Relative Wear Resistance of Soil-Aggregate Mixtures

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This investigation attempts to establish a relationship between the rate of wear due to the loosening and loss of particles and some of the characteristics of soil-aggregate mixtures. A total of 18 treatments consisting of two types of aggregate material, three gradations within each material, and three plasticity indexes within each gradation were studied. A specially designed apparatus, employing a wire brush as an abrading tool, was used to abrade about 50 g from the bottom of each sample. The samples were compacted in the standard $\frac{1}{30}$-cu ft compaction mold at optimum moisture and were cured at an oven temperature of 115 F for 9 hr. The rate of wear, defined as the total amount of material abraded divided by the time it took to abrade it, was determined for each specimen. The data were analyzed by the IBM 650 computer and the equations relating the rate of wear as measured in this experiment and the kind of material, the gradation index, and the plasticity index were deduced.

The results of this investigation indicate that, within the range of the variables studied, the rate of wear due to the loosening of particles varies with the gradation index and the plasticity index of the soil-aggregate mixtures and is also greatly influenced by the geometric characteristics of the aggregates. The resistance to wear of all mixtures increases as the plasticity index increases, and for every plasticity index 2 to 9, there is an optimum gradation index which results in the lowest amount of wear as compared with other mixtures having the same plasticity index. Of the two aggregate materials used in this investigation, the one consisting of the more angular and irregularly shaped particles exhibits better wear resistance qualities than the other material.

• SOIL-AGGREGATE mixtures composed of a more or less controlled combination of coarse aggregates, sand, and binder have been used as surfacing materials for low-cost, low-traffic highways for many years. An enormous number of miles of surfaced

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highways in this country, estimated at over 50 percent of the total mileage, is included in this category. One of the desired qualities of a roadway surface is the ability to resist traffic wear, but these surfaces, and for that matter, many other stabilized surfaces, are somewhat limited with respect to this ability. It is estimated that under normal traffic conditions for which these soil-aggregate surfaces may be economically justified, on the average 0.25 to 1 in. of surface material is lost annually (1). This loss of material must be compensated for in the course of maintenance operations, or it may be controlled to a certain degree by the addition of certain chemical stabilizing agents. Replacement of the surface material lost through wear and erosion often requires as much as 50 percent of the local maintenance dollar (2). This expenditure places a heavy burden on the limited budgets of local highway organizations.

A literature survey has indicated that no basic research has ever been undertaken to evaluate the relative wear resistance of different soil-aggregate mixtures. A few field studies have been carried out to measure the amount of loss from untreated soil-aggregate surfaces and surfaces treated with calcium chloride. Some of the findings of these studies are summarized as follows:

1. Loss from surfaces treated with calcium chloride was about one-third as much as that from the untreated surfaces (1).
2. Loss increased with an increase in traffic volume (1, 3).
3. Loss of depth is progressive but not at a uniform annual rate (4).
4. The loss is not consistently related to the volume of traffic (4).
5. Surfaces with 15 percent or more material retained on the No. 10 sieve resist depth losses much better than surfaces with little or no coarse material (4).

These more or less qualitative, and in some cases contradictory, conclusions by early investigators are indicative of the complex nature of the problem and demonstrate the need for some basic research and quantitative data in this area.

GENERAL CONSIDERATION OF PROBLEM

Traffic wear from soil-aggregate surfaces is dependent on four general factors: (a) the traffic conditions, (b) the roadway geometrics, (c) the climatic conditions, and (d) the characteristics of the soil-aggregate mixture.

Traffic action is instrumental in loosening the particles and removing them from the surface. The traveling vehicle exerts forces which in turn produce shearing stresses on the surface of the road. These shearing stresses must be resisted by the shearing strength of the materials on the surface. The magnitude of these forces and the resulting stresses depend on a number of traffic factors, including traffic volume, type of vehicles using the surface, speed of travel, wheel load, tire type and inflation pressure, acceleration and deceleration, and impact effect.

Of these traffic factors, the most important one generally recognized by engineers is that of traffic volume. Whether the loss is due to fatigue or instantaneous bond failure, every passage of the load means more loss. The total amount of wear varying with the volume of traffic has been realized by many engineers and the volume of traffic has often been used as the criterion for the maintenance operations and betterment program of soil-aggregate roads. Generally speaking, the problem of traffic wear is not very serious on a well-designed and well-built soil-aggregate surface, as long as the daily traffic is below 50 vehicles. When the daily traffic approaches 50 to 100 vehicles per day, dust becomes a problem (5). Dust palliatives can be applied economically when the highway carries approximately 150 to 200 vehicles per day. Finally, a point is reached where a soil-aggregate surface cannot be economically held by any known methods, and a higher-type surface must be provided. There is no universal criterion for these operations, however, because of the variations of the other general factors influencing the amount of wear.

The roadway characteristics, such as horizontal and vertical alignments, the relative elevation of the roadway with respect to the surrounding land, and the condition of the surface, act as modifiers in that they modify the stresses or the process of removal. The amount of wear at the approach to the horizontal curve, in the horizontal curve, and at the exit from the curve is often more than that on the tangent, because of the deceleration and acceleration of vehicles necessary to negotiate the curve and the centrifugal force involved while on the curve. Similarly, the deceleration and acceleration of vehicles on a grade result in an increase in the magnitude of shearing stress and in turn cause more wear. Removal of the material from the surface by wind is facilitated by a high-grade line and is aided by the force of gravity and erosion on steep grades. The smoothness or roughness of the surface affects the impact and the tractive forces acting on the surface and in turn the degree of wear.

