# Relation Between Wear and Physical Properties of Roadstones

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One aspect in the skid-resistant life of a pavement is the polishing of individual roadstones by abrasives on the road. The related problem studied here is the gradual wear (microscopic scale) of homogeneous roadstones to determine the pertinent physical properties of these minerals in the wear process. Wear is measured as a weight loss of material. A brief review of wear is given. A wide range of concepts exists, most studies pertaining to metals. Some of the important parameters are melting temperature, hardness, elastic modulus, and energy.

Ten mineral samples, predominately oxides, were held against the rubber tracks of a rotating drum in the presence of dry fine abrasives. Three loads and speeds were tested for each of three different abrasives. These test conditions simulated actual pavement experience. Microscopic photographs of worn surfaces revealed two phenomena: scratching and pitting. Rapidly wearing minerals suffered both types of damage while slow wearing minerals displayed no scratching, only a small amount of pitting. Rapid wear occurred when the abrasive was harder than the mineral. Wear was proportional to load and inversely proportional to hardness. The slow wear of minerals softer than the abrasive was independent of load. Limited evidence suggested that this wear depended on the ratio of surface to strain energy in a given mineral. Pitting was related to energy concepts while scratching was related to hardness. No correlation could be achieved between wear and melting temperature or modulus. Hardness was found to be the most important parameter in the rapid wear of homogeneous minerals.

•THE predominant variable in tire-pavement friction during wet conditions is the surface texture of the pavement itself. Skid resistance depends on a surface which provides film penetration and drainage channels. One of the factors which can alter these characteristics is the smoothing and rounding of exposed roadstones by abrasives found on the road. This process is caused by particle removal, or wear, on a microscopic scale, and it is commonly referred to as polishing. The amount of this wear over a period of time can have a direct effect on the skid-resistant life of a pavement.

The problem of concern here is the gradual wear (on a microscopic scale) of homogeneous roadstones which occur as constituents in the heterogeneous aggregate. Specifically, it is the nature of the particle removal from the stone surface. A weight or volume loss of material will be used to define the rate of wear. Attempts will be made to (a) relate the wear to physical properties of material and (b) define the probable wear mechanism. To this extent it would be desirable to duplicate as closely as possible the conditions found on the road.

# NOMENCLATURE

- $A_a$  = apparent contact area;
- $A_0$  = equivalent area of piled-up material on a groove;
- $A_r = real contact area;$
- $A_v =$  area of the vertical face of a groove;

 $c_n = any constant;$ 

- d = diameter of hemispherical wear particle;
- E = elastic modulus;
- **F** = friction force;
- **f** = coefficient of friction;
- $H_{w} = Vicker's hardness;$
- $P_m$  = material flow pressure;
  - S = surface energe of formed wear particle;
- oyp = material yield stress;
  - **V** = sliding velocity;
  - v = volume of wear removal for a given distance of travel;
- W = load; and
- $W_0$  = component of wear removal independent of load.

## WEAR CONCEPTS

The complexity of wear processes has led to a large diversity in both theory and approach to its problems. This state exists even though most researchers have limited themselves to studying metal wear, and it is understandable that highway engineers have neglected analytical aspects of wear since pavement materials are much more complex than metals.

Since wear is concerned with the surface of a material, the contact area between two bodies is important. Enlargement of even the most carefully polished surfaces shows hills (referred to as asperities) and valleys which are large compared to molecular dimensions. Small particles, such as abrasives, dispersed between bodies also are called asperities in this paper. A second solid in contact with the first is supported on the summits of the highest of these asperities so that the area of actual contact is very small. This actual or real area of contact,  $A_r$ , is almost independent of the size of the surfaces and is determined by the load, W.

For loads which exceed the yield point, the deformation is plastic and

$$A_{r} = \frac{W}{P_{m}}$$
(1)

where  $P_m$  is the material flow pressure. Measurements (1) of  $A_r$  show that even the lightest loads are sufficient to produce plastic flow.

The energy expended in overcoming friction between rubbing surfaces is dissipated in the form of heat. Since two surfaces touch only with small contact areas, extremely high temperatures may be reached at the contacting tips (2). Often the temperatures are only limited by the melting point of one of the surfaces.

