV.

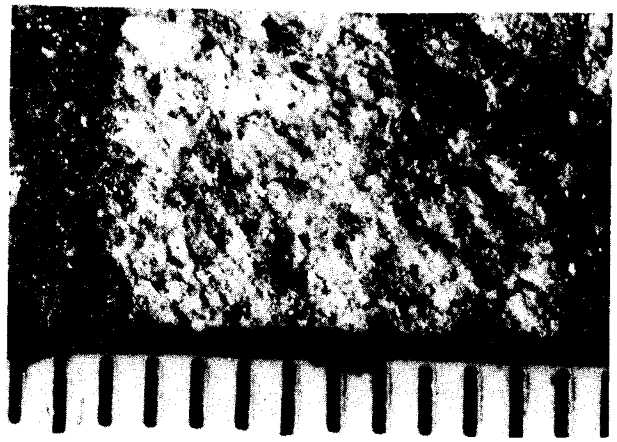


Figure 7. Arch Marble particle with less schistosity and more of an equigranular texture than that shown in Figure 6. Dark specks are biotite, white are calcite, clear are quartz and muscovite. Note the gritty microtexture. Scale: 1 division = 1 mm.

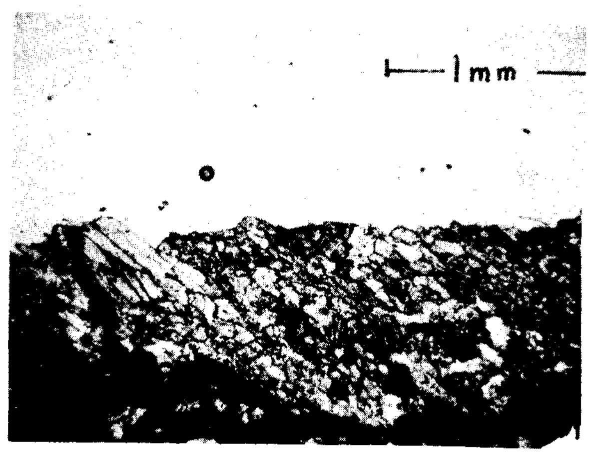


Figure 8. Photomicrograph of a cross section of worn, schistose Arch Marble. Large, light, elongate crystals at left are muscovite. Other grains at the surface are quartz and calcite. Relief is related to grain and schistosity fragment loss across schistosity planes. (x 24, plane polarized light.)

Aggregates Wearing in Response to Tangential Stresses

As grain bond and mineral and structural competency increases, wear by attrition, in response to tangential rubbing stresses increases in importance. For grossly competent aggregates, wear by attrition is prevalent. Individual mineral grains and whole aggregate particles defy degradation. Rocks falling into this category, when mineralogically pure or homogeneously hard, are subject to polishing unless resulting abrasion is coarse enough to provide a minimum degree of microtexture. It has been observed by several investigators that detritus normally found on road surfaces is not sufficiently large or abundant to induce such coarse abrasion (Maclean and Shergold — 1959; Stiffler — 1969). In this light, polishing of such rocks should be the rule rather than the exception. The rate of wear (polish) for these rocks is determined principally by the gross hardness of the constituent mineral particles. Since many limestones fit into this category of rocks and because they are soft, both macroscopic wear* and microscopic polishing are relatively rapid; consequently, even under moderate traffic volumes, pavement slipperiness can result quite rapidly. This combination of rapid macroscopic wear and polish susceptibility has caused widespread attention to be focused on these rocks.

Figures 9 and 10 illustrate the worn texture of a highly polished limestone from the Mosheim or New Market formation.

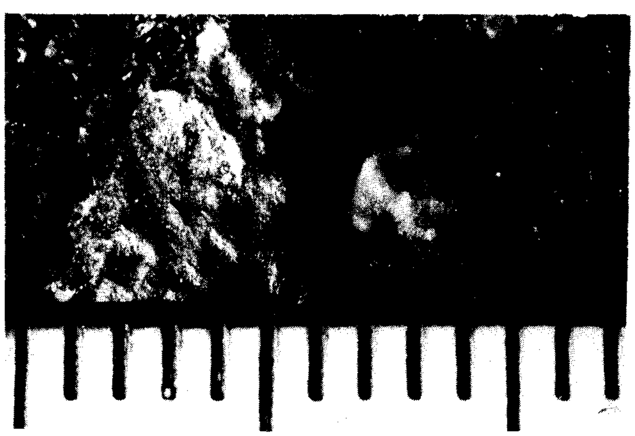


Figure 9. Close-up of a highly polished Mosheim limestone particle. Scale: 1 division = 1 mm.

*Reduction of aggregate and macro-asperity heights as a result of the collective microscopic wear by attrition.

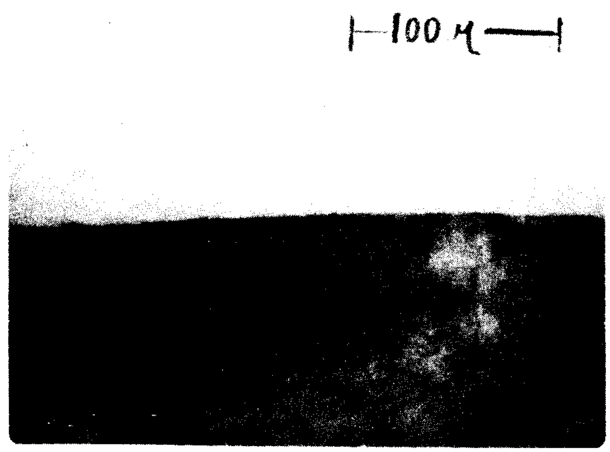


Figure 10. Photomicrograph of a cross section of a typically worn, polished Mosheim limestone particle. Only rarely was significant departure from this mode of wear noted for this fine grained, high calcium limestone. (x 250, plane polarized light.)

The specimens studied were quarried by Chemstone Corporation near Strasburg, Virginia (S-41, Figure 2). The road surfaces containing this aggregate possessed very little harshness, macrotexture or microtexture. The rock itself is a high calcium limestone (approximately 98% calcium carbonate) of a very homogeneous and dense nature.

The average wet SDN_{40} for this surface was 34, reflecting the absence of harshness and macro- and microtexture, and was below the minimum acceptable value. An SDN_{20} was not determined.

Though harder rocks were observed to polish, attention has not been focused upon such rocks because of their relatively slow loss of interparticulate macrotexture and harshness, i.e., the slow rounding and height reduction of angular particles. This resistance to wear can provide adequate interim wet skid resistance properties and critical pavement slipperiness may not result. Extremely high traffic volumes are required to grossly wear and polish these aggregates and the pavements containing them may well be resurfaced for other reasons before they become slippery. One example of such an aggregate is P19, a very coarse-grained, granitic rock, quarried by the Boscobel Stone Company near Manakin, Virginia (P-19, Figure 2). The road surface containing this aggregate was constructed of portland cement concrete, was 26 years old, and very heavily travelled (20,000 + vehicles/day). Rounding of individual particles and polishing were observed for this aggregate. The only large scale macrotexture remaining at the road surface results from the slow wear of the granite (predominantly microcline feldspar) particles relative to the cement-sand matrix. Figures 11 and 12 illustrate typical worn surfaces of the granite particles.

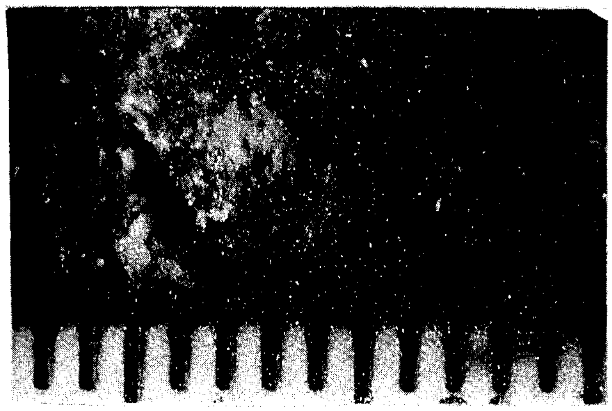


Figure 11. Close-up of a highly worn, subpolished surface of a particle of Boscobel granite. Primarily sericitized microcline with minor quartz. Scale: 1 division = 1 mm.

Figure 12. Photomicrograph of a cross section of a particle similar to that shown in Figure 11. Dark streaks in microcline are sericite alterations parallel to pericline twin planes. Straight fine lines running from upper right to lower left are cleavage traces. Dark fractures are filled with sericite. Note the relief developed at the surface where veins intersect the surface. Also note the local polishing where large cleavage planes intersect the surface. (x 24, plane polarized light.)

Note that only minor degradation is seen to occur where sericite veins intersect cleavage planes and enable large cleavage fragments to "spall". Actually this mechanism is about as detrimental to microtexture as it is beneficial, for the large cleavage planes which are exposed are extremely smooth. Also notice in Figures 11 and 12 the evidence for relatively rapid abrasive wear where the soft sericite veins intersect the surface and are surrounded by the much harder, slow wearing microcline feldspar.

The average SDN_{40} for this surface was 42, only slightly above the minimum acceptable value. The average SDN_{20} was 46.

Additional aggregates observed to wear predominantly in response to tangential stresses were: diabase (P30), gravels (P31 and P32), granite (P20) and limestone (S43). The diabase (P30) and limestone (S43) both were slippery (SDN_{40}'s measuring 37 and 34 respectively). The gravels were somewhat marginal with respect to SDN_{40}'s measuring 45 and 42, respectively. Granite (P20) was not skid tested.

Two carbonate aggregates, S42 and S25, are not listed in this class of aggregates. Reasons for their omission become obvious in the discussion of the next class.

Aggregates Wearing in Response to Tangential and Vertical Stresses

Aggregates of this class display worn surfaces which manifest a combination of wear by degradation and attrition. In order to wear in this manner it is necessary only that degradation take place in a limited or intermittent fashion and that the portion of the aggregate remaining in the pavement be exposed to abrasive actions. In essence, one might consider that in contrast to the relatively dynamic type of wear-by-degradation discussed earlier, this is a considerably less rapid form of wear-by-degradation.

Aggregates considered to fit into this category of rocks generally possess the following petrographic properties:

(1) They are composed of predominantly competent mineral zones which are highly indurated, dense or cemented, and

(2) They possess either minor amounts of relatively soft or weak minerals or subordinate quantities of dispersed microfractures, joints, or weak grain bonds.

Several processes can occur during the wear of such aggregates:

(1) The competent grains are abraded while retained in the aggregate particles;

(2) Subordinate, soft or weak minerals wear rapidly with respect to the hard minerals* and often the hard minerals are undermined by removal of these softer zones; or

*When competent zones are comprised of hard minerals such as quartz or feldspar.

(3) Subordinate fractures or weak grain bonds facilitate limited detachment of mineral grains and fragments from the particle surfaces.

Such processes occurring in somewhat optimum proportions lead to relatively slow wear of hard minerals and development of adequate harsh or sub-harsh textures of either macro- or microscopic proportions depending upon the grain size. With extended wear, however, the surface of even these rocks is reduced to a level coincident with the level of most rapid degradation. As believed by this writer to be the general case, these rocks wear intermittently by attrition and degradation. The rock essentially defies breakdown and abrades during one stage; however, repeated high impact stresses finally cause rupture of the particle at some weak points and a grain or fragment of significant size is detached. This rupture causes the retention of extremely harsh textures at many levels and intermittent attrition is not rapid enough to grossly eliminate this harshness before rupture occurs again. For rocks of this class, composed predominantly of hard minerals, harshness retention is very good. For the softer rocks, harshness retention is less but still observed to be adequate.

Figures 13 and 14 illustrate the worn texture of a hard variety of such an aggregate. This aggregate is a granite quarried by the Burkeville Stone Company (P15, Figure 2). This is a fine-grained rock ranging between approximately 0.2 and 0.5 mm in grain size. It is permeated by randomly oriented microfractures (see Figures 13 and 14) and consists of approximately 50% microcline feldspar, 20% quartz, 15% oligoclase feldspar, 10% biotite and muscovite, and 5% others. Alterations are minor.

As seen in Figure 13 the worn surface of this particle is harsh and gritty. Figure 14 serves to illustrate, (1) the relatively rapid wear of biotite where it is adjacent to the harder minerals and (2) the network of microfractures permeating the rock.

The very coarse intraparticulate macrotexture of surfaces containing this aggregate was only rarely observed but harshness of individual particles was very good. Unfortunately only moderately trafficked pavements could be located containing the Burkeville aggregate so the SDN_{40} value of 67.5 and the SDN_{20} of 77.0 are quite high. However, the harsh nature of the macro- and microtexture of this aggregate surface would be expected to persist even under heavy traffic conditions.