Climatic factors such as precipitation, temperature, wind, and humidity together with the characteristics of the mixture determine the availability of moisture in the surfacing materials. It is generally realized that the actual wear takes place primarily during dry weather and that as long as there is a certain amount of moisture available, the fine particles are not as readily whipped up by traffic. When this moisture is lost through evaporation by the actions of wind and temperature, the dust problem initiates and the particles on the surface are gradually loosened by the actions of traffic. Since the average soil moisture parallels in general the average annual rainfall (6), the in-place moisture content for a given soil-aggregate mixture is generally high in areas of high rainfall, resulting in a relatively short period of active wear. On the other hand, a soil-aggregate mixture in a wet climate may be under a plastic condition for a long period of time and hence be subject to deformation, leading to rugged surface irregularities and to high rates of wear when climatic conditions are favorable.

The characteristics of the soil-aggregate mixture influencing its resistance to wear are those that govern the strength of the mixture in general and the ability of the mixture to retain moisture in particular. The strength of the mixture is derived from the mechanical interlocking of the granular fraction and the binding action of the fine soil fraction. The ability of the mixture to retain moisture, as well as its capacity to develop cohesion or binding action, depends on the quantity and quality of the binder. In practice, these principal characteristics of soil-aggregate mixtures may be controlled in specifications by placing limits on gradation and plasticity index. In this connection, it is generally realized that soil-aggregate surface materials must be reasonably well graded to provide an adequate internal skeleton of grains of aggregate touching each other or interlocking with each other to furnish internal stability. Most important of all, the quantity and quality of the binder must be such that the binder is capable of cementing the material together and yet when it expands in the presence of excessive moisture it just fills the rest of the voids in the mixture without destroying its internal stability. The quantity of the binder is indicated by the material passing the No. 200 sieve; the quality of binder is generally controlled by specifying a plasticity index for the mixture.

Other characteristics of a soil-aggregate mixture which are related to its wear resistance include the geometric characteristics and size of its particles. Because part of the shearing resistance of a mixture is derived from particle interlocking, it is reasonable to expect that angular, flat, or elongated, and roughly textured particles are more resistant to wear than rounded and smooth-faced aggregate because of higher particle interlocking and greater mutual protection. Likewise, wear from surfaces containing larger aggregate particles is often less than those containing smaller particles because they provide better protection to the mortar surrounding them, thus making their removal more difficult.

MECHANISM OF TRAFFIC WEAR

Traffic wear from the soil-aggregate surfaces takes place in two ways: (a) the loosening and subsequent loss of materials, and (b) the polishing and breakdown of individual particles. The first kind of traffic wear arises when the fine material in the surface is loosened by traffic and whipped away. This component of wear is largely determined by the binding properties of the sand-clay mortar and the ability of the binder material to hold the larger particles in place. The second kind of wear is essentially a function of the hardness and toughness of the aggregate particles and may

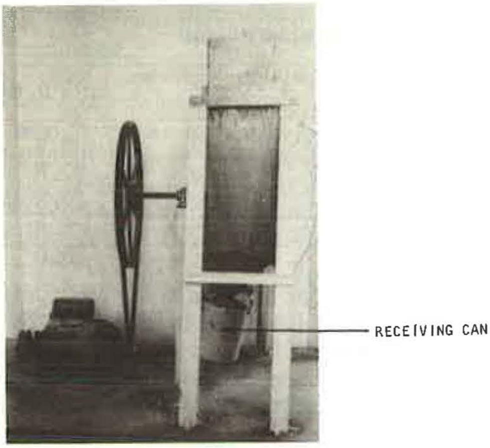

Figure 3. Wear apparatus.

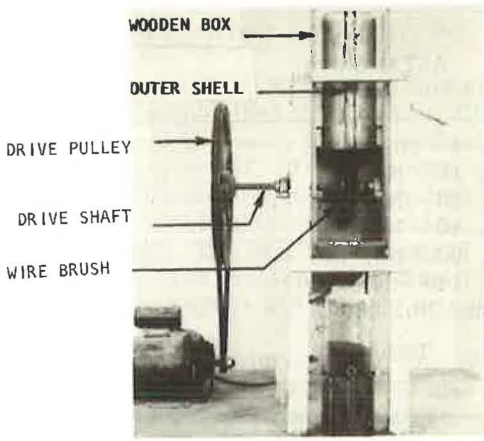

Figure 4. Wear apparatus with front removed, and loading assembly.