Abrasive wear occurs when a rough hard surface or a soft surface, containing hard particles, slides on a softer surface and plows a series of grooves in it. The material is thought to be gouged out of the grooves to form loose wear particles. Such gouging involves local deformation. The resistance to deformation is commonly called hardness. To measure it a hard indenter may be pressed into the surface with a known load, and the size of the indentation is measured. The Vicker's indenter, a square pyramid of diamond, is frequently employed in metal hardness determinations. The impression is permanent since the overriding effect is the plastic flow of the metal around the indenter. The Vicker's hardness number, the mean pressure over the area of the indentation, is expressed as

$$H_v = \frac{load}{projected area of indentation}$$

It can be shown (3) that

$$H_v \sim P_m$$
 (2)

a desirable relationship. Other testers or methods to measure hardness, such as those bearing the names of Brinell, Rockwell, or Mohs, employ scales which vary as some power of the flow pressure.

Avient, Goddard, and Wilman (4) abraded a number of metals using a wide size range (5 to 150  $\mu$ ) of emery abrasive. If v is the volume loss for one particle per unit distance of travel, v = (A<sub>V</sub> - A<sub>O</sub>), where A<sub>V</sub> = f(A<sub>r</sub>) is the area of the verticle face of the wear track and A<sub>O</sub> is the equivalent area of the piled-up ridge along the groove. Since the frictional force F = P<sub>m</sub>A<sub>V</sub>,

$$\mathbf{v} = \frac{\mathbf{F}}{\mathbf{P}_{\mathrm{m}}} \left( 1 - \frac{\mathbf{A}_{\mathrm{O}}}{\mathbf{A}_{\mathrm{v}}} \right) \tag{3}$$

Assuming that  $A_0/A_V$  is constant for most metals, and using the fact that F = fW,

$$v = \frac{c_1 W}{P_m}$$
(4)

where the coefficient of friction f depends on the shape of the abrasive particle, but is independent of its size. Mulhearn and Samuels (5) tested silicon carbide abrasive on metals, and their results agreed with Eq. 4.

The abrasive wear in these tests was of the two-body type (abrasive fixed to an adhesive backing), but Rabinowicz et al (6) experimented using a three-body geometry, i.e., the abrasive is loose. The wear was an order of magnitude lower than with two-body abrasion since the grains were rolling about 90 percent of the time. However, the results agreed also with Eq. 4.

Spurr and Newcomb (7) slid various metals against emery paper. The wear of these metals was inversely proportional to the elastic modulus and did not correlate as well with hardness. Microscopic examination revealed that, when a surface is pressed against emery paper and moved a small distance, the abrasive plows through the surface, but no wear particles are formed until sufficient sliding has occurred for a new groove to run into an earlier produced one. When the first abrasive grain slides along the surface, it displaces metal ahead of it, but the metal behind it recovers elastically. The second grain removes the recovered material and the volume removed was related to elasticity:

$$v \sim \frac{W}{E}$$
 (5)

Selwood (8) abraded metals as well as nonmetals against carborundum paper  $(60 \mu)$ . He found that extensible or elastic solids were abrasion resistant and that hardness was a minor factor. For instance, antimony is three times harder than cadmium yet it was abraded more rapidly.

Rabinowicz (9) proposed an interesting theory for particle size formation based upon energy concepts. If a particle breaks loose beneath an asperity the elastic energy stored in the particle while it was being formed must equal or exceed the energy of adhesion which binds it to its substrate. Let T = elastic energy and Y = energy required to create a new surface, then for a hemispherical fragment of diameter d,

$$T \sim \sigma_{yp}^2 \frac{d^3}{E} \tag{6}$$

$$Y \sim Sd^2$$
 (7)

where  $\sigma_{vp}$  is the yield stress and S is the surface energy per unit area. Thus,

$$T \ge Y \text{ or } d \ge \frac{c_2 ES}{\sigma_{yp}^2}$$
 (8)

This parameter may provide a measure of wear resistance although there is no indication of average size or frequency of wear particle detachment. For instance, one of the first useful empirical rating of wear resistance, 1/v, (10) was the property  $\sigma_{vn}/E$ . This property does give some measure of a material's ability to store strain

energy upon deformation.