Other aggregates studied which wear in response to both traffic stresses are: gravel (S53), carbonates (S25 and S42), and greenstone (P24). The average SDN_{40}'s were 54, 51, 48, and 48 respectively. Carbonate aggregates S25 and S42 possessed on the order of 18%-25% total insoluble residues, 7% and 4% greater than 50μ, respectively (Sherwood — 1959). Siliceous grains as large as 60μ were observed in the thin section analyses of both these rocks. Because of abundant bedding planes, shaley partings, siliceous zones, fractures, etc. these rocks were observed in some instances to degrade by fracturing. This fracturing and fragment loss enable the particles to retain significant macrotexture, microtexture and harshness. In addition, mineral grains retained in the aggregate surfaces were observed to wear very slowly.

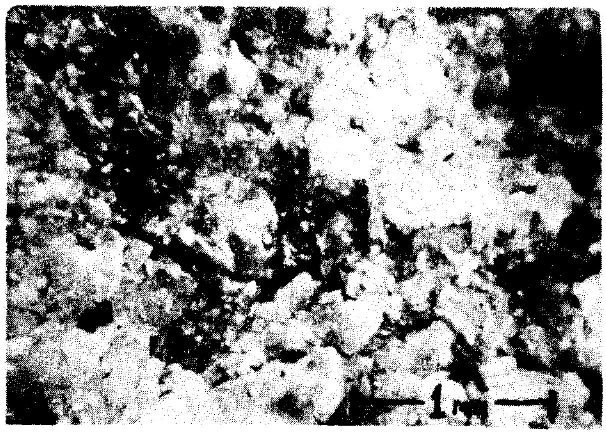


Figure 13. Photomicrograph of the surface of a Burkeville granite particle. Note the harshness due to fracturing and grain loss. Rock predominantly of microcline and plagioclase feldspar, quartz and biotite (x 24).

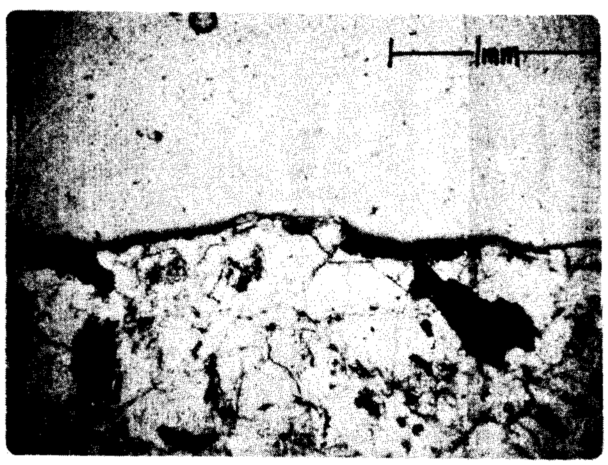


Figure 14. Photomicrograph of the cross section of a particle similar to that shown in Figure 13 with many visible hairline fractures. Mostly microcline at surface, some quartz, with dark areas of biotite. Note the low relief of the biotite areas. (x 24, plane polarized light, section 0.05 mm thick.)

Microtexture resulting from the protrusion of hard, insoluble mineral grains was seen to be present upon many such particles. Other particles wearing by attrition were observed to be polished-to-sub-polished. Figure 15 illustrates the texture of a worn particle of S25. The direct significance* of insoluble mineral grains would be difficult to rigidly assess in light of an abundance of such worn particles. However, the insoluble mineral constituents must be a direct and indirect contributing factor to the overall textures and wet skid resistance of this aggregate.

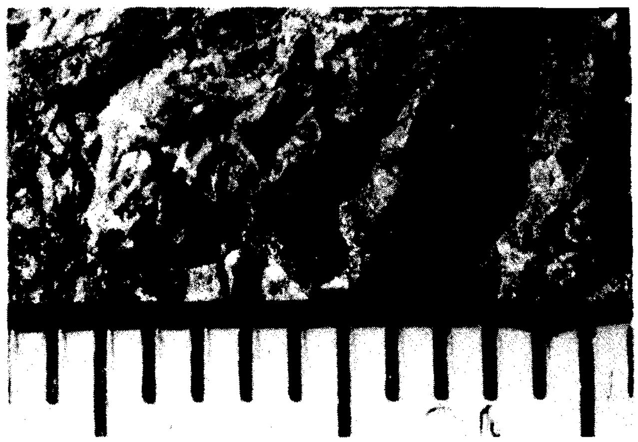


Figure 15. Close-up of a single, worn S25 dolomite particle. Note abundant fracturing and resulting intraparticulate macrotexture. Scale: 1 division = 1 mm.

Based upon these observations it is believed that not only the quantity and size of insoluble residues affect the skid performance of carbonate aggregates, but also their manner of occurrence. Such reasoning would help account for the minor discrepancies observed when correlating insoluble residue contents with skid values. P24, a greenstone containing epidote and plagioclase grains set in a soft, chloritic groundmass, wears in a manner similar to the two carbonates of this class.

Wearing Properties of Portland Cement Concrete Surfaces

As only a relatively few portland cement concrete surfaces were studied in detail, the writer presents only the general wearing characteristics for those studied; most of which were somewhat low in wet skid resistance (SDN_{40} of 40-50).

In general it was observed that fine-grained (sandy) concrete surfaces wear by a process similar to that described under the section entitled "Aggregates Wearing in

*In the sense of protruding from worn particle surfaces.

Response to Tangential Stresses." Concretes are essentially man-made rocks consisting of fine, hard mineral grains (if siliceous) set in a softer cementing agent.

Wear is primarily by attrition and unless a sufficient quantity of sand grains is present, adequate microtexture cannot develop. In addition, unless some means of artificial texturing is employed, these surfaces were generally observed to be unable to retain macrotexture unless they are extremely old, and coarse aggregate is well exposed. Concrete surfaces observed by the author to become slippery seemed to possess lower quantities of siliceous sand than did surfaces observed not to have polished. It is certain that relatively large areas of mortar were exposed and polished in these slippery to near slippery concrete surfaces. Figure 16 illustrates this fact. Areas such as that depicted in Figure 16 were quite prevalent for surfaces exhibiting low skid resistance.

Figure 16. Photomicrograph of the worn surface profile of portland cement concrete. The black area is cement and the light areas are quartz and granite particles. The average SDN_{40} of this surface was 44.0 and polishing is present locally. (x 24, plane polarized light.)

Macrotexture and Wet Skid Resistance

Having qualitatively discussed aggregate petrography, wear, and texture it is now important to consider the texture needed to impart various skid resistance properties to pavements.

As pointed out in the section dealing with procedures, quantitative evaluations of macrotexture were limited. However, several observations are noteworthy and some general relationships can be discussed based upon these observations.

Kummer and Meyer (1967) cover in some detail the effects of large and small scale macroscopic roughness upon wet friction values. They state "the large-scale macroscopic texture of the pavement surface, as described by mean void width or a similar parameter, determines the drainage properties of the surface and, thereby, the rate by which the shear strength (adhesion) and the volume, Q, of the rubber being deformed (hysteresis) is reduced with speed." Continuing, they relate that "Sharply tipped, unpolished aggregate of adequate void width produces high slip and skid resistance, whereas rounding of the tips due to traffic polish drastically reduces the friction properties without significantly affecting the pavement's drainage properties." Figure 17 schematically depicts these relationships.

Point (1) in Figure 17 hypothetically represents the friction level and gradient characteristics of a new pavement surface which is graded somewhat coarsely of crushed aggregate. Because the large aggregate tips are sharp, both the adhesion and hysteresis components of friction are effective and the friction value high. Because of the initial high level of macrotexture the gradient or slope of the curve is low, i.e., the decrease in wet skid resistance with an increase in sliding speed is minimal.

Points (2), (3), and (4) hypothetically represent the friction and gradient characteristics at successive stages of wear. ΔY represents the change (decrease) in friction due to a loss of harshness (rounding of aggregate tips) and ΔX represents a similar and probably smaller relative increase in gradient because of decreased macro-asperity heights.

As indicated, point (4) represents the skid and gradient properties of the surface at some equilibrium stage of wear. The final position of point (4) is determined by the wearing characteristics of the aggregate. If wear is principally by attrition, uniform rounding of aggregate tips will occur and macro-asperity height will steadily decrease with wear, (or with the rate of wear being dependent upon the hardness). If the aggregate is polish susceptible it will polish and friction losses will be maximal due to the additional loss of microtexture (discussed later). If, on the other hand, the aggregate can degrade, harshness can be retained as indicated in the section on Rock Wear, and the microtexture or macrotexture at point (4) will be determined by the level at which degradation occurs.

Point "A" in the figure hypothetically represents a point similar to point (1) except the aggregate is an uncrushed, rounded siliceous gravel. Therefore, initial harshness is not likely to be present and the surface is effectively worn to begin with; thus, the initial lower friction value. However, the gradient can still be relatively low if the macro-asperities are large enough and spaced appropriately. In addition, it is seen that friction and gradient changes will be less from "A" to "D" than from (1) to (4) because the worn state of the uncrushed gravel will be not too dissimilar from its original state, relative to changes in the crushed aggregate. The actual displacement between the friction and gradient properties of the two aggregates will depend upon the modes of wear which the two aggregates display. Points (4) and "D" may coincide or be farther apart than shown in friction and/or gradient values. The relative changes in the friction and gradient characteristics for both aggregates may be greater or less than shown, again dependent upon their individual wearing properties.

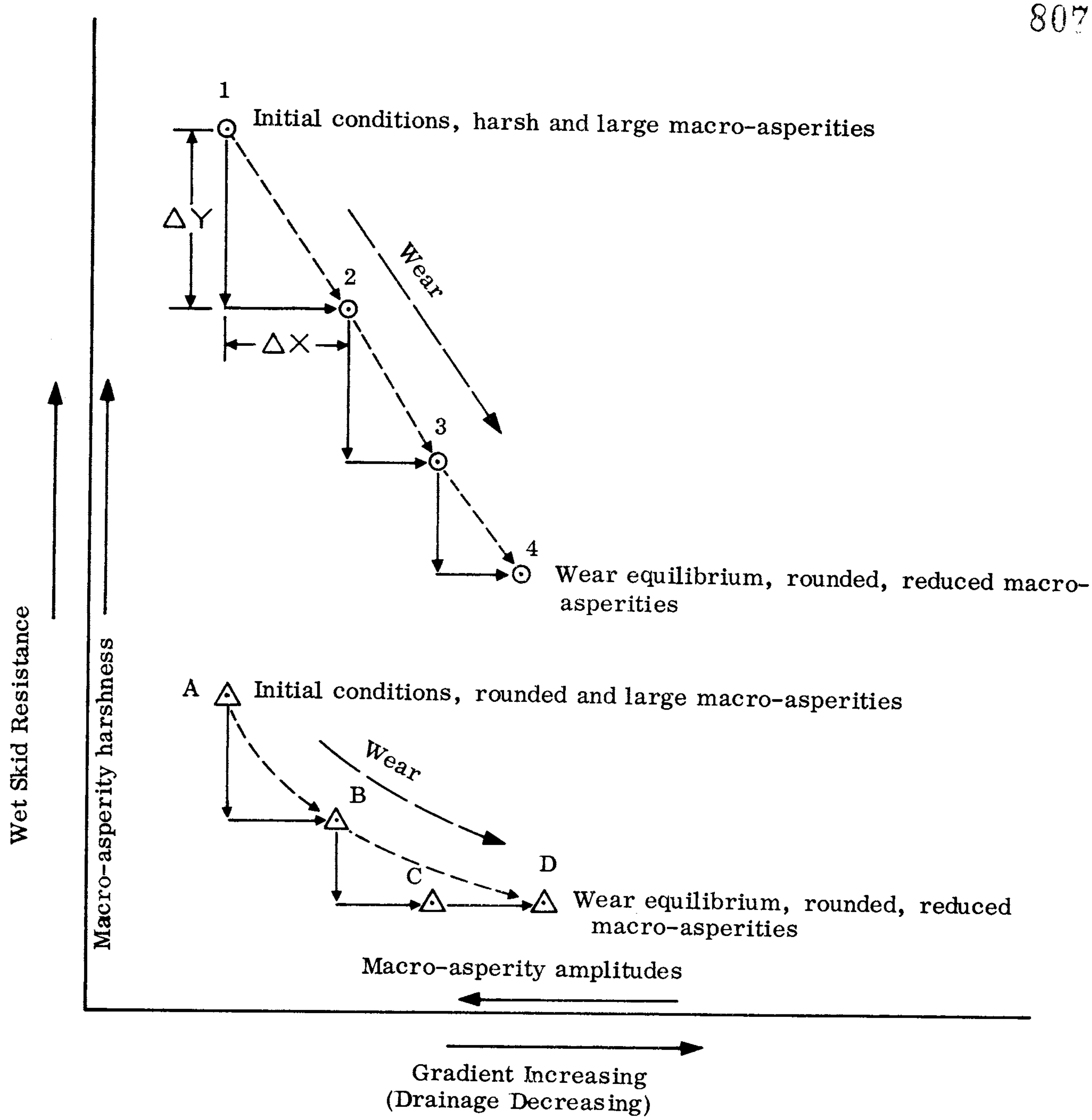


Figure 17. Schematic diagram depicting the effects of wear upon skid and gradient properties of two pavements each constructed of crushed and uncrushed aggregate.