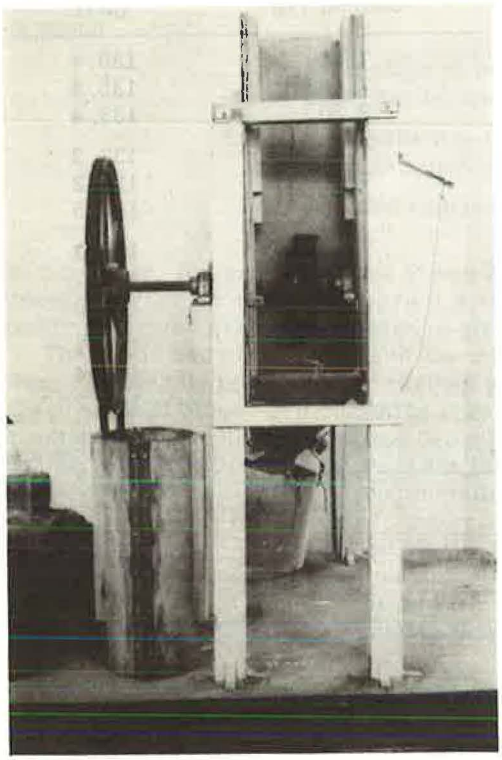

Figure 5. Wear apparatus with front and outer shell removed.

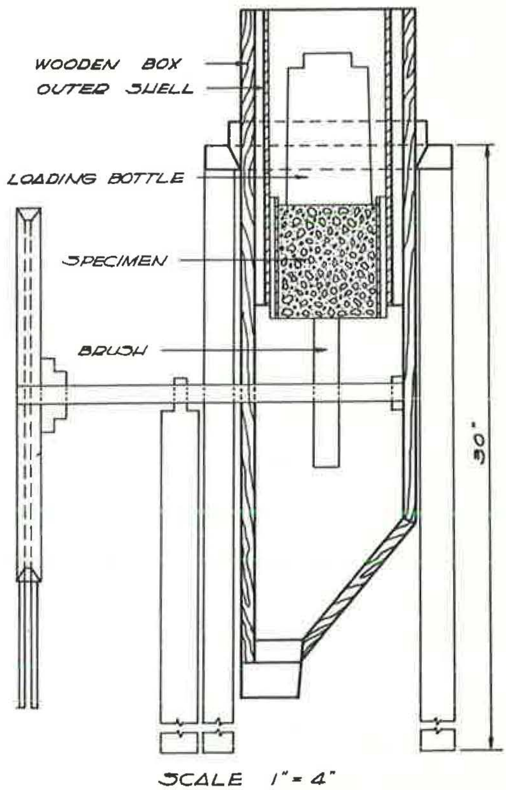

Figure 6. Cross-section of wear apparatus.

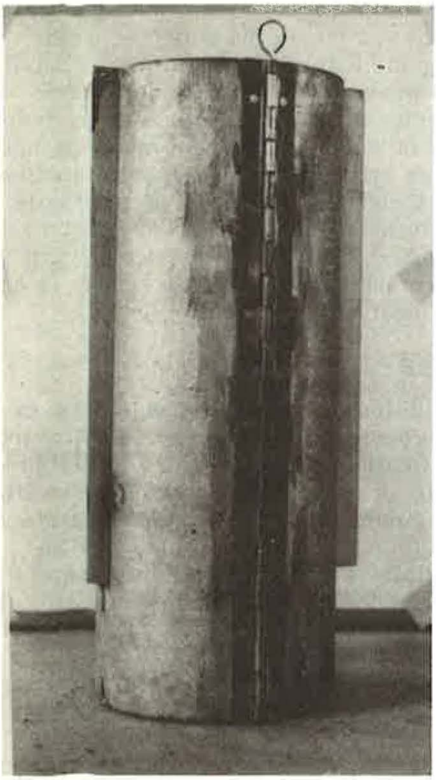

Figure 7. Outer shell.

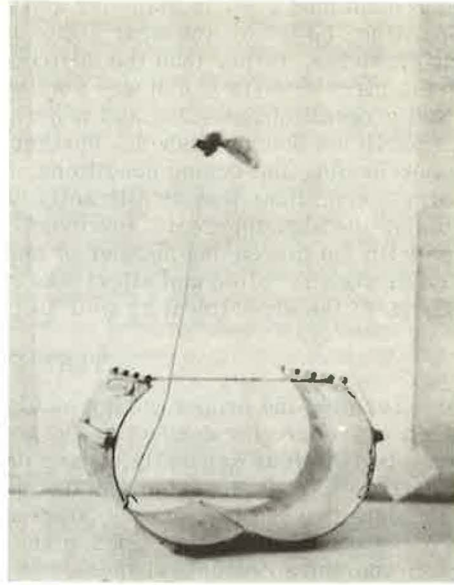

Figure 8. Specimen holder.

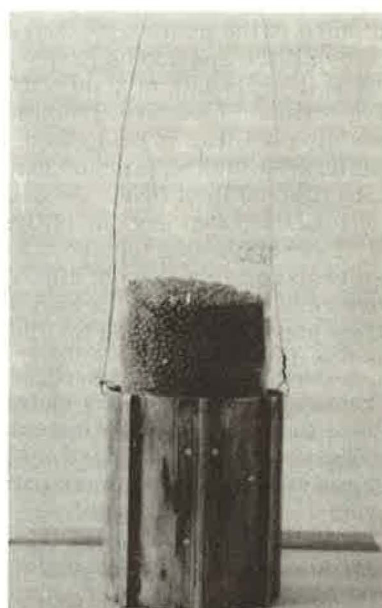

Figure 9. Loading assembly.

is used to turn the wire brush and to reduce the speed. It receives its power from a $\frac{1}{3}$-hp motor through a $\frac{3}{4}$-in. motor pulley. The turning speed of the pulley-operated wire brush is 1,725 rpm.