Most of the above studies were concerned primarily with the wear of metals. Some nonmetallic materials, in particular minerals, are known to possess bulk properties which make them much more brittle than metals. King and Tabor (11) investigated the sliding contact regions of brittle solids and found that the high pressure developed around the deformed region were often sufficient to inhibit brittle fracture. Under these conditions the deformation is primarily plastic, although some cracking and surface fragmentation occurred.

The abrasion of graphite with emery paper (5 to  $150 \mu$ ) by Porgess and Wilman (12) was similar to that of Eq. 4; however, wear did not vary linearly with the friction coefficient f, or abrasive size. Microscopic inspection revealed cracking and fragmentation along the wear grooves. For emery particles larger than  $50\,\mu$  the wear was about four times as much as predicted from metal wear theory. Dobson and Wilman (13) continued the abrasion tests of nonmetals wearing sodium chloride against emery  $\overline{abr}$  asive (0.5 to 150 $\mu$ ). The results agreed with those obtained with graphite in that the proportion of the groove volume removed as wear due to brittle fracture increased with abrasive size. One important new feature was reported though. In the lowest region of abrasive particle size, where a large number of particles share the load and indentations are shallow in the specimen, wear characteristics agree with the studies done on metals. Two types of wear then are distinguished and are thought to be operative in different ranges of the depth of indentation. At depths less than  $0.5 \mu$ , fractures and cracking are negligible, and wear is identical in magnitude to that of metals of the same hardness. In this instance the deformation is entirely plastic. For depths beyond 5u, the wear increases strongly with increasing spread of fractures around the indenting abrasive particle. No attempts were made to relate fracture wear to strain energy properties.

Previously it was noted that frictional heating is often limited only by the melting point of the rubbed surface, particularly for materials with low thermal conductivity. In addition the mechanical strength of most materials at high temperature declines rapidly near the melting point. Can melting temperature than be expected to give a measure of wear between material pairs?

The influence of melting point is very pronounced in work by Bowden (14) where metals were worn with a block of pure camphor (melting point 178 C). The observed wear is given in Table 1. The loss of weight primarily depended on melting point, not hardness. If the melting point of the rubbing material is lower than the rubbed material, the rubbing material will be relatively ineffective. For example calcite (melting point 1330 C) which showed little wear when rubbed with cuprous oxide (melting point 1230 C) was readily worn by zinc oxide (melting point 1800 C). Quartz (melting point 1700 C), which is considerably harder than zinc oxide, was worn by it.

Bowden and Scott (15) studied the wear of glass due to a diamond slider. Wear was negligible below a critical value of  $VW^{\frac{1}{2}}$  where V is the velocity. Surface examination revealed melting, and  $VW^{\frac{1}{2}}$  was related to the melting temperature of the particular glass. The polishing of glass with diamond dust gave the same type of surface deformation as the diamond slider.

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Metal	Melting Point (°C)	Vicker's Hardness (kg/mm²)	Loss of Weight (gr/cm)		
Lead	327	5	<0.1 × 10 <sup>-7</sup>		
Wood's alloy	69	25	3.2 × 10 <sup>-7</sup>		
Gallium	30	6.6	165 × 10-7		

TABLE 1							
MPHOR	BLOCK	SLIDING	ON	METALS			

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This abridged review of wear theory highlights the complexity of wear processes through simplified models and their empirical disagreement. One reason for these discrepancies is the degree of correlation that often exists between the macroscopic properties of hardness, melting temperature and modulus, which ultimately depend upon the atomic structure of the material. Thus, strong atomic bonding promotes high values for these variables. However, relations between wear and more fundamental properties have not evolved.

# PROCEDURE OF THE INVESTIGATION

#### **Experimental Variables**

It is commonly accepted that the tire-pavement wear process is essentially of the three-body abrasion type. Abrasives, present on the road, are probably derived primarily from the pavement itself. Rolling tires provide enough relative motion to abrade the exposed aggregate. To learn more about this process a limited microscopic study was made of the abrasives found on the road and tires of vehicles. The collection was done with adhesive tape. Attention was given to size rather than type. The debris collected from the road surface was dominated by particles in the 5- to  $40^{-\mu}$  range. Tires were found to be coated with an extremely fine powder, dominated by 1- to  $10^{-\mu}$  particles. Roadstones, that had been exposed to traffic, are quites smooth in appearance. A number were collected, and the exposed surfaces were examined further. The observed scratch lines could be produced only by abrasives less than  $10^{-\mu}$  diameter, presumably the debris clinging to the tires.