Based solely upon these relationships one might, in assuming all else constant, consider that the friction level is controlled by the degree of macro-asperity harshness, and gradients are controlled by the macro-asperity heights and spacings.

Figure 18 depicts 21 pavement surface profiles measured with the profile-o-meter with the observed SDN_{40} gradient relationships. The numerical values at a given point correspond to the range into which the maximum observed macro-asperity amplitude falls for the surface represented by the point. In the writer's opinion, the maximum amplitude value can at best be some crude indicator of the coarseness of texture and it tells very little of the average texture. The small insets among the plotted points are actual sections of worn pavement profiles considered as more or less typical of the surfaces for the areas in which they are located. Though it is difficult, or sometimes impossible, to distinguish visual differences between any two adjacent profiles, in general it is seen that the relationships appear as previously described. It is pointed out that as finer textures become prevalent in the figure, both smaller level macrotexture and microtexture increase in relative importance and these textures are not distinguishable in the figure. Textural reasons for the spread of points appear only at a gross level (from the finest to coarest textures). Another consideration is that some of the finer textured surfaces (0-1 mm maximum amplitude) may have slightly greater maximum amplitude values than shown since all of the surfaces so designated are portland cement concrete and only a single six-inch core was used to obtain each profile.

In any event, it is seen in the figure that for assurance of adequate gradient properties (say less than 0.5 skid units/mph) a surface should possess macro-asperities of at least 2 mm amplitude. For maximum wet skid resistance the asperities should be harsh.

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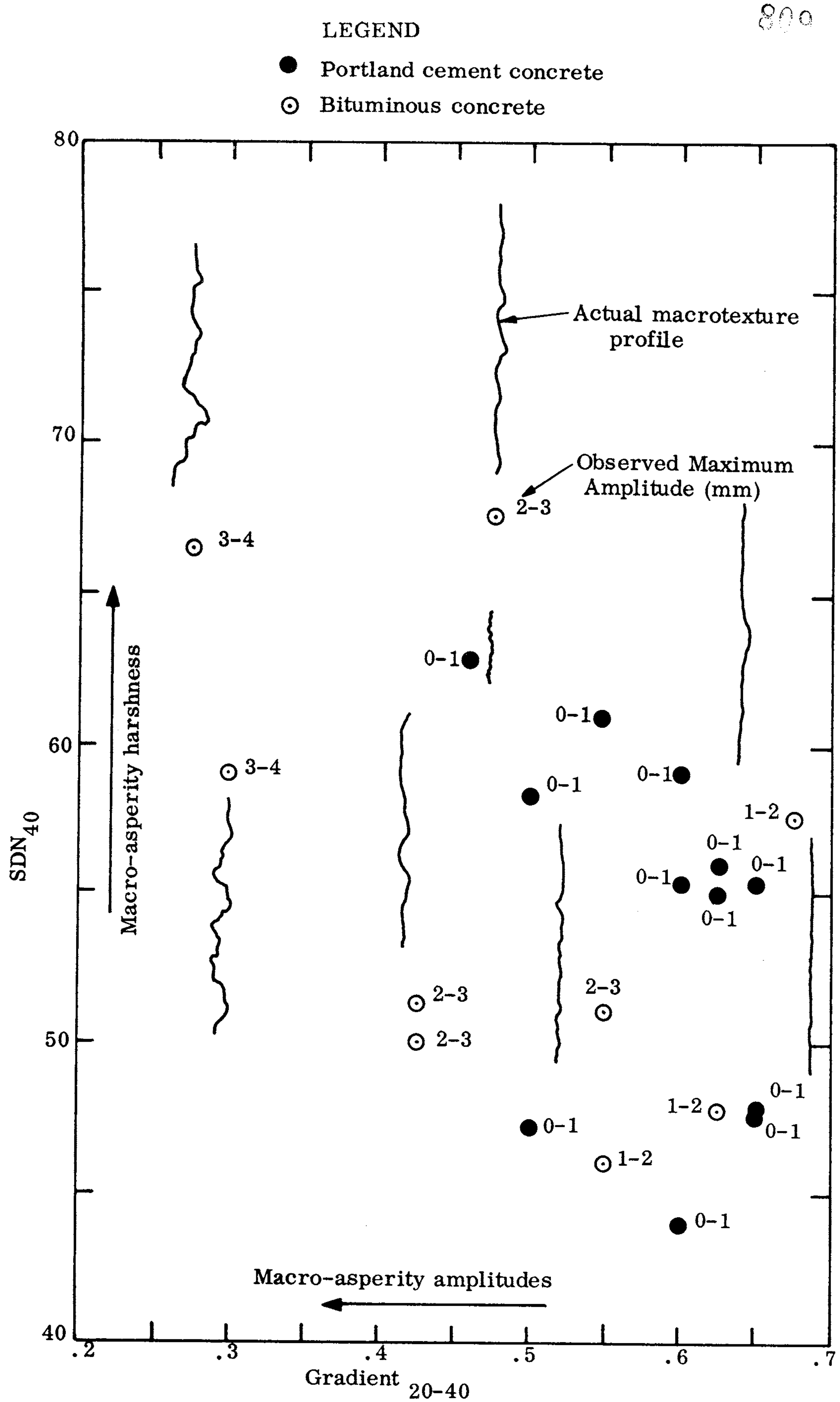

Figure 18. SDN_{40} vs. gradient $_{20-40}$.

Microtexture and Wet Friction

General

This section relates primarily to surfaces which possess a minimum of macrotexture, as the result of wear. Such surfaces rely almost solely on microtexture for thin water film penetration and establishment of adhesion between the pavement surface and vehicle tire. Surfaces not possessing substantial microtexture are usually referred to as "polished".

Even with appreciable macrotexture, with the loss of both harshness and microtexture a surface may become slippery. Macrotexture primarily provides gross drainage of water from beneath a sliding tire and if harshness and microtexture are absent thin film penetrations will not take place and a large portion of the very important adhesion component of friction will be lost.

Because of variable field conditions laboratory tests were used to evaluate microtexture and wet friction relationships. The wet friction values were obtained using a British Pendulum Tester described in Appendix I. Microscopic profile analyses of the laboratory worn surfaces were performed as outlined in the Procedures section and Figure 4.

Results

Figure 19 shows four curves illustrating the relationships existing between laboratory wet friction values and the abrasive sizes used to polish the surfaces indicated. The writer believes the vertical translations of the curves to be primarily due to the different methods of friction measurement employed by the investigators and, to a minor degree, possibly due to variable water film thicknesses. The importance of these data lie in the fact that all show a leveling off of wet friction values beyond a certain abrasive size. This insensitive region lies somewhere between the 40μ and $80\ \mu$ abrasive sizes. Similar relationships have been found to exist for other polished materials and the relationships seem independent of material type (Stutzenberger and Havens — 1958).

Figure 20 shows two curves representing the relationships between (1) wet friction and micro-asperity maximum amplitudes and (2) wet friction and micro-asperity density. In addition to the microtexture values for the laboratory polished specimens, microtexture values (densities) of selected traffic worn surfaces* are also plotted in the future. Reasons for not plotting the micro-asperity maximum amplitude value for the traffic worn samples are given below.

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*See Appendix IV for surface identifications.

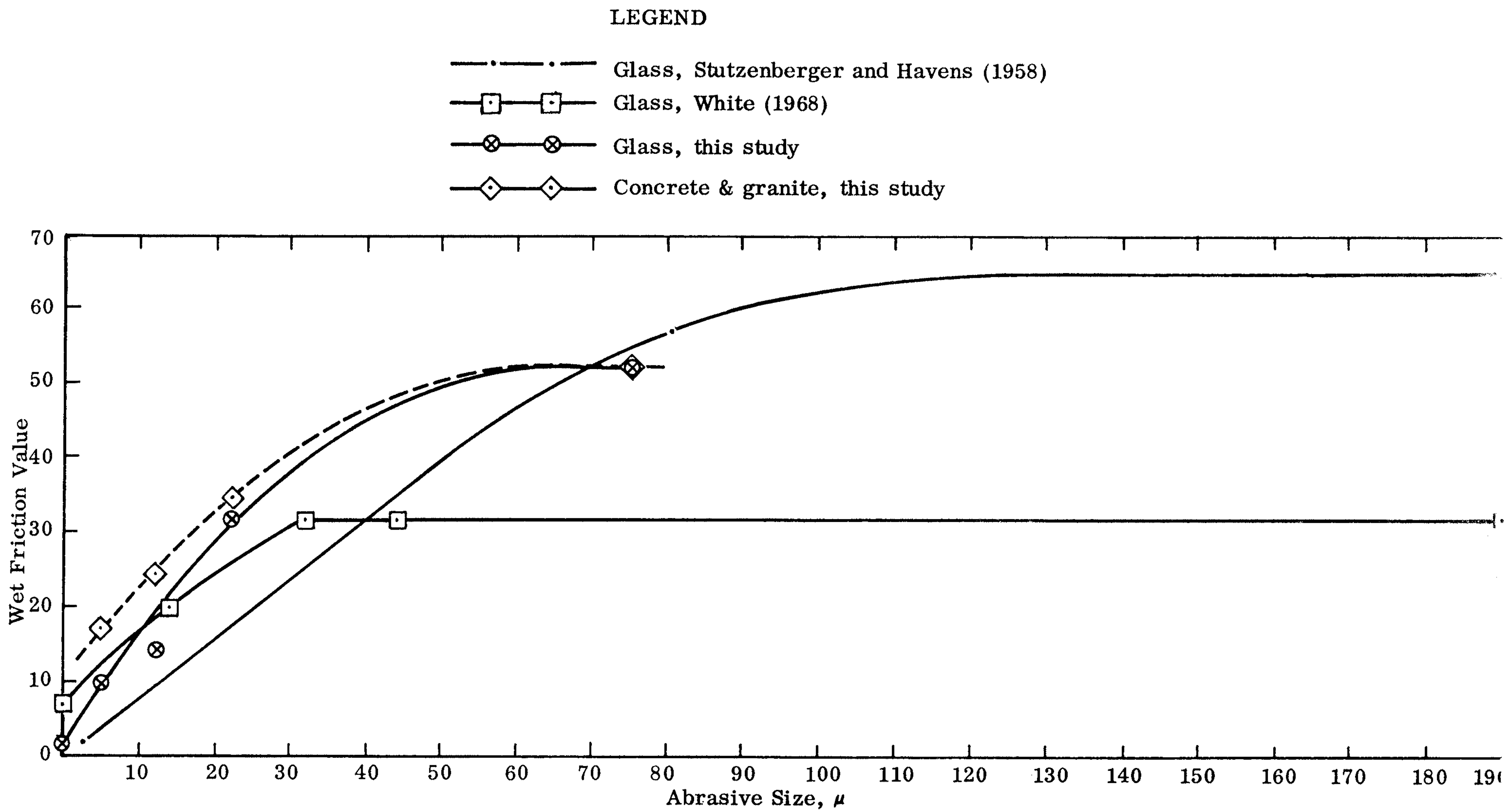

Figure 19. Wet friction value versus abrasive size.