The specimen holder shown in Figure 8 is made from $\frac{1}{16}$-in. thick sheet metal. Its inside diameter is 4 $\frac{3}{16}$ in. and it is 4 $\frac{3}{4}$ in. high. It is hinged in two places and is provided with one removable pin. There are four lugs welded to it to provide a close fit inside the outer shell. The loading assembly (Fig. 9) consists of the sample, the specimen holder, and a bottle partially filled with lead shots. The total weight of the load may be adjusted by an increase or a decrease of the number of lead shots in the bottle.

In regard to the abrading tool for the wear device, before the wire brush was finally adopted, several other abrading materials had been considered and experimented. In this connection, a 6-in. "industrial heavy duty solid" rubber wheel was the first used. It was hoped that the results obtained might make later correlations with field observations easier, but only the rubber wheel showed any wear and the method had to be discarded. Subsequently, a pair of medium grade grindstones 6 in. in diameter and 1 in. wide was experimented. With this type of apparatus, however, the wear action taking place was due to the polishing of the larger particles, rather than the desired loosening and loss of fine particles. Finally, the 6-in. circular wire brush was employed. The wear or loss of material by this tool was a result of loosening and removal of particles with no indications of the individual particles being polished. Further, the rate of wear for different mixtures under the same loading and curing conditions, or the same mixtures under different loading and curing conditions was significantly different. Consequently, the wire brush was adopted as the abrading tool. However, the effectiveness of the brush was found to decrease with the increasing number of specimens tested. This fact was viewed with particular consideration and effort was subsequently made to remove this effect in the design of the experiment as well as in the data analysis.

TEST PROCEDURE

To determine the proper curing and loading conditions of the specimens and to establish a procedure for conducting the wear test, a series of trial tests was performed. Because traffic wear generally occurs during dry weather, it was decided to measure the relative wear after dry-curing the specimens in an oven. Previous studies in Illinois indicate that the in-place moisture content of a number of soil-aggregate surfaces in DeWitt County during the summer season range from 27.8 to 59.8 percent of the optimum moisture contents of these surface materials, with only 3 out of a total of 37 values exceeding 50 percent (10). In an effort to produce a moisture content within the preceding range for the soil-aggregate mixtures in this study, an arbitrary temperature of 115 F was selected and a series of tests was performed on a typical material to determine the curing time required. The results of this study indicated that a curing time of 9 hr would produce a moisture content of approximately 40 percent of the optimum moisture of the material. Consequently, this curing condition was chosen as the standard for all the specimens prepared for this study. The average moisture contents of various soil-aggregate mixtures after curing, expressed as a percentage of their respective optimum moisture contents, are summarized in Table 3.

To establish the load to be applied, another series of tests was performed on the typical material after the samples had been cured for 9 hr. Observations were made with 10, 15, and 20 lb of load. As expected, it was found that the wear varied with the amount of load, and that any one of these loads would be satisfactory for the particular mixture. To avoid having too short a contact time for the mixtures that were believed to be less resistant to wear, or slippage of the belt with mixtures that were believed to be more resistant to wear, a load of 12 lb was selected for use in this study.

The final procedure adopted for the preparation of specimens and for the wear test is outlined as follows:

1. Proportion 2,200 g of dry material for any given gradation and plasticity index.
2. Place the 2,200 g of dry material in the mixer, mix for 2 min, add sufficient water to obtain the predetermined optimum moisture content, and mix for 3 min more.
3. Compact the sample to maximum dry density in three equal layers in the 4-in. mold having a capacity of $^1/_{30}$ cu ft, using a 5.5-lb rammer and a 12-in. drop.
4. Level off the top and weigh the sample and the mold.
5. Extrude the compacted sample, weigh and place it in the oven with the temperature of the oven controlled at 115 F.
6. Remove the sample from the oven after 9 hr and weigh it.
7. Place the sample in the specimen holder, with the lower end in contact with the wire brush, close and put in the removable pin. Two to four narrow sheets of paper must be placed between the specimen and specimen holder to insure that the specimen and specimen holder act as one unit and that the specimen cannot be pressed out.
8. Put enough lead shot in the loading bottle such that the total weight of the specimen, the specimen holder, the loading bottle, and the lead shot is 12 lb.
9. Place the specimen holder with the accompanying specimen in the apparatus and center the loading bottle on the top of the specimen.
10. Raise the whole assembly and turn on the switch.

11. At approximately 30 sec from the time that the switch was turned on, bring the specimen into contact with the brush, abrade about 50 g of material, raise the assembly, turn off the switch, and record the total time in seconds.

12. Collect all the material abraded and record the weight and total time that the specimen was in contact with the brush.

13. Calculate the rate of wear by dividing the weight of the material abraded by the total time expressed in grams per second.