There are numerous physical properties and test variables that could play a part in the wear process. One would like to investigate as many of these properties as possible

MINERAL AND ABRASIVE SOURCE					
Substance	Name and Source				
(a) Mineral					
MgO	Magnorite crude, Norton Co., Cippawa, Ontario				
ZrO2	Zırconia H (¾ ın. and finer), Norton Co , Cippawa, Ontario				
Al <sub>2</sub> O <sub>3</sub>	Alundum (No. 4 mesh), Norton Co., Cippawa, Ontario				
SıC	Crystolon (½ 1n lump), Norton Co., Cippawa, Ontario				
Slag	Assorted chips for pavement, U.S Steel Corporation, Pittsburgh, Pa.				
51O2(f)	Clear fused quartz rod (6-mm dıa ), Engelhard Industries, Inc., Newark, N.J.				
CaCO <sub>3</sub> (1)	Limestone chips (No. 4B), Metal Finish, Inc., Newark, N J.				
Al <sub>9</sub> S1 <sub>2</sub> O <sub>13</sub>	Shamva mullite chips (¼ to ¾ in.), H. K. Porter, Co., Shelton, Conn.				
S1O₂(c)	Glass-like lump, Earth and Mineral Sciences Dept.				
CaCO <sub>3</sub> (c)	Crystal-like with cleavage planes, Earth and Mineral Sciences Dept.				
	(b) Abrasive				
MgO	Magnorite Type II, Norton Co, Cippawa, Ontario				
S1O2	Microsil silica sand (35 percent smaller than 7 $\mu$ ), Standard Silica Co., Ottawa, III.				
Al <sub>2</sub> O <sub>3</sub>	Alundum No. 38 (900 mesh), Norton Co., Cippawa, Ontario				

TABLE 2 MINERAL AND ABRASIVE SOURCE and yet keep the scope of the experiments in bounds. The following selections were made:

- 1. Ten minerals;
- 2. Three abrasives;
- 3. Three loads; and
- 4. Three speeds.

The minerals were selected for consistent and known physical properties. Mineral oxides were the primary choice. In this respect, the selection differed somewhat from actual paving practice, although quartz, slag, and limestone were included. The final choice was a compromise between variability of properties and availability of material. The abrasive selection was a similar compromise; oxides of aluminum, silicon, and magnesium. Size was specified as less than  $10\mu$ . A complete list and source of the minerals is given in Table 2.

A rolling tire can produce lateral movements of the order of  $\frac{1}{4}$  in. in the contact zone (<u>16</u>). Using a value of 8 in. for the tire contact length and a vehicle speed of 60 ft/sec, one arrives at 3 ft/sec for these contact velocities. A selected speed range (1 to 6 ft/sec) therefore is considered realistic. Loads were chosen to give



Figure 1. Test drum and assembly.

contact pressures above and below normal tire inflation pressure (10 to 50 psi). Higher pressures were avoided since they caused tearing and wear of the rubber carrier.



Figure 2. Loading plunger with specimen holder.

#### Apparatus

The apparatus is shown in Figure 1. A channel iron frame supported a 14-in. diameter steel drum to whose outside strips of rubber tape were applied. The drum could be rotated at any desired speed. Ten  $\frac{3}{4}$ -in. strips of rubber tape were applied to the drum to rub against the ten mineral specimens. A V-shaped bin for holding abrasive was placed around the lower half of the drum. Two springs urged the bin against the rubber strips so that the rotation of the drum produced a steady abrasive coating.

A block above the drum held ten radially movable plungers to which the specimens were fastened. The plungers were urged by air pressure toward the drum. A rolling diaphragm served as seals (Fig. 2). Mineral specimens consisting of cubes of about  $\frac{1}{4}$ -in. side length were bonded to the end of steel plugs. The plugs were held in the plungers by set-screws (Fig. 2). The moving parts were protected from the fine abrasive by a thin plastic membrane.