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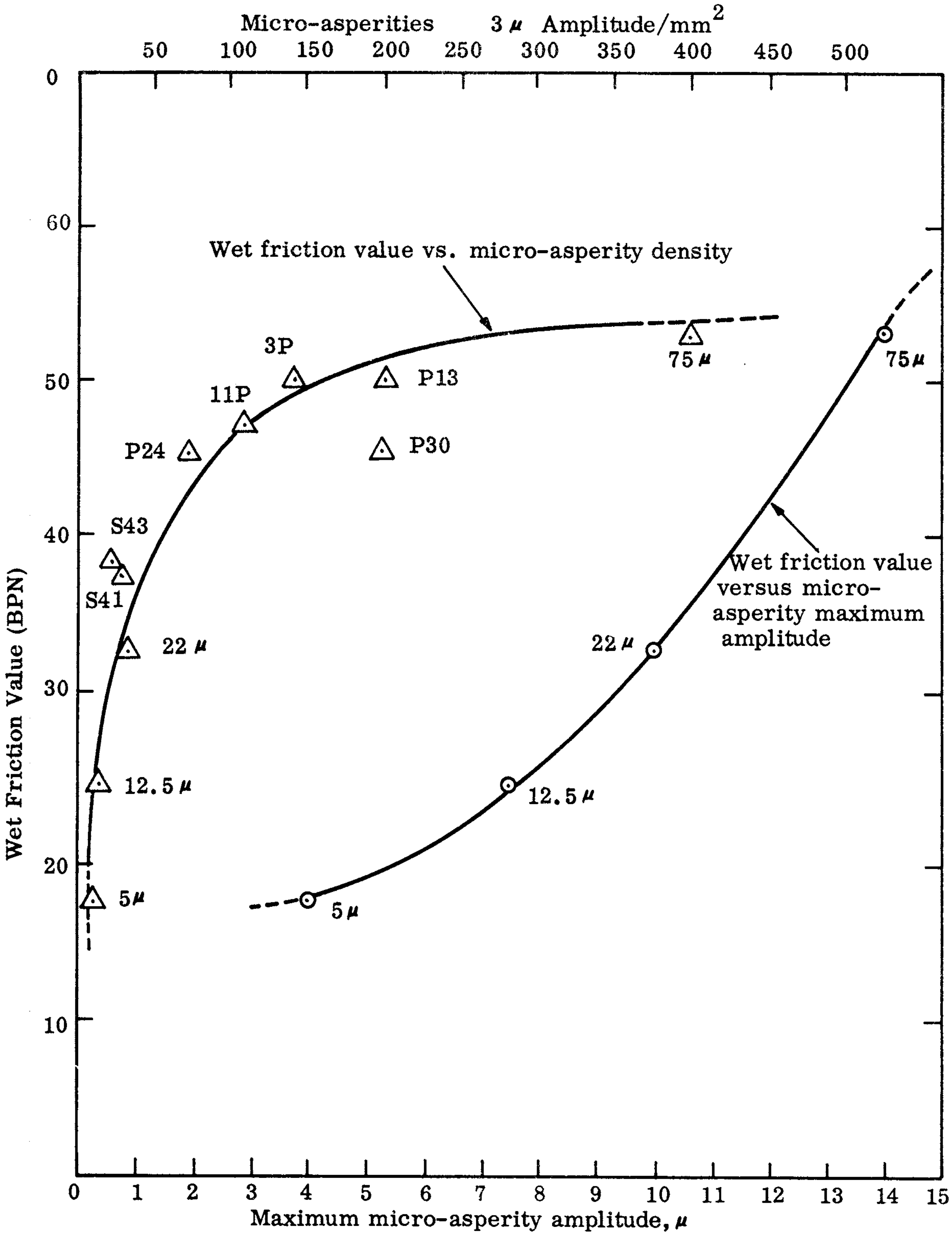

Figure 20. Wet friction values versus microtexture.

Based upon the data and the estimated curve, wet friction values appear sensitive to micro-asperities greater than 3μ amplitude. On the density curve a marked decrease in sensitivity is noted to occur beyond the $100/mm^2$ point. Assuming these relationships to be valid in the field as well as in the laboratory, it is little wonder that prediction of wet skid resistance has been so difficult, especially with highly worn, macro-smooth pavements. Even minor contamination, indistinguishable with the unaided eye, could render such fine microtexture ineffective. Possibly, removal of this contamination is a major reason for the marked increases in wet skid resistance values noted to occur on many slippery pavements following extended periods of precipitation (Kummer and Meyer — 1967; Colley, Christensen and Nowlen — 1969). The relationships depicted in Figure 20 cannot be considered conclusive as the data are few and, it is difficult to evaluate the effect of macrotexture on the friction values. The laboratory values at least provide some control at the extremities and, based upon this, it is believed that the relationships shown are reasonably valid. However, in the case of the laboratory specimens, maximum micro-asperity amplitudes are observed to increase with an increase in micro-asperity densities but the relationship must, in part, be only an apparent one as it is intuitively obvious that the density and size of the micro-asperities must ultimately assume an inverse relationship.

For the artificially worn laboratory specimens it is believed that both the micro-asperity density values and maximum micro-asperity amplitude values are important aspects of the microtexture present upon these surfaces. On the other hand, for the traffic worn surfaces it is believed that micro-asperity densities, but not maximum micro-asperity amplitudes, are valid measurements of microtexture. This observation is related to the nature of the measurement and the fact that a few randomly occurring micro-asperities have relatively little effect on the overall density measurement. By the same reasoning such is not the case for maximum micro-asperity amplitudes and a single, nonrepresentative, relatively large micro-asperity will significantly affect the maximum micro-asperity measurement. Not being able to distinguish the non-representative maximum amplitude micro-asperities present on a given traffic worn surface the writer did not attempt to plot these values. Nonetheless, such large micro-asperities were observed and since they had little effect on wet friction measurements, it is believed that friction values do not increase in response to amplitudes much beyond the 14μ maximum amplitude point. This is based upon general observations of traffic worn surfaces and the fact that even those traffic surfaces possessing greater than 35μ micro-asperities do not show significantly higher wet friction values than the laboratory polished sample possessing only a 14μ maximum amplitude.

From the above relationships it appears that not only are micro-asperity amplitudes important, but also that the indicated micro-asperity densities are important with these textures. The true relationship existing between microtexture and wet friction then must be expressed by an integration of the two microtextural components. Apparently, microtexture reaches a maximum with respect to effecting increases in wet friction values. White (1968) hypothesizes the existence of this condition and discusses the general relationship believed to exist between molecular junction forces (adhesion) and microroughness (microtexture).

Figures 21 through 24 show photomicrographs of the surface profiles of the laboratory abraded granite specimens included to illustrate the nature of the microtextures of these surfaces. Microtextural differences are readily discernible even though the rougher surfaces are slightly blurred because of double imagery.

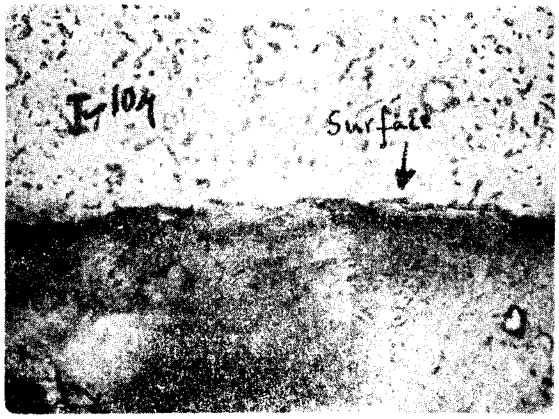

Figure 21. Microcline feldspar abraded with 75 μ abrasive. (x 100, plane polarized light).

Figure 22. Microcline feldspar abraded with 22 μ abrasive. (x 500, plane polarized light.)

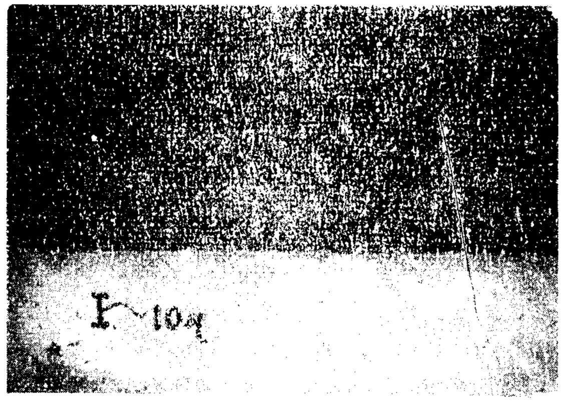

Figure 23. Microcline feldspar abraded with 12 μ abrasive. (x 500, cross-polarized light.)

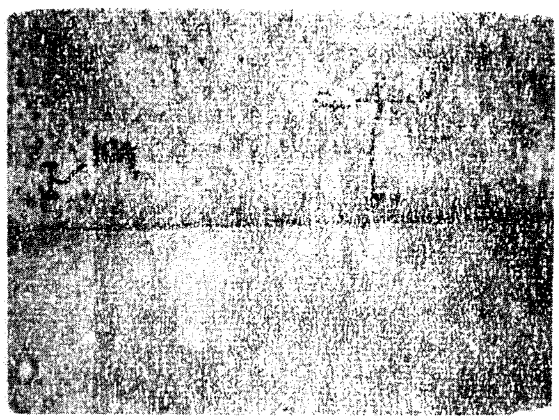

Figure 24. Microcline feldspar abraded with 5 μ abrasive. (x 500, plane polarized light.)

A PROPOSED CLASSIFICATION OF AGGREGATES BASED ON WEARING PROPERTIES

General

Based upon the preceding discussion a classification of aggregates based on wear is proposed. Figure 25 illustrates the classification scheme and the aggregates and textures which fall into the individual classes. It is based on the results of detailed macroscopic and microscopic analyses of the worn surfaces of individual aggregate particles.

Aggregates have been classified into three categories (see Figure 25) based on petrographic properties and wearing characteristics: (A) homogeneous aggregates wearing predominantly by abrasion, (B) aggregates with marked structural weaknesses wearing predominantly by degradation and (C) intermediate aggregates wearing by both abrasion and degradation. Types A and C are also subdivided into soft and hard members.

Criteria Used for Aggregate Classification

Abrading Aggregates -- Soft Variety

The soft variety of abrading aggregates wear rapidly and are quite polish susceptible. Characteristically, these aggregates are; (1) soft (≤ 3 on Moh's scale), (2) dense, and (3) physically homogeneous, i.e. essentially devoid of exceptionally hard mineral grains, fractures, or other planar weaknesses.

Typically, well indurated carbonate rocks possessing low insoluble residue contents or no hard insolubles greater than clay size (none $> 6\ \mu$) fall into this class of aggregates. Carbonates S41, already discussed, and S43 are examples. Figure 26 shows a photomicrograph of the profile of a worn S43 particle. With increases in either coarse insolubles or zones of weak material these rocks might shown preceptible degradation.

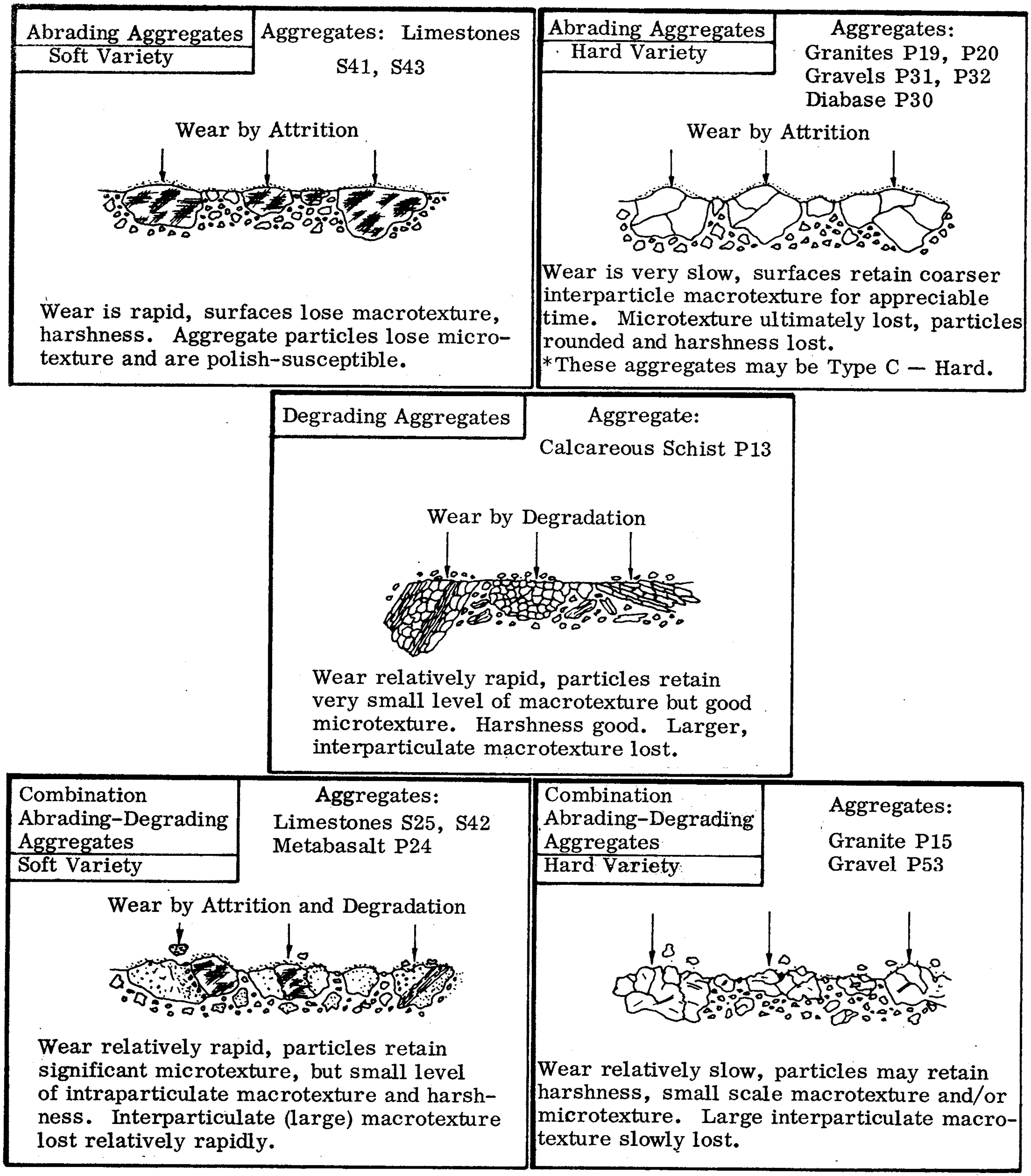

Figure 25. **Diagrams of worn aggregate profiles showing the petrographic properties and resultant wear, characteristic of each aggregate type.**

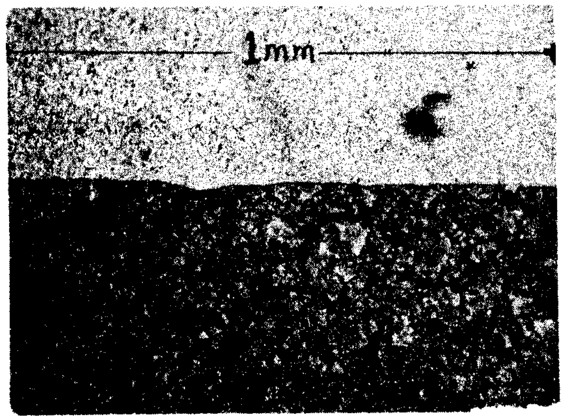

Figure 26. Photomicrograph of the profile of a polished S43 particle. A microcrystalline, slightly clayey, limestone (x 72, plane polarized light).