TABLE 3

AVERAGE RELATIVE MOISTURE CONTENTS OF SOIL-AGGREGATE MIXTURES TESTED

Material	Gradation Index	Plasticity Index	Percent of Optimum
113	0.3	2.0	42
		6.0	44
		10.0	48
	0.4	2.0	35
		6.0	43
		10.0	48
	0.5	2.0	36
		6.0	41
		10.0	46
178	0.3	2.0	42
		6.0	42
		10.0	49
	0.4	2.0	38
		6.0	41
		10.0	48
	0.5	2.0	35
		6.0	42
		10.0	47

EXPERIMENTAL DESIGN

The experiment was performed according to a statistical procedure to eliminate personal bias in the interpretation of the results and to determine the effects of the selected controlled factors on the wear resistance of soil-aggregate mixtures on the basis of mathematical probabilities. As described previously, the study involved two types of material, three gradations within each material, three plasticity indexes within each gradation or a total of 18 treatments. It was decided to replicate each treatment six times, and to use a total of six brushes for the entire study. The specimens were to be prepared, cured, and tested under uniform conditions in groups of nine. These conditions suggested a factorial design with six blocks. Each block, employing a different brush, contained all 18 treatments in a randomized order, with the restriction that gradation indexes and plasticity indexes be equally represented in the first and second halves of each block.

To determine the nine treatments assigned to the first half of the blocks and those to the second half of the blocks, the signs of the products of the orthogonal polynomials were determined first. The nine plus signs were assigned to the first half of the blocks and the nine minus signs to the second half. The nine specimens that were to occupy each half of a block were then numbered one to nine, and the random arrangement of these specimens was determined by the use of a random numbers table (11). The arrangement of the tests, designated in terms of "material-gradation index-plasticity index," is given in Table 4.

ANALYSIS AND RESULTS

The rate of wear of various soil-aggregate mixtures obtained according to the preceding procedure is summarized in Table 5. The results in the table represent the combined effect of the many factors involved in the experiment. Not only the variations of the material factors (such as the type of aggregate, gradation index, and plasticity index) but also the differences in the effectiveness of the brushes used and the decrease of the effectiveness of a given brush with the increasing number of specimens tested are reflected in the results of the tests. The mathematical relationship between the rate of wear as measured by the aforementioned procedure and the several factors involved was determined using the general regression model:

$$\hat{y} = \overline{y} + \sum C_i X_i \qquad (2)$$

in which

$\hat{y}$ = rate of wear;
$\overline{y}$ = average rate of wear for all observations;
X_i = independent variables, p, p^2, g, g^2, m, pg, p^2g^2, pg^2, p^2g, mpg, mpg^2, mp^2g^2, mgp^2, mp, mp^2, mg, mg^2, B_1S, B_1S^2, B_2S, B_2S^2, B_3S, B_3S^2, B_4S, B_4S^2, B_5S, B_5S^2, B_1, B_2, B_3, B_4, B_5, S, and S^2;
C_i = regression coefficients;
g = gradation index;
p = plasticity index;
m = material;
B_i = brush i; and
S = sequence.

The data were analyzed by the IBM 650 computer using the library routine program "STAMP" of the University of Illinois Digital Computer Laboratory by the method of least squares. Based on the results with a significance level of at least 95 percent from the regression analysis, two equations for the materials tested in terms of all the independent variables previously listed were obtained. Considering an average brush which would not decrease its effectiveness following usage, the two equations were subsequently reduced to the following forms in terms of only the material factors:

$$y_{113} = 48.25 - 230.6g + 328.4g^2 + 0.87gp^2 + 13.8gp - 0.75p - 0.33p^2 - 33.0g^2p \qquad (3)$$

$$y_{178} = 54.22 - 248.0g + 328.4g^2 + 22.5gp - 4.24p - 0.09p^2 - 33.0pg^2 + 0.27gp^2 \qquad (4)$$

The standard error of the estimate is 0.74, and the multiple correlation coefficient is 0.97.

The preceding equations indicate that the rate of wear as measured in this study varies with quadratic functions of the gradation index and the plasticity index. The relationship between the rate of wear and the gradation index for the two materials with various plasticity indexes are shown in Figures 10 and 11. These graphs indicate that the rate of wear decreases as the plasticity index increases, and that for each