Wear was determined as weight loss; to this end the complete specimen-plug assembly was weighed repeatedly on an analytical basis. Weight loss was converted to volume loss using material density.

An exploratory program was carried out with  $SiO_2$  abrasive to study the wear effects of changes in the apparent contact area. From friction and wear theory dependency is not expected. Minerals of  $CaCO_3$ , MgO, and  $Al_2O_2$  were included. A typical example of the results is shown in Figure 3. Wear was independent of apparent contact area for a given load. Similar behavior was assumed to hold for all the remaining mineral-abrasive combinations.

The majority of abrasion tests reported by others showed wear to be proportional to distance of travel. This fact was also verified in the preliminary tests. Thus, the distance of travel (16, 200 drum revolutions) was the same for all tests, and an adjustment of running time was made at each speed.







(c) SiO<sub>2</sub> (f) by MgO Abrasive



(d) SiO<sub>2</sub> (c) by MgO Abrasive



(e) SiC by MgO Abrasive



(f)  $CaCO_3$  (c) by  $SiO_2$  Abrasive

Figure 4. Microphotographs of several worn minerals (magnification 50x).



(g) Mullite by SiO<sub>2</sub> Abrasive



(h) Slag by SiO<sub>2</sub> Abrasive



(i) CaCO<sub>3</sub> (c) by Al<sub>2</sub>O<sub>3</sub> Abrasive



(j) CaCO<sub>3</sub> (i) by Al<sub>2</sub>O<sub>3</sub> Abrasive



(k) Mullite by Al<sub>2</sub>O<sub>3</sub> Abrasive





Figure 4. Continued.

Mineral	Melt Temp. (°C)	Modulus (ps1 × 10 <sup>6</sup> )	Yield Stress (psi × 10 <sup>4</sup> )	Specific Gravity	Vicker's Hardness (kg/mm <sup>3</sup> )	Abrasive Wear (mm <sup>3</sup> × 10 <sup>-2</sup> )		
						Al <sub>2</sub> O <sub>3</sub>	S1O <sub>2</sub>	MgO
CaCO <sub>3</sub> (c)	825	_	-	2.70	460	42.2	30.7	13 5
CaCO <sub>3</sub> (1)	825	-	-	2.70	400	38 0	40.9	12.5
Slag	1400	-	_	2.70	620	24.0	16.3	9.4
S1O2(f)	1700	6	-	2.10	1100	11.0	11.0	2.6
Mullite	1810	21	0.9	2,95	1720	11.0	6.5	3.1
S1O₂ (c)	1700	7	0.7	2.65	2000	7.7	65	1.7
MgO	2620	42	15	3,60	1240	34	1.3	0.2
ZrO2	2650	21	20	5.70	1700	2.4	0.6	02
S1C	2200	50	5.0	3,00	4500+	0.7	0.4	0.07
Al <sub>2</sub> O <sub>3</sub>	2000	45	4.0	4,00	3300	0.3	0.7	0.03

TABLE 3 LIST OF MINERAL PROPERTIES WITH AVERAGE WEAR

#### RESULTS

It was seen that numerous material properties, notably melting temperature, hardness, modulus and strain energy, could provide a means to predict the degree of wear between mineral pairs. In particular the wear concepts throw doubt on the usually accepted parameter, scratch hardness. Table 3 lists these properties and gives the wear (average of all loads and speeds) for each abrasive. Hardness was measured directly by the author. The remaining values were found from an assortment of publications on material constants.

A correlation of wear and melting point was attempted initially. At first glance the postulated correlation seems to hold: low melting point materials tend to have high wear. The highest melting point materials (i. e, MgO and  $ZrO_2$ ), however, do not exhibit the best abrasion resistance. In fact, closer inspection of the table reveals numerous exceptions. Al<sub>2</sub>O<sub>3</sub> (2000 C) abrasive wore MgO (2600 C) and  $ZrO_2$  (2650 C) much faster than it wore SiC (2200 C) or itself; MgO (2600 C) abrasive wore  $ZrO_2$  (2650 C) much faster than it wore SiC (2200 C) or Al<sub>2</sub>O<sub>3</sub> (2000 C). Also the wear rates of fused and natural quartz differ by almost 50 percent though both have the same thermal properties. Apparently melting point does not provide a unique measure of wear.

