Aggregate Degradation in Bituminous Mixtures

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A laboratory study was performed using a gyratory testing machine to determine the factors affecting the degradation of aggregate in bituminous mixtures.

Three kinds of aggregates with different Los Angeles values were used. The aggregates were blended according to three different gradations ranging from an open gradation to a Fuller maximum density gradation. Four different asphalt contents were used. Use of a gyratory testing machine made it possible to change the compactive efforts in two different ways: change in magnitude of load and change in repetition of load.

The results of this study indicated that, regardless of type of aggregate, gradation, compactive effort, method of compaction, and presence of asphalt, each fraction of aggregate degraded in such a way that its sieve analysis curve was a smooth curve approaching a parabola, which implied that the pattern of degradation is constant. The magnitude of degradation, as measured by percent increase in surface area, was found to vary and to depend on the foregoing variables. Gradation was found to be the most important factor affecting degradation; the denser the mix the less the degradation. Soft aggregate with a high Los Angeles value degraded less than hard aggregate with a low Los Angeles value when the former was blended in a dense mixture and the latter in an open mixture.

Degradation also varied with type of aggregate. In general, aggregates with high Los Angeles values resulted in more degradation than those with low Los Angeles values. The rocks with good interlocking and strong cementation between the grains produced less degradation than rocks with loose interlocking and weak cementation. Increase in compactive effort, either by increase in magnitude of load or by increase in number of repetitions of load, increased the degradation. However, the magnitude of load was found to effect degradation more than repetition of load. The effect of asphalt was found to be dependent on other factors, and there was no definite pattern for the effect of asphalt content on degradation without considering other variables.

• A BITUMINOUS mixture is essentially a three-phase system consisting of bitumen, aggregate and air. In order for such a mixture to serve its purpose, it is compacted

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to a certain degree during construction. During its life, the mixture is subjected to further compaction due to the action of traffic. This further densification of a bituminous mixture under traffic may produce progressive deterioration of the pavement, either by reduction of voids to the point where a plastic mixture results, or by producing raveling. In either case, degradation of the aggregate may play an important role.

Compaction is an energy-consuming process, which results from the application of forces to the mixture. The mixture withstands these forces in many ways, such as by interlock, frictional resistance, and viscous or flow resistance. When the applied forces have a component in any direction greater than the resistance of the mat, the material will move and shift around until a more stable position is attained. This rearrangement of the material, especially the aggregate phase, causes a closer packing of particles, a new internal arrangement or structure, and a higher unit weight.

The energy required for the relocation or rearrangement of particles is provided by contact pressure, and the particles while adjusting to their new locations are subjected to forces which cause breakage and wear at the points of contact. This phenomenon, called degradation, reduces the size of particles and changes the gradation of aggregate which in turn causes a reduction in void volume and an increase in density. Any change in the gradation of the aggregate in a mix causes an associated change in basic properties of the bituminous mixture, namely, stability and durability. In some mixtures the change of gradation due to degradation of aggregate causes the asphalt present in the voids to be pushed out and an unstable mix to result, whereas in other mixtures the amount of asphalt present is not sufficient to coat all the newly produced surfaces and disintegration of the mat results. Degradation may reduce the angularity of aggregate particles, and thus decrease the interlocking which in turn results in a loss in stability of the mixture with resulting shoving, distorting, and corrugating.

A review of the literature concerning aggregate qualities shows that numerous methods have been used to determine the suitability of aggregates for road-building purposes. The most important objective of these methods is to provide reliable criteria for accepting or rejecting aggregates. In general the properties of aggregate can be divided into two classes: (a) those belonging to the individual piece and (b) those belonging to the aggregation of pieces. Obviously, the properties of the second group depend on the properties of the first. Determination of the relationship between properties of the two classes may not be difficult when the pieces are all identical, but it is a difficult problem when the pieces exist in a range of sizes, a variety of shapes, and sometimes even have different compositions. The most important tests among the first group are those concerned with petrographic analysis and with impact and crushing strength. Among the second group, tests such as abrasion tests, compression tests, and field and laboratory roller tests, are pertinent to the degradation of aggregates, especially in bituminous mixtures.

The relative importance of factors affecting the degradation of aggregates is generally a matter of controversy among investigators. Factors such as type of aggregate, maximum size and gradation of particles, aggregate shape, asphalt content, and compactive effort are all cited in the literature as controlling factors of aggregate degradation.

The purpose of this investigation was to evaluate the degradation characteristics of aggregates in bituminous mixtures and to analyze the factors which are effective in causing this degradation. In so doing, the following factors were investigated: (a) type of aggregate, (b) gradation of aggregate, (c) aggregate shape, (d) aggregate size, (e) asphalt content, and (f) compactive effort.