TABLE 4

RANDOM ARRANGEMENTS OF SOIL-AGGREGATE MIXTURE SPECIMENS

Order of Testing	Material-Gradation Index-Plasticity Index					
	Block 1	Block 2	Block 3	Block 4	Block 5	Block 6
1	178-0.4-10.0	113-0.5-10.0	113-0.5- 2.0	178-0.4-10.0	178-0.4- 2.0	113-0.4- 6.0
2	178-0.5- 6.0	178-0.4- 2.0	113-0.5-10.0	114-0.3- 2.0	113-0.5-10.0	178-0.3- 6.0
3	113-0.5- 2.0	178-0.3- 6.0	113-0.3-10.0	113-0.5-10.0	178-0.4-10.0	113-0.3-10.0
4	113-0.3- 2.0	113-0.3-10.0	113-0.4- 6.0	113-0.3-10.0	178-0.5- 6.0	178-0.5- 6.0
5	178-0.3- 6.0	178-0.5- 6.0	113-0.3- 2.0	178-0.5- 6.0	113-0.3- 2.0	178-0.4- 2.0
6	113-0.5-10.0	113-0.3- 2.0	178-0.4- 2.0	178-0.3- 6.0	113-0.4- 6.0	113-0.3- 2.0
7	113-0.3-10.0	113-0.4- 6.0	178-0.5- 6.0	178-0.4- 2.0	178-0.4- 6.0	113-0.5-10.0
8	178-0.4- 2.0	178-0.4-10.0	178-0.4-10.0	113-0.5- 2.0	113-0.5- 2.0	113-0.5- 2.0
9	113-0.4- 6.0	113-0.5- 2.0	178-0.3- 6.0	113-0.4- 6.0	113-0.3-10.0	178-0.4-10.0
10	113-0.4-10.0	113-0.3- 6.0	178-0.5-10.0	113-0.4- 2.0	178-0.3-10.0	113-0.5- 6.0
11	113-0.5- 6.0	178-0.5-10.0	113-0.4- 2.0	113-0.4-10.0	113-0.4- 2.0	178-0.3-10.0
12	178-0.3- 2.0	178-0.5- 2.0	178-0.5- 2.0	178-0.5-10.0	178-0.4- 6.0	113-0.4- 2.0
13	178-0.4- 6.0	113-0.4-10.0	178-0.3- 2.0	178-0.3- 2.0	178-0.3- 2.0	113-0.4-10.0
14	178-0.5- 2.0	178-0.3- 2.0	178-0.3-10.0	178-0.5- 6.0	113-0.4-10.0	178-0.4- 6.0
15	178-0.5-10.0	178-0.4- 6.0	113-0.5- 6.0	178-0.5- 2.0	178-0.5- 2.0	178-0.3- 2.0
16	113-0.4- 2.0	113-0.4- 2.0	113-0.3- 6.0	113-0.4- 6.0	178-0.5-10.0	178-0.5- 2.0
17	178-0.3-10.0	178-0.3-10.0	178-0.4- 6.0	178-0.3-10.0	113-0.3- 6.0	113-0.3- 6.0
18	113-0.3- 6.0	113-0.5- 6.0	113-0.4-10.0	113-0.3- 6.0	113-0.5- 6.0	178-0.5-10.0

TABLE 5

RESULTS OF WEAR TESTS OF SOIL-AGGREGATE MIXTURES[a]

Material	Gradation Index	Plasticity Index	Rate of Wear (g/sec)					
			Brush 1	Brush 2	Brush 3	Brush 4	Brush 5	Brush 6
113	0.3	2.0	11.10 (4)	4.82 (6)	11.34 (5)	10.44 (2)	9.72 (5)	9.64 (6)
		6.0	7.14 (18)	4.29 (10)	10.02 (16)	9.20 (18)	8.57 (17)	7.74 (17)
		10.0	7.70 (7)	3.54 (4)	8.14 (3)	8.31 (4)	5.72 (9)	4.83 (3)
	0.4	2.0	7.36 (16)	3.80 (16)	8.60 (11)	9.87 (10)	7.82 (11)	6.70 (12)
		6.0	6.48 (9)	2.71 (7)	7.69 (4)	9.91 (9)	7.08 (6)	6.76 (1)
		10.0	5.75 (10)	1.80 (13)	6.78 (18)	6.34 (11)	6.14 (14)	4.78 (13)
	0.5	2.0	13.98 (3)	5.89 (9)	13.04 (1)	12.18 (8)	12.10 (8)	11.02 (8)
		6.0	6.10 (11)	2.47 (18)	7.44 (15)	6.50 (16)	6.82 (18)	6.28 (10)
		10.0	5.89 (6)	2.38 (1)	7.46 (2)	6.36 (3)	6.68 (2)	4.65 (7)
178	0.3	2.0	8.80 (12)	4.61 (14)	9.82 (13)	8.82 (13)	8.75 (13)	7.88 (15)
		6.0	8.33 (5)	4.92 (3)	8.50 (9)	6.92 (6)	5.92 (7)	6.94 (2)
		10.0	3.45 (17)	0.88 (17)	4.79 (14)	4.13 (17)	3.81 (10)	3.67 (11)
	0.4	2.0	6.26 (8)	5.00 (2)	8.50 (6)	7.05 (7)	8.60 (1)	6.40 (5)
		6.0	4.70 (13)	2.00 (15)	6.79 (17)	5.73 (14)	6.25 (12)	4.60 (14)
		10.0	4.02 (1)	1.48 (8)	6.20 (8)	5.80 (1)	5.21 (3)	3.66 (9)
	0.5	2.0	9.96 (14)	4.17 (12)	11.56 (12)	10.10 (15)	13.14 (15)	8.92 (16)
		6.0	7.78 (2)	3.54 (5)	7.16 (7)	8.24 (5)	8.42 (4)	7.78 (4)
		10.0	3.21 (15)	1.44 (11)	5.23 (10)	5.51 (12)	5.20 (16)	4.18 (18)

[a]Sequence of test shown in parenthesis after value of rate of wear.

plasticity index 2 to 9, there is a gradation index at which the rate of wear is a minimum. This gradation index is referred to hereafter as the optimum gradation index. These optimum values are given for the two materials in Table 5.

The trends of these optimums are not the same for the two materials. The optimum gradation index for material 113 increases as the plasticity index increases, whereas that for material 178 changes little or none at all. It seems that the difference is due to the influence of the geometric characteristics of the aggregates in these mixtures. For a mixture with sharply angular particles such as material 178, the protection shared by adjacent particles became very important. Because this mutual protection also depended on the relative position of the particles or simply the gradation index, it is conceivable that some optimum combination of the particle index and the gradation index would provide maximum protection irrespective of the plasticity index.