A relation between wear and elastic modulus does not appear to be satisfactory. Mullite is much more brittle than  $SiO_2(c)$  but the amount of wear is similar. The same is true for MgO and  $ZrO_2$ .

Comparing wear with hardness in Table 3, the following generalization can be made: for those minerals softer than the abrasive, the amount of wear is large; if the mineral are harder than the abrasive, the wear is an order of magnitude lower than the softer materials. Several worn samples were preserved after the experiments and microphotographs were taken of their surfaces. The surfaces are shown in Figure 4. Two phenomena can be seen: (a) scratching or grooving, and (b) pitting or scabbing. The scratches appear to be well formed; little, if any, fragmentation occurs at their edges. Scratches on minerals harder than the abrasive are considerably reduced from those scratches on the softer minerals, see Figure 4 c, d, e. Pitting is found on all mineral regardless of their hardness relative to that of the abrasive. The number and size of the pits differ from mineral to mineral and the pits seem little affected by the type of abrasive used.

## Low Hardness Minerals

Abrasive wear theories for metals suggest that wear can be caused by plastic deformation of the contact and subsequent plowing-out of wear debris when movement commences. Wear was found to be directly proportional to load and inversely proportional to flow pressure. Porgess and Wilman showed that this relation holds for rock salt.



Figure 5. Wear inversely proportional to hardness for Al<sub>2</sub>O<sub>3</sub> abrasive.

Figure 6. Wear inversely proportional to hardness for SiO<sub>2</sub> abrasive.

This agreement with metals may be expected since salt is an extremely soft mineral. No other experiments were found which directly verify these proportionality relationships for nonmetals.

The minerals used in this research are much harder than salt, still no fragmentation of the grooves is evident from the photographs. Thus one might expect the wear to be inversely proportional to the flow pressure or Vicker's hardness. A log-log plot of wear against hardness was made for each abrasive, Figures 5 through 7. In each case the wear was generally found to be inversely proportional to the first power of hardness (in Fig. 7 SiO<sub>2</sub>(f) is nearly as hard as the abrasive). But exceptions occurred for the SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> abrasives. Both MgO and  $ZrO_2$  gave less wear than the hardnesswear relationship for the other materials would predict.

Figure 8 shows the effect of load on wear. Wear increases with the load, provided the mineral is softer than the abrasive. From abrasive wear theory, wear should be



Figure 7. Wear inversely proportional to hardness for MgO abrasive.



Figure 8. Wear as a function of load for Al<sub>2</sub>O<sub>3</sub> abrasive.

proportional to load. The graph indicates a load independent intercept  $W_0$  that is not accounted for in the theory. Its value increases as the mineral hardness decreases. The constant term  $W_0$  apparently is related to the pitting. This matter, as well as the behavior of MgO and ZrO<sub>2</sub>, is discussed further in the following section.

Melting point does give an indication of a material's high temperature strength. The room temperature hardness might be lowered to some degree by the heat generated at the rubbing contacts. Heat generation depends on the relative speed of the rubbing surfaces. Higher speeds should, therefore, lower the instantaneous hardness and increase wear. Figure 9 is an example of the wear for each abrasive as function of speed. The results show



Figure 9. Wear as a function of speed for AbO3 abrasive.

a definite increase in wear as the sliding speed increases. The slope for  $Al_2O_3$  abrasive increases in proportion to the decrease in mineral melting point (Table 3).

#### **High Hardness Minerals**

The wear of the minerals harder than the abrasive was relatively low. It was also independent of load. Microphotographs revealed that grooving was minimal although some pitting remained. The appearance of the surfaces suggested applicability of Rabinowicz's theory of a balance between strain energy and surface energy. The diameter of a detached particle is given by

$$\geq \frac{\mathrm{EH}_{\mathbf{V}}^{1/3}}{\sigma_{yp}^{2}}$$
(9)

where the surface energy S is approximated by the  $\frac{1}{3}$  power of the hardness, valid for many materials according to Rabinowicz. The theory does not give the average

d



Figure 10. Relation between slow wearing minerals and energy parameter.

size of the particles nor give an average size of the particles nor does it indicate the frequency of detachment. Values of the ratio in Eq. 9 computed for several materials are mullite, 3; MgO, 2; SiO<sub>2</sub>, 1.8; and Al<sub>2</sub>O<sub>3</sub>, ZrO<sub>2</sub>, and SiC, 0.5. Visual inspection of several microphotographs, Fig. 4 g, k, d, (<u>1</u>), shows that the average size and frequency of detachment are in the same order as these ratios. Thus it may be possible to relate wear to the same ratios.