MATERIALS AND PROCEDURE

Three kinds of aggregates were used in this study—dolomite, limestone and quartzite. Selection was based on a relatively wide range of Los Angeles values and on petrographic structure. Table 1 gives data on origin, specific gravity, Los Angeles value, and compressive strength. Table 2 summarizes petrographic analysis results.

An 85- to 100-penetration grade asphalt cement was used in this study; test results are given in Table 3.

TABLE 1

RESULTS OF LOS ANGELES ABRASION AND COMPRESSIVE STRENGTH TESTS[a]

Grading or Specimen Size	Dolomite	Limestone	Quartzite
(a) Los Angeles Abrasion			
Grading[b]:			
A	40.0	26.7	22.0
B	41.0	25.0	23.7
C	33.0	27.5	24.9
(b) Compressive Strength (psi)[c]			
Specimen size (in.):			
1.0 × 1.0 × 1.0	10,100	15,000	25,200
1.0 × 1.0 × 2.0	8,500	14,300	29,600

[a]Each value is the average of three tests.
[b]According to ASTM Method C 131.
[c]Rate of loading 0.025 in./min.

TABLE 2

PETROGRAPHIC ANALYSIS

Determination	Dolomite	Limestone	Quartzite
Megascopic identification	Dolomite, medium-grained, indistinct banding	Calcite, medium-grained, indistinct banding	Hematitic, medium-grained quartzite, indistinct banding, numerous recemented fractures
Bulk minerals:			
Kind	Dolomite Fine pyrite	Calcite Pyrite Organics	Quartz Pyrite
Volume (%)	99 1	>95 1-2 1	90 4-7
Avg. grain size (mm)	0.2 -	0.5 0.2 -	0.8 0.1
Range (mm)	0.1-0.4 -	0.1-1 0.1-0.3 -	0.01-1.0 -
Composition and nature of matrix and cementing material	Smaller mesh of dolomite	Fine-grained carbonate matrix	Very fine-grained quartz and sericite (fibrous)
Decomposition	Nil	Nil	Nil
Degree of leaching	Minor	Nil	Nil
Secondary minerals	Negligible, where present consist limonite and hematite	Total % (vol.) 1 limonite, hematite	Hematite as coatings and finely disseminated grains; sericite in seams and disseminated throughout
Secondary cementation	Absent	Unobservable	-
Percent void	6.0	0.7	0.5
Nature of the grain boundaries	Loose interlocking	Good interlocking	Rock and grains are both highly fractured (cataclastic structure); all quartz grains display a prominent wave extinction, indicating a highly-stressed rock
Fracturing and cracking	Low	Not significant	-
Particle orientation	Random (sometimes lineation due to deposition)	Random	Moderate lining along the long axis of the grains
Banding	Indistinct	Indistinct banding; lenses of fine particles	Moderate banding depending on particle size
Other structure	Several pockets with concentration of very fine-grained materials; low porosity in pockets	Marked change from very coarse mesh to very fine mesh	Recemented granulated matrix

TABLE 3

RESULTS OF TESTS ON ASPHALT CEMENT

Specific gravity, 77/77 F	1.032
Softening point, ring and ball (°F)	114.0
Ductility, 77 F (cm)	200+
Penetration (mm):	
100 g, 5 sec, 77 F	90
100 g, 5 sec, 32 F	20
Flash point, Cleveland open cup (°F)	600
Solubility in CCl_4 (%)	99.8

TABLE 4

ORIGINAL GRADATIONS

Sieve	Analysis (% passing)		
	Grading O	Grading B	Grading F
½ In.	100.0	100.0	100.0
⅜ In.	75.0	86.0	86.6
No. 3	50.0	62.0	70.7
No. 4	25.0	50.0	61.2
No. 6	0.0	45.0	51.4
No. 8	--	36.0	43.3
No. 12	--	25.0	36.3
No. 16	--	16.0	30.0
No. 30	--	11.0	22.0
No. 50	--	6.0	15.0
No. 100	--	4.0	10.9
No. 200	--	3.0	7.7

The three gradations (Table 4 and Fig. 1) ranged from an open grading, consisting only of the top four sizes, to a Fuller gradation for well-graded material. The maximum size of all three gradations was one-half inch.