Abrading Aggregates — Hard Variety

These aggregates are characteristically; (1) hard ($\gtrsim$ 5 on Moh's scale), (2) dense, and (3) devoid of significant microfractures, joints, schistosity, or other planes of weakness. In addition, soft or weak minerals such as mica, clay, etc. are minor or absent and grain bonds are strong. The presence of homogeneous, resistant mineral constituents, while tending to polish, will wear so slowly that these aggregates may retain adequate skid resistance for long periods of time.

Granitic rocks P19 and P20, diabase P30, and gravels P31*, and P32* were observed to fall into this class. P19 was discussed earlier under mechanisms of wear. Figures 27 and 28 show photomicrographs of worn particle profiles of P20 and P30, respectively.

*These are marginal to Type C (hard) aggregates.

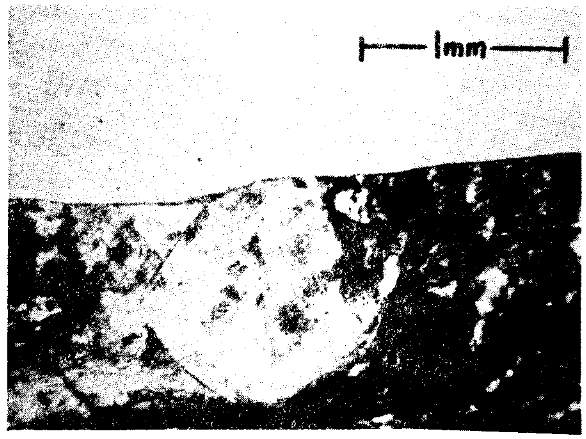

Figure 27. Photomicrograph of a cross section of worn P20 aggregate, an augen gneiss. It is seen that physical differences among the constituents are not significant and as a result microtexture is slight. Large porphyroclast is microcline marginally granulated with formation of secondary quartz and saussurite. (x 24, plane polarized light.)

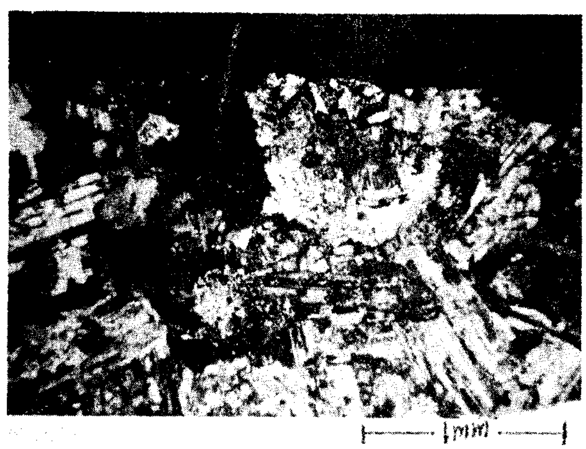

Figure 28. Photomicrograph of a cross section of a worn, highly chloritized-sericitized, massive region of P30, a pyroxene diabase. Areas such as these are abundant in this rock and are polished-to-subpolished. (x 24, cross polarized light.)

Degrading Aggregates

This group of aggregates are those which wear predominantly by the process of particle loss or degradation. The primary criteria for inclusion in this category are the presence of some or all of the following; (1) structural weaknesses in the form of abundant weak minerals such as mica, clay, etc.; (2) planar weaknesses in the form of schistosity planes lined with platy minerals, joints, fractures, etc. and (3) weak grain bonds resulting from the absence of a cementing agent or the presence of a weak cementing agent such as clay.

Schistose carbonate P13 was the only aggregate studied and observed to fall distinctly into this class. Its petrographic and resulting physical properties are primarily (1) and (2) above. Weakly cemented sandstones would also typically fall into this class.

A few weakly cemented graywacke particles were identified in aggregate S53. These particles serve to illustrate the importance of grain bonds and cementation. The graywacke particles possess an abundance of limonite-clay cementing quartz and microcline grains. This imparts a physical weakness to the particles, allowing grains to "pluck" from the surface. However, because of the added presence of authigenic silica cement, such weaknesses are restricted. Figures 29 and 30 illustrate these particles which might wear by degradation, in cases where silica cement is minor or absent.

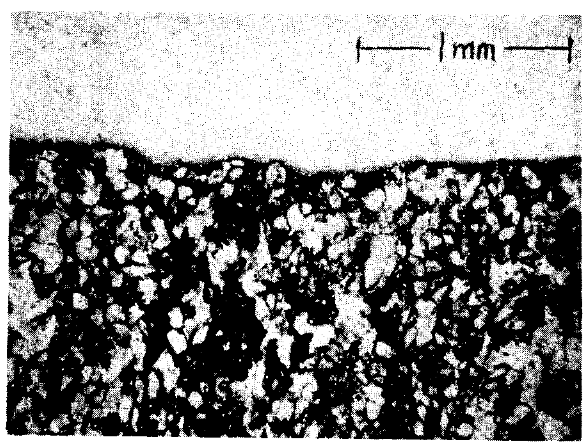

Figure 29. Photomicrograph showing cross section of a worn S53 sandstone particle. Particle is a graywacke with approximately 30% detrital microcline, 40% quartz, 30% clay, silt, and liminite. Note the intergranular grain loss and differential wear between the siliceous (light) grains and clayey (dark) areas. The larger, lighter areas are siliceous grains and areas of authigenic silica cementation. (x 24, plane polarized light.)

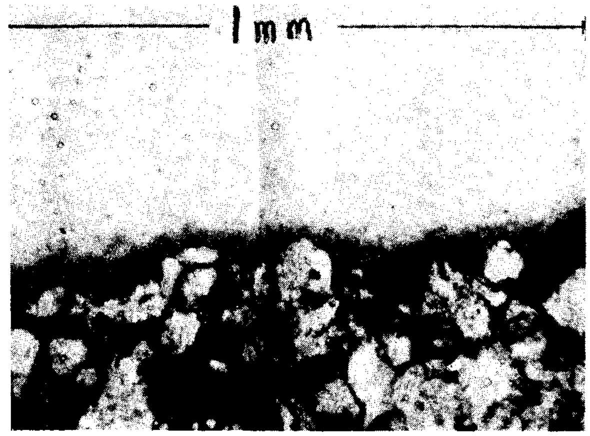

Figure 30. Same as Figure 29 except at higher magnification. Note the quartz and microcline grains produce a harsh microtexture and the relief developed where interstitial clay and limonite wear rapidly and grains have been plucked. Authigenic quartz is particularly visible at lower right. (x72, plane polarized light.)

Combination Abrading-Degrading Aggregates — Soft Variety

Most aggregates wear by a combination of abrasion and degradation. The soft variety, differs from soft abrading aggregates by containing; (1) significant amounts of coarse, hard grains in the soft matrix and/or (2) zones or planes of weakness. These allow the aggregate to degrade as well as abrade under the action of rubber tired traffic. The Catoctin greenstone and two of the carbonates studied fall into this class. The greenstone contains hard epidote grains set in a relatively soft and weak schistose, chlorite matrix.

Of the carbonates, S25 incorporates both coarse insolubles and zones and planes of weakness while S42 contains primarily coarse insolubles and fewer zones of weakness. By weight, S25 contains on the average 23% total insoluble residues with 7% by weight greater than 53 μ in size while S42 contains 18% total insoluble and 4.5% greater than 53 μ in size (Sherwood — 1959). Figures 31 through 34 illustrate the wearing characteristics of carbonate S25 and Figures 35 and 36 those of greenstone, P24.

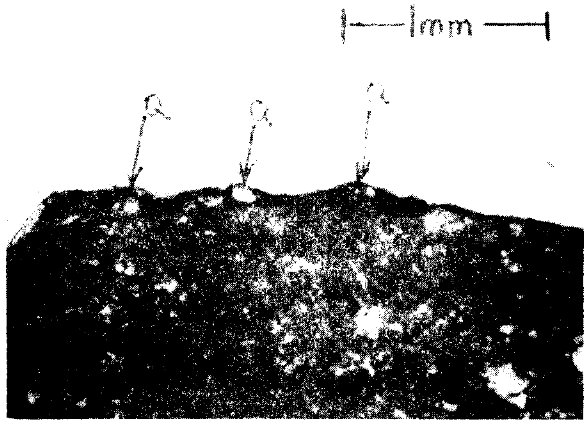

Figure 31. Photomicrograph showing quartz grains (Q) exposed at the worn surface of an S25 dolomite particle. Note the microtexture development due to intergranular differential wear between the quartz grains and the darker, clayey dolomite matrix. (x 24, plane polarized light.)

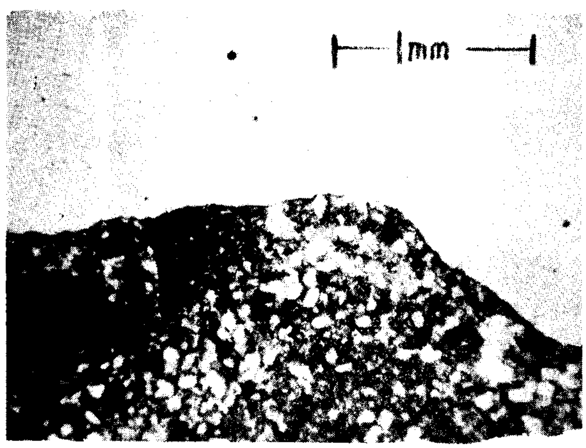

Figure 32. Photomicrograph of cross section of a worn, microcline and quartz-rich particle of S25 dolomite. Note the bedding plane separating the siliceous, detrital zone on the right from the finer grained, clayey dolomite, siliceous zone on the left. Evidence for fracturing and loss of a fracture fragment is seen at right. (x 24, plane polarized light.)

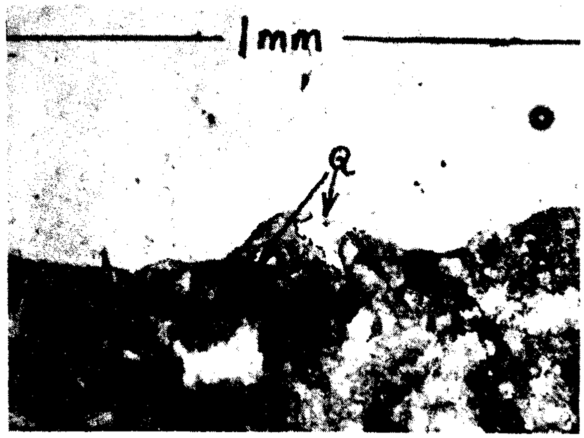

Figure 33. Photomicrograph of cross section of a worn S25 dolomite particle. The "Q" and arrows designate quartz thought to be replacing dolomite. The lightest areas are quartz. The intermediately dark areas are sparry dolomite. The darker and black areas are clay zones. Note the lows where the clay zones are wearing more rapidly than the adjacent siliceous dolomite zones. (x72, plane polarized light.)

Figure 34. Photomicrograph of the cross section of a worn S25 particle. Predominantly microcrystalline dolomite and clay, cut by sparry veins and joints (x24, plane polarized light; surface very slightly disturbed).

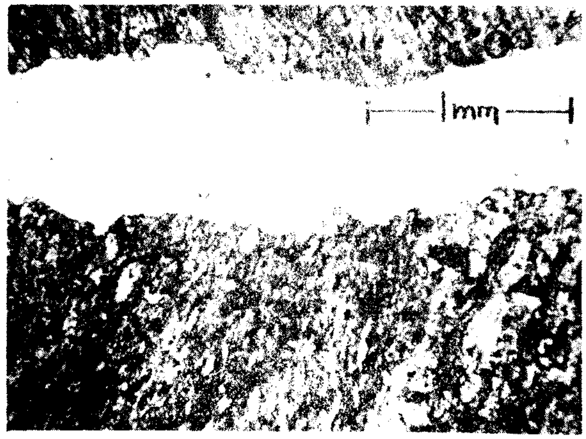

Figure 35. Photomicrograph of the cross section(s) of a worn schistose greenstone particle. Schistosity almost perpendicular to surface. Highs of epidote, actinolite-tremolite, and plagioclase. Lows formed where chlorite has worn rapidly or fragment has plucked from surface. (x 24, plane polarized light.)