Figures 10 and 11 also show that the general shape of the curves changes gradually and approaches a straight line as the values of the plasticity index are increased. It has been described previously that wear due to loosening of particles is controlled primarily by cohesion. Because cohesion is reflected by the plasticity index, the rate of wear decreases as the plasticity index increases. As the plasticity index increases, the relative importance of cohesion also increases. This fact is illustrated by the flatness or the decrease in curvature in the proximity of the optimum points as the plasticity index increases.

To make a comparison of the wear resistance of all the soil-aggregate mixtures tested, two terms, "relative wear" and "relative wear resistance," are introduced here. The relative wear of a given mixture is defined as the ratio of wear at optimum gradation index for the given plasticity index to the wear at optimum gradation index for a mixture composed of material 178 and having a plasticity index of 9.0. Relative wear resistance is defined as the reciprocal of the relative wear. The relative wear and relative wear resistance values are given in Table 6. The relationship between relative wear resistance and plasticity index for the two materials is shown in Figure 12. As expected, the material with a higher particle index has a superior quality of wear resistance.

From the practical point of view, the results of this study provide a quantitative set of data relating wear resistance to gradation and plasticity index of soil-aggregate mixtures, which may be of some value in the understanding and future control of the wear of these materials. These results indicate that within the range of the variable studied,

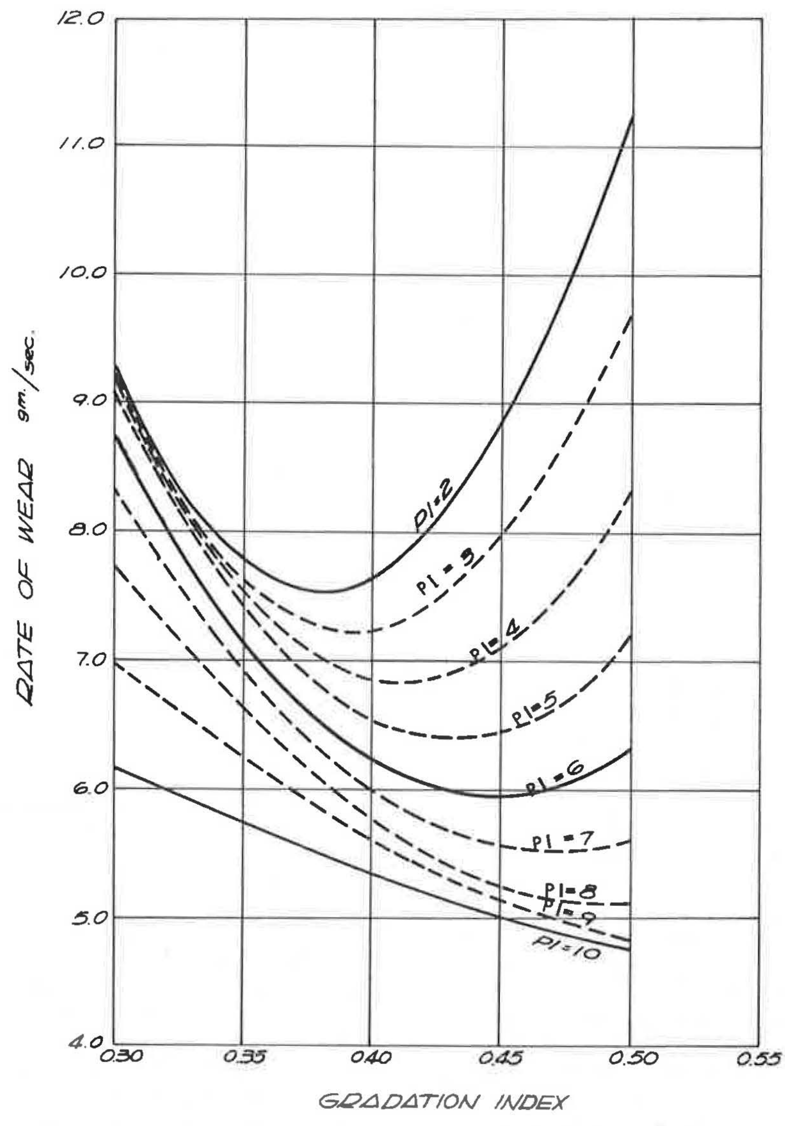

Figure 10. Relationship between rate of wear and gradation index for material 113.

an increase in the plasticity index increases the wear resistance, and that for any given plasticity index there is an optimum gradation index. There are also clear indications that the particle index plays an important role in the mechanism of wear resistance. The fact that, as the plasticity index increases, the rate of wear in the proximity of the optimum gradation index becomes less sensitive to changes in the gradation index appears rather significant. It means that at higher plasticity indexes a wider range of gradations can be used without increasing the rate of wear by any significant amount. The importance of this phenomenon becomes rather obvious when one considers the fact that even with the best practical degree of field control, it is difficult to produce a mixture with a given optimum gradation index.

It must be noted, however, that the findings are limited to the types of the materials and the curing and test conditions under which they were investigated. For field applications, additional studies are needed to substantiate the laboratory findings and to evaluate the other major variables not covered in this investigation.