Wear for minerals harder than the abrasive is plotted against  $EH_V^{1/3}/\sigma_{yp}^2$  (Fig. 10). The plotted points were obtained with the three different abrasives. The evidence is that the wear may be directly proportional to this ratio although more data are desirable. If the mineral is considerably harder than the abrasive, e.g., MgO, the wear is less than the value this relation would be expected to provide. Referring to Figure 4 e little pitting occurs with the MgO abrasive. Perhaps relative hardness has some influence on the frequency of detachment. Rabinowicz has verified that minimum particle size does obey Eq. 8 but no attempts have been made by anyone to evaluate volume of particle removal in terms of the parameter.

The microphotographs show substantial pitting for the minerals softer than the abrasive. Since the pitting type of wear appears independent of load, it seems plausible to relate it to the constant  $W_0$  found for these minerals. According to Rabinowicz, the substitutions  $E \sim 1/H_v$ ,  $S \sim H_v^{1/3}$ , and  $\sigma_{yp} \sim H_v$  are valid for many materials. Thus,

the size of the detached particle can be described by

$$\frac{\mathrm{ES}}{\sigma_{\mathrm{yp}}^{2}} \sim \mathrm{H}_{\mathrm{v}}^{-3/4} \tag{10}$$

Hardness can therefore be taken as a measure of the particle detachment size when the terms on the left of Eq. 10 are not known. Indeed, the microphotographs for the softest minerals,  $CaCO_3$  and slag, show a higher number of detachments and a larger increase in their size compared to harder minerals. In Figure 9, W<sub>0</sub> does increase in proportion to the softness of the minerals.

Eq. 10 was given because the properties on the left side are not always known. That the pitting phenomenon should be related to hardness is not surprising since good correlation of hardness with wear was achieved for the softer minerals. Eq. 9 was used for the studies of minerals harder than the abrasive because hardness was not a good indication of the particle detachment diameter as seen from the ratios above. Values for  $ZrO_2$  and MgO were comparable to SiC and  $SiO_2(c)$ , even though the latter are much harder. If there is less pitting for  $ZrO_2$  and MgO than their hardness indicates, it would explain why the wear of these minerals did not correlate better with hardness when worn by a harder abrasive. The available microphotograph for  $ZrO_2$  does show much less pitting than materials of comparable hardness. Figure 9 also shows that the term  $W_0$  for  $ZrO_2$  and MgO is small is view of their hardness.

#### CONCLUSIONS

Wear concepts provided several parameters that could be used to predict the wear of homogeneous minerals or roadstones under simulated road conditions. The results of relating wear to mineral melting temperature or modulus were negative.

Microscopic photographs of worn surfaces revealed two phenomena: scratching and pitting. No cracking from brittle fracture was evident along the scratches. Rapidly wearing minerals suffered both types of damage while slow wearing minerals displayed no scratching, only a small amount of pitting. The criterion which established whether or not a mineral would wear rapidly was its hardness relative to that of the abrasive. Rapid wear occurred when the abrasive was harder than the mineral. For each of the three fine abrasives the rapid type of wear correlated well with mineral hardness with the exception of two minerals which appeared to have little pitting.

The pitting that is evident in the microphotographs strongly suggests some energy mechanism involved with the material removal. However, no adequate model is known which will relate, quantitatively, the volume of wear to the energy properties of minerals. Qualitative relations were developed to explain the behavior of the above two minerals and the slow wear of minerals harder than the abrasive.

The significant aspect of this wear study 1s that hard minerals were worn with abrasives of comparative hardness; this combination has been neglected in wear literature. The evidence of scratching by the abrasive and the relation of rapid wear to mineral hardness is also a characteristic of the work reported for metals, but the phenomenon of pitting of the minerals which accompanies the scratching represents a new observation.

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