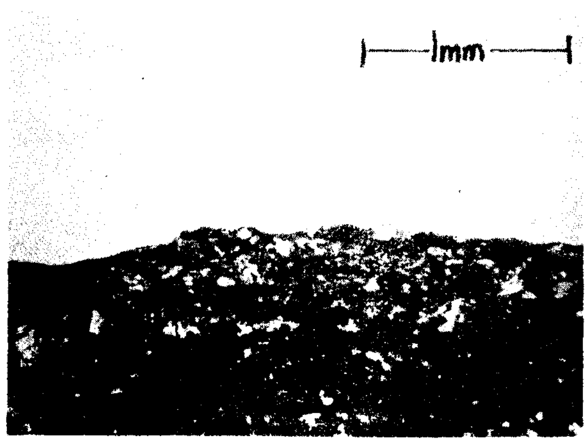

Figure 36. Photomicrograph of cross section of a worn greenstone particle. Asperities on surface consist of epidote and/or plagioclase set in chloritic ground-mass. (x 24, plane polarized light.)

Combination Abrading-Degrading Aggregates — Hard Variety

Aggregates of this type typically possess; (1) competent, indurated or cemented areas of hard minerals ($\geq$ 5 on Moh's scale), (2) subordinate fractures, bedding planes, etc., (3) soft mineral zones ($\leq$ about 3 on Moh's scale), and (4) restricted, weak grain bonds. In possessing these features an aggregate will tend to wear by both abrasion and degradation. Given this mode of wear together with the hardness of the mineral constituents, polishing is likely to be at a minimum and high skid resistance will result.

Granite aggregate P15, discussed earlier, is representative of this type, also gravel S53 falls into this class — the particles being cemented largely by hard silica. Figure 37 illustrates the wearing characteristics of S53, a competent, variably cemented, relatively pure, quartzose sandstone particle.

Figure 37. Photomicrograph of a cross section of a worn particle of S53. Note the limited, but effective, grain loss and presence of variable grain boundary distinction. Limonite is present interstitially where well-defined grain boundaries exist. (Dark fringe along surface is due to the bleeding into the epoxy of the ink used in marking the cutting line.) (x 24, plane polarized light.)

Limitations

It is realized that there are many aggregates which may be borderline between two types. Such aggregates will either be borderline to A (soft) and C (soft), or A (hard) and C (hard). The most critical case would be that of A (soft) and C (soft) because wear for these aggregates is quite rapid. A (hard) and C (hard), both wear slowly, and a petrographic misclassification would probably not be realized for a considerable period of time, if at all. Evaluation of worn aggregate particles, source homogeneity, and skid results would eliminate most potential misclassifications.

CONCLUSIONS

The points offered here are the outgrowth of a combination of several input factors. As always, the work of previous investigators, both at the Virginia Highway Research Council and elsewhere, provided indispensable background information. This material together with the findings and interpretations resulting from the present work have provided the basis for the following conclusions:

(1) Mineral aggregates representing different rock types were found to show widely different surface textures when worn by highway traffic.

(2) Aggregate textures can be described as intraparticle and interparticle in nature. The finer intraparticle asperities are generally referred to as microtexture and the coarser, interparticle asperities as macrotexture.

(3) The ability of an aggregate to retain these textural elements is dependent on its mineralogy, texture and fabric, i.e. its petrographic properties.

(4) Depending on the fundamental lithologic properties involved, aggregates wear by; (1) abrasion, (2) degradation, and (3) a combination of abrasion and degradation. The dominant tire induced stresses thought to be involved are respectively: (1) tangential, (2) vertical, and (3) a combination of tangential and vertical components.

(5) A classification of mineral aggregates based on petrographic properties and wearing characteristics is proposed:

   (a) Aggregates with homogeneous texture and few planes or zones of weakness tend to wear dominantly by abrasion. Such aggregates are likely to become polished under traffic, the rate being dependent upon the relative hardness of the minerals involved.

   (b) Aggregates containing abundant zones and planes of weakness tend to wear by the process of degradation or particle removal. This constant surface renewal largely excludes polishing.

   (c) Aggregates wearing by both abrasion and degradation are intermediate with respect to physical structure and wear by a combination of abrasion and particle removal.

(6) A combination of macro- and micro-asperities are required for optimum wet pavement friction. Macro-asperities contribute to the drainage properties and hysterisis component of friction while micro-asperities contribute dominantly to the molecular attraction or adhesion component.

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REFERENCES

Allen, Rhesa M. Jr., 1963, Geology and mineral resources of Greene and Madison Counties: Virginia Division of Mineral Resources, Bull. 78, 102 pp.

Allen, T. M., and Dillard, J. H., 1960, Measurements of pavement friction by a decelerometer: Hwy. Research Bd., Bull. 264, pp. 27-35.

Bowden, F. P., and Tabor, D., 1956, Friction and lubrication: Methuen's Monographs on Physical Subjects, London, Methuen and Co. Ltd; N. Y., John Wiley and Sons, Inc., 150 pp.

Brent, William B., 1960, Geology and mineral resources of Rockingham County: Virginia Division of Mineral Resources, Bull. 76, 174 pp.

Brown, Carl B., 1937, Outline of the geology and mineral Resources of Goochland County, Virginia: Virginia Geological Survey, Bull. 48, 68 pp.

Brown, M. G., and Finney, E. A., 1958, Michigan's skid testing program: Hwy. Research Bd., Bull. 186, pp. 54-57.

Brown, William Randall, 1958, Geology and mineral resources of the Lynchburg Quadrangle Virginia: Virginia Division of Mineral Resources, Bull. 74, 99 pp.

Burnett, W. C., Gibson, J. L., and Kearney, E. J., 1968, Skid resistance of bituminous surfaces: Hwy. Research Bd. Rec. No. 236, pp. 49-60.

Clemmer, H. F., and Smith, N. G., 1958, Supplemental tests of pavement skidding resistance with a three-wheel trailer: Hwy. Research Bd., Bull. 186, pp. 48-53.

Close, Wm., 1961, Lock-wheel friction tests on wet pavements: Hwy. Research Bd., Bull. 302, pp. 18-34.

Colley, B. E., Christensen, A. P., and Nowlen, W. J., 1969, Factors affecting skid resistance and safety of concrete pavements: Hwy. Research Bd., Special Rept. 101, pp. 80-89.

Commonwealth of Virginia, Dept. of Highways, 1968, Average daily traffic volumes on interstate, arterial and primary routes, 138 pp.

Commonwealth of Virginia, Dept. of Highways, 1966, Road and bridge specifications, 546 pp.

Csathy, T. I., 1964, Skidding and skid resistance, Ontario Dept. of Hwys., Report No. 46, 85 pp.

Dillard, J. H., 1958, Supplemental pavement skidding tests in Virginia: Hwy. Research Bd., Bull. 186, pp. 46-47.

Finney, E. A., and Brown, M. G., 1959, Relative skid resistance of pavement surfaces based on Michigan's experience: First Int. Skid Prev. Conf., Proc. Part II, pp. 435-457.

Gallaway, B. M., and Harper, W. J., 1968, Laboratory considerations for the use of lightweight aggregates for hot-mix asphalt pavements: Hwy. Research Bd., Rec. No. 236, pp. 61-75.

Giles, C. G., and Sabey, Barbara E., 1959, Recent investigations on the role of rubber hysteresis in skidding resistance measurements: First Int. Skid Prev. Conf., Proc. Part II, pp. 219-225.

Gooch, E. O., Wood, R. S., and Parrott, W. T., 1960, Sources of aggregate used in Virginia highway construction: Mineral Resources Rept. 1, Virginia Division of Mineral Resources, 65 pp.

Gray, J. E., and Goldbeck, A. T., 1959, Skid proofing of asphaltic concrete pavement surfaces: reprinted from Crushed Stone Jour., 11 pp.

___________, and Renninger, J. A., 1960, Limestones with excellent non-skid properties: Crushed Stone Jour., vol. XXXV, No. 4, pp. 6-11.

___________, 1963, Limestone and dolomite sands in skid resistant portland cement mortar surfaces: Research Rept., Nat'l. Crushed Stone assoc., Sept. 1963, 16 pp.

Hurlbut, Cornelius S., Jr., Dana's manual of mineralogy, 17th Ed.: London, John Wiley and Sons, Inc., 609 pp.

Hveem, F. N., 1960, Devices for recording and evaluating pavement roughness: Hwy. Research Bd., Bull. 264, pp. 1-26.

Hyyppa, J. M. I., 1969, The polishing of mineral aggregate in road surfacings: The State Institute for Tech. Research, 47 pp.

Kerr, Paul F., 1959, Optical mineralogy, 3rd Ed.: N. Y., McGraw-Hill Book Co., 442 pp.

Klein, Kenneth M., and Brown, W. J., 1939, Skid-resistant characteristics of Oregon pavement surfaces: Oregon State Hwy. Dept., Tech. Rept. No. 39-5, 78 pp.

Knill, Diane G., 1959, Petrographical aspects of the polishing of natural roadstones, Journal of Applied Chemistry, Vol. 10, No. 1, pp. 28-35.

Kummer, H. W., 1966, Unified theory of rubber and tire friction: The Penn. State University, Engineering Research Bull. B-94, 132 pp.

_______________, and Meyer, W. E., 1967, Tentative skid-resistance requirements for main rural highways: National Coop. Hwy. Research Program Rept. No. 37, 80 pp.

Maclean, D. J., and Shergold, F. A., 1959, The polishing of roadstones in relation to their selection for use in road surfaces: First Int. Skid Prev. Conf., Proc. Part II, pp. 497-506.

Marian, J. E., 1963, Surface texture in relation to adhesive bonding: Am. Soc. Testing Mat'ls., Mat'ls. Sci. Ser. 4, Spec. Techn. Pub. No. 340, pp. 122-149.

Marshall, A. F., Jr., and Gartner, W., Jr., 1962, Skid characteristics of Florida pavements determined by Tapley decelerometer and actual stopping distances: Hwy. Research Bd., Bull. 348, pp. 1-17.

Mercer, Samuel, Jr., 1958, Locked wheel skid performance of various tires on clean, dry road surfaces: Hwy. Research Bd., Bull. 186, pp. 8-25.

Meyer, W. E., and Kummer, H. W., 1969, Pavement friction and temperature effects: Hwy. Research Bd., Special Rept. 101, pp. 47-55.

Meyertons, Carl Theile, 1963, Triassic formations of the Danville Basin: Virginia Division of Mineral Resources, Rept. of Invest. 6, 65 pp.

Michael, Harold L., 1959, Effects of pavement type and composition on slipperiness — a summary of research in Indiana: First Int. Skid Prev. Conf., Proc. Part II, pp. 485-487.

Mills, John A., III, 1969, A skid resistance study in four western states: Hwy. Research Bd., Special Rept. 101, pp. 3-17.

Moore, Desmond, F., 1966, Prediction of skid-resistance gradient and drainage characteristics for pavements: Hwy. Research Bd., Rec. No. 131, pp. 181-203.

_________________, 1969, The logical design of optimum skid-resistant surfaces: Hwy. Research Bd., Spec. Rept. 101, pp. 39-45.

_________________, 1969, Recommendations for an international minimum skid-resistance for pavements: Hwy. Research Bd., Spec. Rept. 101, pp. 35-38.

Moyer, R. A., 1934, Skidding characteristics of automobile tires on roadway surfaces and their relation to highway safety, Bull. 120, Iowa Engineering Experiment Station, Iowa State College, Ames, Iowa, 58 pp.

____________, 1959, A review of the variables effecting pavement slipperiness: First Int. Skid Conf., Proc. Part II, pp. 411-433.

______________, 1959, Effects of pavement type and composition on slipperiness — California experience: First Int. Skid Conf., Proc. Part II, pp. 469-484.

______________, and Shupe, John W., 1951, Roughness and skid resistance measurements of pavements in California: Hwy. Research Bd., Bull. 37, pp. 1-35.

Nelson, Wilbur A., 1962, Geology and mineral resources of Albemarle County, Virginia: Virginia Division of Mineral Resources, Bull. 77, 92 pp.

Nichols, F. P., Jr., 1959, Further studies on skid resistance of Virginia pavements: First Int. Skid Conf., Proc. Part II, pp. 461-468.

______________, Dillard, J. H., and Alwood, R. L., 1957, Skid resistant pavements in Virginia: Virginia Council of Hwy. Investigation and Research, Reprint 18, 59 pp.

Pettijohn, F. J., 1957, Sedimentary rocks, 2nd Ed: N. Y., Harper and Row, 718 pp.