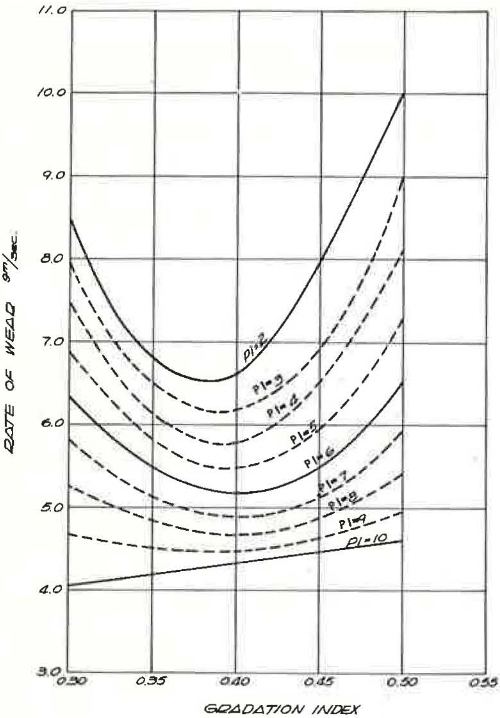

Figure 11. Relationship between rate of wear and gradation index for material 178.

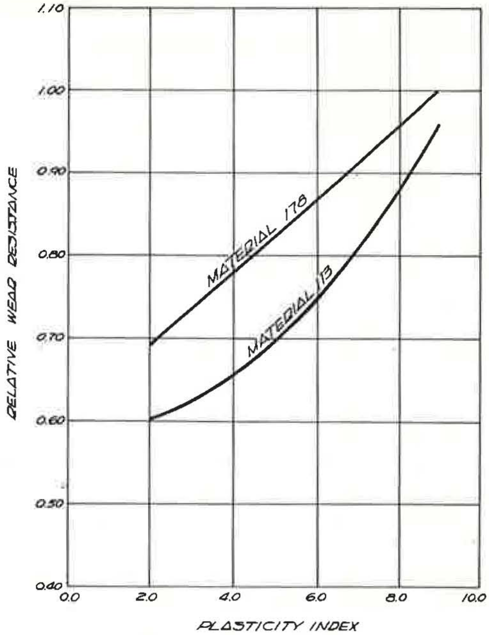

Figure 12. Relationship between relative wear resistance and plasticity index.

TABLE 6

OPTIMUM GRADATION INDEX AND RELATIVE WEAR RESISTANCE OF SOIL-AGGREGATE MIXTURES

Material	Plasticity Index	Opt. Gradation Index	Relative Wear	Relative Wear Resistance
113	2.0	0.38	1.68	0.60
	3.0	0.40	1.61	0.62
	4.0	0.41	1.52	0.66
	5.0	0.43	1.42	0.70
	6.0	0.45	1.32	0.76
	7.0	0.47	1.23	0.81
	8.0	0.50	1.14	0.88
	9.0	0.58	1.04	0.96
178	2.0	0.38	1.46	0.68
	3.0	0.39	1.37	0.73
	4.0	0.39	1.29	0.78
	5.0	0.39	1.22	0.82
	6.0	0.40	1.15	0.87
	7.0	0.40	1.09	0.92
	8.0	0.39	1.04	0.96
	9.0	0.38	1.00	1.00

SUMMARY AND CONCLUSIONS

In this study the characteristics of soil-aggregate mixtures controlling the wear or loss of material from soil-aggregate surfaces due to the loosening of the fine particles were investigated. A total of 18 treatments consisting of two types of material, three gradations within each material, and three plasticity indexes within each gradation were studied. A specially designed apparatus, employing a wire brush as an abrading tool, was used to abrade about 50 g of material from the bottom of each specimen. The specimens were compacted in the standard $\frac{1}{30}$-cu ft compaction mold at optimum moisture content, and then oven-cured for 9 hr at a constant temperature of 115 F. The rate of wear, defined as the total amount of material abraded divided by the time it took to abrade it, was determined for each specimen.

The experimental design used to collect the data was a factorial design with six randomized and restricted blocks. The restriction was equal representation of gradation indexes and plasticity indexes in the first and second halves of each block. A different brush was employed to test each block. The data were analyzed by the IBM 650 computer using the library routine program "STAMP" by the method of least squares. The output was used to write the regression equations relating wear to the type of material, gradation index, and plasticity index.

Based on the results of this research, the following conclusions regarding the relative wear resistance of soil-aggregate mixtures have been drawn. It is to be understood that these conclusions are based on the relationships established in this test series, applying the wear apparatus and the procedures developed in this investigation.

1. Using the wear apparatus and the procedures developed in this investigation, a wear index reflecting the traffic wear due to the loosening of particles may be obtained.
2. Within the range of variables studied, wear due to the loosening of particles varies with quadratic functions of gradation index and plasticity index.
3. Resistance to wear increases with an increase in plasticity index.
4. For every plasticity index there is an optimum gradation index which will result in the lowest amount of wear as compared to other mixes having the same plasticity index.
5. Any deviation from the optimum gradation index has a decreasing effect on the change in the rate of wear as the plasticity index increases. Thus, at higher plasticity indexes, wider ranges of materials can be used without decreasing the wear resistance of the mixtures by a significant amount.
6. The trend followed by this optimum gradation index is greatly influenced by the particle index, or the geometric characteristics of the aggregates.
7. Materials with higher particle index values have better wear-resistance qualities.

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