Powers, M. C., 1953, A new roundness scale for sedimentary particles, J. Sediment. Petrol., Vol. 23, pp. 117-119.

Rose, Jerry G., Hankins, Kenneth D., and Gallaway, Bob M., 1969, Macro-texture measurements and related skid resistance at speeds from 20 to 60 mph: Texas Transportation Institute, Texas A & M University, Texas Hwy. Dept., paper presented at 49th Annual Meeting of the Hwy. Research Bd., Jan. 1970, 17 pp.

Sabey, Barbara E., 1959, Pressure distributions beneath spherical and conical shapes pressed into a rubber plane, and their bearing on coefficients of friction under wet conditions: First Int. Skid Conf., Proc. Part II, pp. 539-546.

________________, and Lupton, G. N., 1967, Measurement of road surface texture using photogrammetry: Road Research Laboratory, Ministry of Transport, RRL Report LR57, 21 pp.

Schonfeld, R., 1969, Photo-interpretation of skid resistance: Dept. of Highways, Ontario, paper presented at 49th Annual Meeting of the Hwy. Research Bd., 1970, 22 pp.

Shelburne, T. E., and Sheppe, R. L., Skid resistance measurements of Virginia pavements: Hwy. Research Bd., Res. Rept. 5-B, 27 pp.

Sherwood, W. C., 1959, A study of the crystallization and mineral content of some Virginia limestones with possible relationship to their skid resistance performance: Progress Rept. No. 1, Virginia Council of Hwy. Investigation and Research, 30 pp.

____________________, and Mahone, D. C., 1969, Predetermining the polish resistance of limestone aggregates: Virginia Hwy. Research Council, paper offered for presentation at the 49th Annual Meeting of the Hwy. Research Bd., Jan. 1970, 17 pp.

Shupe, J. W., and Lounsbury, R. W., 1959, Polishing characteristics of mineral aggregates: First Int. Skid Conf., Proc. Part II, pp. 509-536.

Skeels, P. C., 1958, Measurement of pavement skidding resistance by means of a simple two-wheel trailer: Hwy. Research Bd., Bull. 186, pp. 35-45.

Steidtmann, Edward, 1945, Commercial granites and other crystalline rocks of Virginia: Virginia Geol. Survey, Bull. 64, 151 pp.

Stephens, J. E., and Goetz, Wm. H., 1961, Effects of aggregate factors on pavement friction: Hwy. Research Bd., Bull. 302, pp. 1-17.

Stiffler, A. Kent, 1969, Relation between wear and physical properties of roadstones: Hwy. Research Bd., Special Rept. 101, pp. 56-68.

Stutzenberger, Wm. J., and Havens, James H., 1958, A study of the polishing characteristics of limestone and sandstone aggregates in regard to pavement slipperiness: Hwy. Research Bd., Bull. 186, pp. 58-81.

Tabor, D., 1959, The importance of hysteresis losses in the friction of lubricated rubber: First Int. Skid Conf., Proc. Part II, pp. 211-218.

Toewe, Clayton E., 1966, Geology of the Leesburg Quadrangle Virginia: Virginia Division of Mineral Resources, Rept. of Invest. 11, 52 pp.

Tons, Egons, and Goetz, Wm. H., 1968, Packing volume concept for aggregates: Hwy. Research Bd., Rec. No. 236, pp. 76-96.

Van der Burgh, A. J. P., and Obertop, D. H. F., 1959, Surface texture and non-skid properties of road surfaces: First Int. Skid Conf., Proc., Part II, pp. 489-495.

Webb, John W., 1970, The wearing properties of mineral aggregates in highway surfaces: unpublished master's thesis, University of Virginia, 84 pp.

White, A. M., and Thompson, H. O., 1958, Test for coefficient of friction by skidding car method on wet and dry surfaces: Hwy. Research Bd., Bull. 186, pp. 26-34.

White, David L., 1968, The effects of roadstone microroughness on rubber friction: Joint Road Friction Program, Penn. Dept. of Hwys., Penn. State University, Rept. No. 316, Nov. 1968, 79 pp.

Whitehurst, E. A., and Goodwin, W. A., 1958, A device for determining relative potential slipperiness of pavement mixtures: Hwy. Research Bd., Bull. 186, pp. 1-7.

Williams, Howel, Turner, Francis J., and Gilbert, Charles M., 1954, Petrography: San Francisco, W. H. Freeman and Co., 406 pp.

Zube, Ernest, and Skog, John, 1968, Skid resistance of screenings for seal coats: Hwy. Research Bd., Rec. No. 236, pp. 29-48.

APPENDICES

APPENDIX I

GLOSSARY OF TERMS

Adhesion Losses — The component of friction equivalent to the shear strength of the interface boundary between two bodies. The magnitude is dictated by the number of molecular junctions occurring at the interface. The number of junctions for wet surfaces is controlled by the harshness and/or microtexture of the surfaces.

BPN — British pendulum number, equivalent to the coefficient of friction x 100 and obtained using a British pendulum tester. The speed of the slider is 6-7 mph.

Coefficient of Friction — Friction force divided by the normal load. Range from 0 to 1 as friction increases.

Friction Force — The resistance to motion in a direction parallel to the plane of contact between two bodies.

Hysteresis Losses — The component of friction derived from the energy losses associated with the macroscopic deformation of rubber. Macrotexture is mainly responsible for this component.

Interparticulate — Between particles, i.e., between individual rock particles in a pavement surface.

Intraparticulate — Within, or upon, a given rock particle.

Particle — Rock particle in this study, and referring to a single piece of rock or mineral aggregate which is representative of all other such aggregate in the pavement surface.

Macro-asperity — A surface projection readily distinguished with the unaided eye. In this study generally considered greater than 0.2 mm or much larger commonly up to 4 or 5 mm) in height (amplitude). Can be intraparticulate or interparticulate.

Macrotexture — A combination of macro-asperity amplitudes and frequencies and used in a general sense. Also, there are inter- and intraparticulate macrotextures.

Micro-asperity — A surface projection, less than 0.2 mm in height or amplitude.

Microtexture — A combination of micro-asperity amplitudes and frequencies, used in a general sense. There is only intraparticulate microtexture in this study.

Wet Skid Resistance — Wet coefficient of friction x 100, obtained upon a pavement surface by field methods. A skid trailer was used in this study and tests were performed at a sliding speed of 40 mph. A minimum value of 40 is considered critical.

Wear — A volume loss resulting from traffic stresses. Also the configuration attained by aggregate particles under the action of traffic.

APPENDIX II

LABORATORY POLISHING PROCEDURES

The laboratory polished specimens were wet ground with 75 μ , 22 μ , and 12 silicon carbide abrasives and a 5 μ aluminum oxide abrasive compound. The medium of the abrasive compound was lightweight oil for the core specimens and water for the glass plates. Core specimens were composed of predominantly coarse microcline feldspar fragments (granite) and a fine sand-cement mortar. The core specimens were polished on a lapwheel and mechanically held in place. Polishing time varied between one and two hours.

The glass plates were polished by hand using a figure eight pattern and a metallic plate to move the abrasive-water mixture over the surface. Polishing time generally was 5 to 30 minutes, or more for the finer abrasives. Visual inspection of the glass and core surfaces and friction stability were the primary methods used to determine whether or not a stable degree of polish had been achieved.

Figure 38 shows the observed relationships between abrasive size and the measured properties — maximum asperity amplitude and density of asperities $\geq 3\ \mu$ per square millimeter. Obviously, if abrasive size had continued to increase the density value would have leveled off and began to drop to the right.

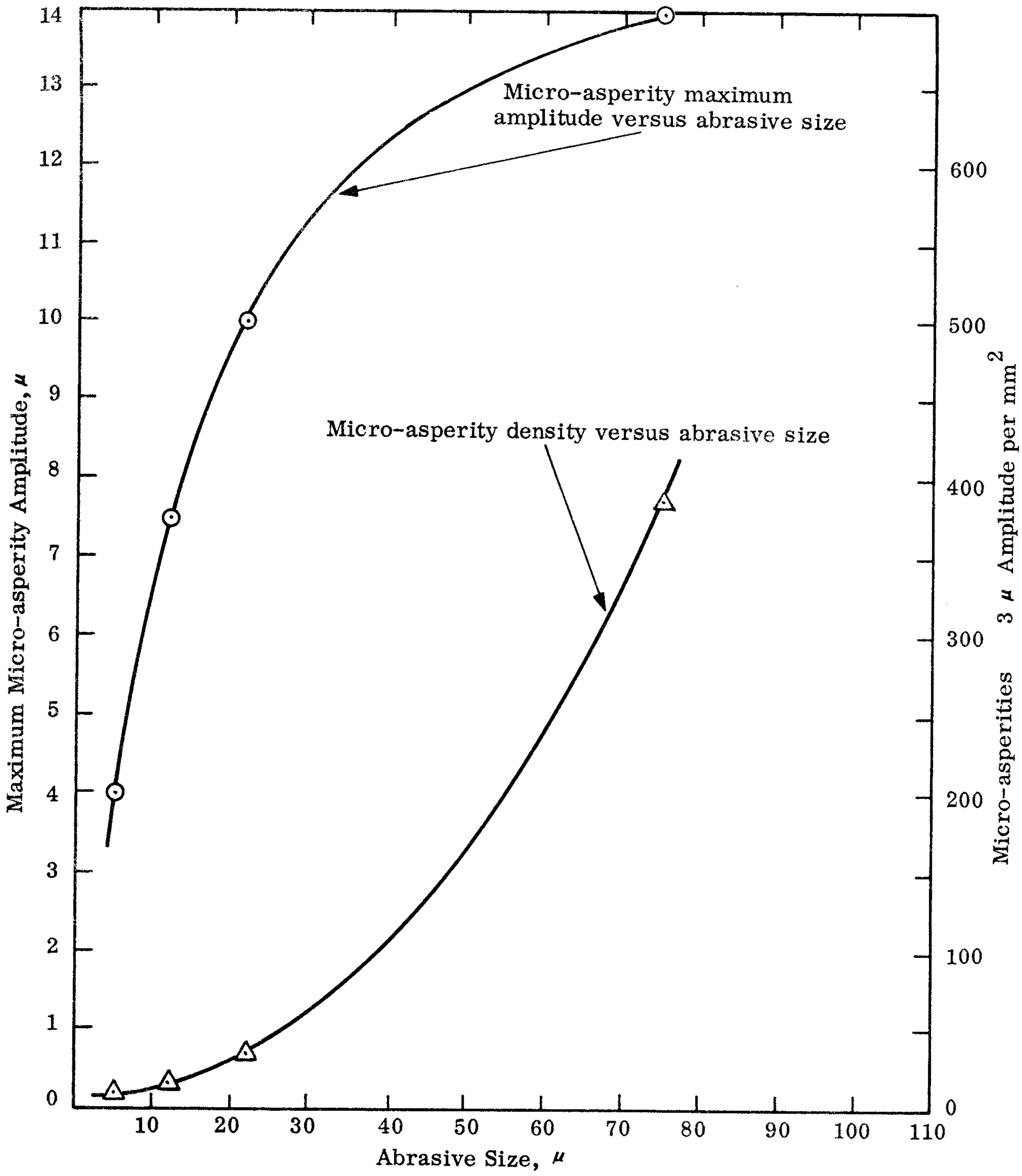

Figure 38. Microtexture versus abrasive size.

APPENDIX III

LABORATORY WET FRICTION DETERMINATIONS

The British Pendulum Tester

In addition to the skid trailer tests, it was believed that selected laboratory wet friction tests would be more meaningful for the reasons given in the Procedures section.

For such testing, a portable tester known as the British Pendulum Tester was used (Figure 39). Simply stated, this apparatus consists of a pendulum with a spring-loaded rubber slider mounted at one end. The pendulum in dropping from a constant height and striking a constant surface area with its rubber slider, completes its swing to a degree proportional to the difference between its initial energy and the energy expended in sliding over the specimen surface. The decreased resulting energy of the pendulum is measured by an indicator needle which is mechanically activated by the pendulum as it passes through its point of lowest swing. The needle comes to rest at the point where the pendulum reaches its maximum forward swing, and the British Pendulum Number is read off an arc-scale opposite the needle point.

Normally, contact areas are adjusted between the rubber slider and specimen surface so that an area 3 inches wide by 5 inches long is contacted. For six-inch pavement cores this was not completely possible, but the contact area was approximately 14.5 square inches for these specimens. Core specimens only four inches in diameter were also tested. These test results were corrected to six-inch core readings by making a calibration curve correlating six-inch core readings with their four-inch equivalents. This was accomplished by conducting pendulum tests on six-inch cores, cutting them to four-inch diameter and again conducting pendulum tests. The resulting calibration curve is seen in Figure 40. Only two four-inch specimens were corrected in this manner in the final analyses.

It is interesting to note, as a check on the validity of Figure 40, that points taken from the estimated "best fit" line come very close to satisfying the equation for friction due primarily to adhesion, or:

$$F_a = s \sum_{i=1}^{n} A_i = sA \quad \text{(Kummer and Meyer, 1967)}$$

where:

F_a = friction due to adhesion; for six-inch cores = BPN_L; for four-inch cores = BPN_S

A_i = contact area with given asperity

n = number of asperities contacted

A = lumped, actual contact area; for six-inch cores = A_L; for four-inch cores = A_S

s = shear strength of interface, constant

and

$$s = BPN_L/A_L = BPN_S/A_S \text{ for a given point.}$$

Solving the equation yields very close to equality, indicating that the BPN's are mostly the result of the adhesion component of friction and to a reasonable degree verifying the calibration curve of Figure 40.

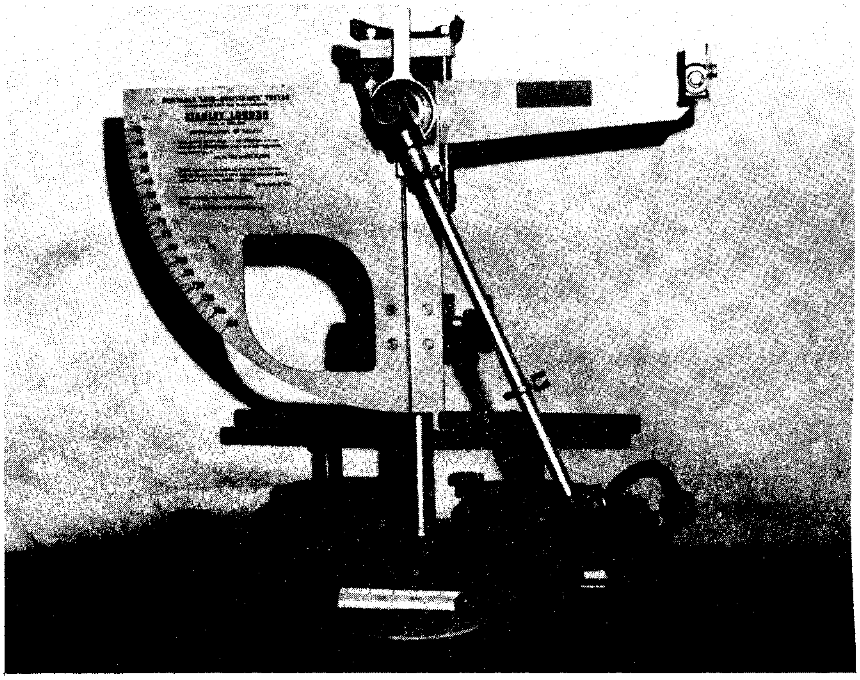

Figure 39. British Pendulum Tester

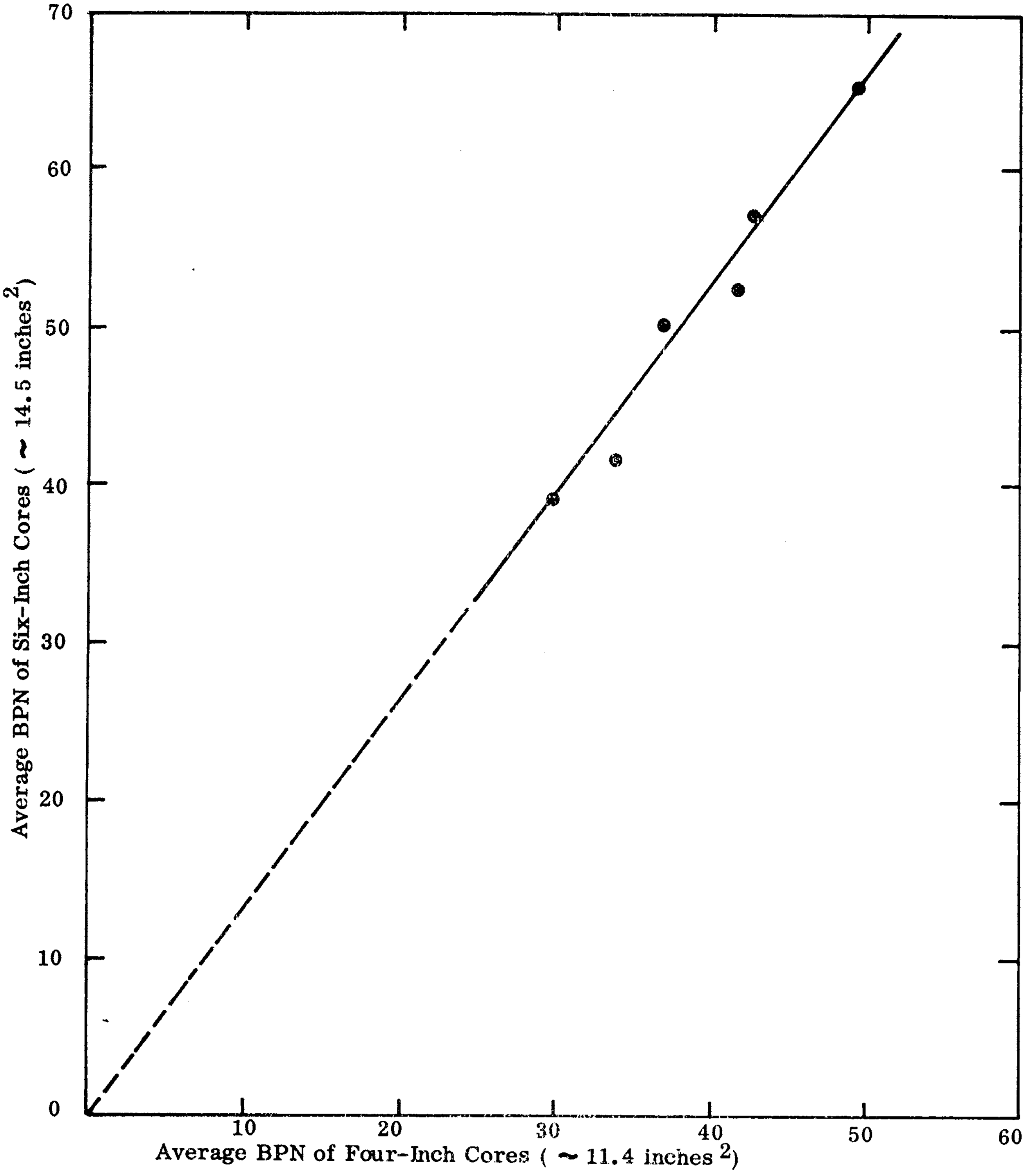

Figure 40. Calibration curve for BPN of cores.

APPENDIX IV

GRADATIONS, AGES, TRAFFIC VOLUMES, FRICTION VALUES, AND TEXTURE MEASUREMENTS FOR SURFACES AND AGGREGATES

TABLE I

SURFACE TYPES, GRADATIONS

Va. Dept. of Hwys. Design (1966)	Percentage Finer than U. S. Standard Sieve Size									
	1 in.	3/4 in.	1/2 in.	3/8 in.	#4	#8	#30	#50	#100	#200
S-1					100	95-100	50-95	25-65	8-25	0-8
S-5			100	80-100	50-70	35-55	15-30	7-22	3-15	2-10
I-2	100	95-100	—	60-80	40-60	25-45	—	5-14	2-9	
Others including Portland Cement Concrete; Bituminous Surface Treatment	Variable									

TABLE II

SURFACE TYPES, AGES AND TRAFFIC VOLUMES FOR SURFACES STUDIED

Pavement or Aggregate	Type	Age (Nearest Year)	Traffic Volume (Vehicles/Day) (1968)	Miscellaneous, *2 Lane — **3 Lane or ***4 Lane Road
P-13-2	S-5	5.0	7,065	***
P-13-1	S-5	6.0	6,310	50% P-13 + #4 sieve 50% S-25 - #4 sieve*
P-20-1	S-5	3.0	2,730	*
P-20-2	S-5	3.0	16,875	***
P-15-1	S-5	4.0	1,625	*
P-15-2	I-2	3.0	1,625	*
P-19-1, P-31-1,) P-32-1, S-43-1 P-30-1	All Portland Cement Concrete	26.0	27,000 ±	***
S-53-1	S-5	10.0	7,000	50% S-53 = +4 sieve 50% 1s = -#4 sieve *
S-53-2	S-1	2.0	11,350	**
S-53-3	S-5	5.0	2,320	*
P-24-1	S-5	3.0	10,000	***
P-24-2	S-5	3.0	5,200	*
S-41-1	S-5	9.0	600	*
S-42-1	I-2	20.0	2,700	*
S-25-1	S-5	13.0	7,000	***
S-25-2	S-5	6.0	7,000	***
1P	Portland Cement Concrete	Treated	8,000-9,000	***
2P	"	Treated	8,000-9,000	***
3P	"	4.0	8,000-9,000	***
4P	"	Treated	8,000-9,000	***
5P	"	Treated	8,000-9,000	***
6P	"	Treated	8,000-9,000	***
7P	"	Treated	8,000-9,000	***
8P	"	Treated	8,000-9,000	***
9P	"	Treated	8,000-9,000	***
10P	"	Treated	8,000-9,000	***
11P	"	4.0	8,000-9,000	***
12P	"	4.0	8,000-9,000	***

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TABLE III

FRICTION AND MACROTEXTURE VALUES

Pavement or Aggregate	Ave. Wet SDN_{20}	Ave. Wet SDN_{40}	Gradient = $\frac{SDN_{20} - SDN_{40}}{20}$	BPN	Max. Amp. Macro-asperity (mm)	$\bar{\lambda} \geq 1$ mm (mm)
P-13-1	60.0	51.5	0.425	53.0	< 3	68.0
P-13-2	57.0	46.0	0.550	50.0	< 2	118.0
P-20-1	—	—	—	—	< 2	42.3
P-20-2	—	—	—	46.0	< 2	111.0
P-15-1	77.0	67.5	0.475	56.0	< 3	28.0
P-15-2	72.0	66.5	0.275	—	< 5	15.8
P-19-1	45.5	42.0	0.175	54.0	< 3	49.0
P-30-1	45.0	37.0	0.400	46.0	< 2	74.0
P-31-1 *	50.0	45.0	0.250	54.0	< 3	74.0
P-32-1	46.0	42.0	0.200	50.0	< 3	44.0
S-43-1	39.0	33.5	0.275	39.0	< 3	41.0
S-53-1	—	59.0	—	54.0	< 4	19.6
S-53-2	—	46.0	—	55.0	< 2	44.0
S-53-3	—	59.5	—	56.0	< 4	18.0
P-24-1	71.0	57.5	0.675	—	< 2	62.0
P-24-2	60.5	48.0	0.625	46.0	< 2	55.0
S-41-1	—	34.5	—	37.5	< 2	67.0
S-42-1	—	47.5	—	—	< 3	73.2
S-25-1	58.5	50.0	0.425	44.0	< 3	28.8
S-25-2	60.0	51.0	0.550	—	< 3	36.4
1P	72.5	61.5	0.550	64.0	< 1	> 100
2P	72.5	63.0	0.461	54.0	< 1	> 100
3P	67.5	55.5	0.600	50.0	< 1	> 100
4P	68.5	55.5	0.650	53.0	< 1	> 100
5P	68.5	56.0	0.625	65.0	< 1	> 100
6P	68.5	58.5	0.500	59.0	< 1	> 100
7P	72.5	55.0	0.625	57.0	< 1	> 100
8P	61.0	48.0	0.650	65.0	< 1	> 100
9P	71.0	59.0	0.600	58.0	< 1	> 100
10P	56.0	44.0	0.600	64.0	< 1	> 100
11P	61.0	48.0	0.650	47.0	< 1	> 100
12P	57.0	47.0	0.500	47.0	< 1	> 100

*Only 6 inch core samples used to measure textures. Texture measurements may not be representative of actual pavement textures in every case. Textures quite variable for a given surface and core to core. Skid tests performed by stopping distance method.

TABLE IV

BPN AND MICROTEXTURE DATA

Aggregate or Surface	BPN	Coarse Aggregate Exposed %	Micro-asperity Density and Maximum Amplitude Respectively
75 μ polished	53.0	50-60	400/mm^2, 14 μ
22 μ polished	34.0	50-60	34/mm^2, 10 μ
12 μ polished	25.0	50-60	16/mm^2, 7.5 μ
5 μ polished	18.0	50-60	12/mm^2, 4 μ
S-43-1	39.0	$\sim$ 40	25/mm^2, $\sim$10 μ ?
S-41-1	37.5	$\sim$ 55	31/mm^2, $\sim$10 μ ?
P-24-2	46.0	$\sim$55	71/mm^2, $>$ 35 μ
11P	47.0	Fine Aggregate	110/mm^2, $>$ 35 μ
3P	50.0	Fine Aggregate	140/mm^2, $>$ 35 μ
P-30-1	46.0	$\sim$35	142/mm^2, $>$ 35 μ
P-13-2	50.0	$\sim$55	200/mm^2, $>$ 35 μ