Aggregates for each specimen were batched by component fractions according to the blend formula. A batch consisted of 1,000 g. The blended aggregates for specimens containing asphalt were heated to 275° ± 10°F. The asphalt was heated separately

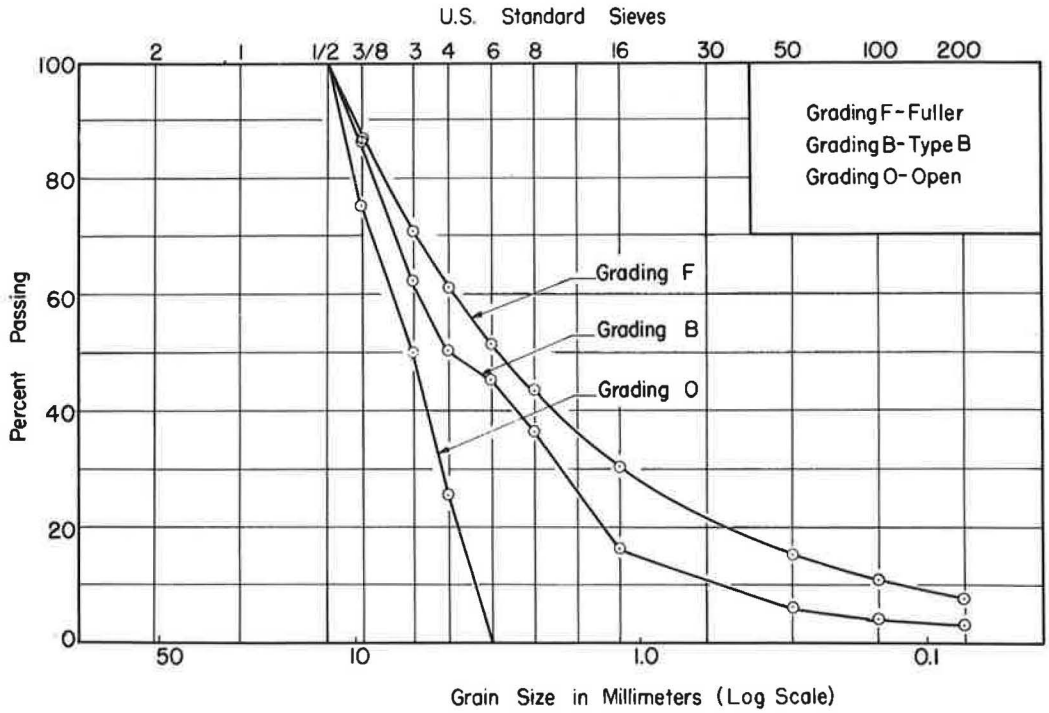

Figure 1. Gradation curves for original gradations.

to 290° to 300°F. Mixing was for 2 min using a Hobart electric mixer modified with a special paddle and a scraper. For those cases in which the aggregate was tested without asphalt, the aggregate was not heated or subjected to mixing.

Because this study was solely a laboratory investigation, a fundamental part of it was the selection of testing equipment which would produce specimens similar to pavement with respect to density and structure. Many methods of compaction have been devised and used to simulate field compaction in the laboratory. Most methods are based principally on the concept of equal density. Equal density without regard to orientation and degradation of particles cannot produce representative specimens and, unfortunately, there is no way to measure the structure of specimens quantitatively. The only way in which it seems possible to compare the structure of the compacted materials is to compare the forces involved in producing the laboratory specimen and the field mat. The methods that incorporate horizontal forces and apply shear to the specimen throughout its depth seem to be the most suitable ones. Therefore, of all available methods, gyratory compaction appeared to be the most promising one to produce specimens similar to the field mat from the density and structure standpoint.

A gyratory testing machine (Fig. 2) was used. It was possible to change the compactive effort in two ways: (a) change in magnitude of load, and (b) change in repetition of load. The magnitude of load, controlled by vertical pressure, was varied from 50 to 250 psi; and the repetition of load, controlled by the number of gyrations, ranged from 30 to 250, for the most part, but in some cases up to 1,000 gyrations were used.

The mixtures were brought from the mixing temperature to 230°F and were placed in the gyratory machine for compaction. Electric heating elements around the mold provided an elevated temperature throughout the test. After gyration, an extraction test was made on the whole specimen, and the gradation of the extracted aggregate was determined for comparison with gradation before mixing and compaction.

To study the effect of particle shape on degradation, it was desirable that the rounded pieces not differ from the crushed ones in composition. Therefore, artificially rounded pieces were produced by subjecting angular pieces to a few thousand revolutions in a Los Angeles machine (Fig. 3).

To investigate how various sizes of aggregate degrade in an aggregation of pieces of different sizes, the three top sizes were dyed different colors so that after compaction and extraction of asphalt the newly produced pieces could be associated with the original piece by colored faces. For this purpose the dyes had to be soluble in water, stay on the surface of the piece, and not be soluble in asphalt or the trichloroethylene used in extraction. The following dyes were found to have such characteristics: (a) orseillin BB red, (b) crystal violet, (c) malachite green oxalate.

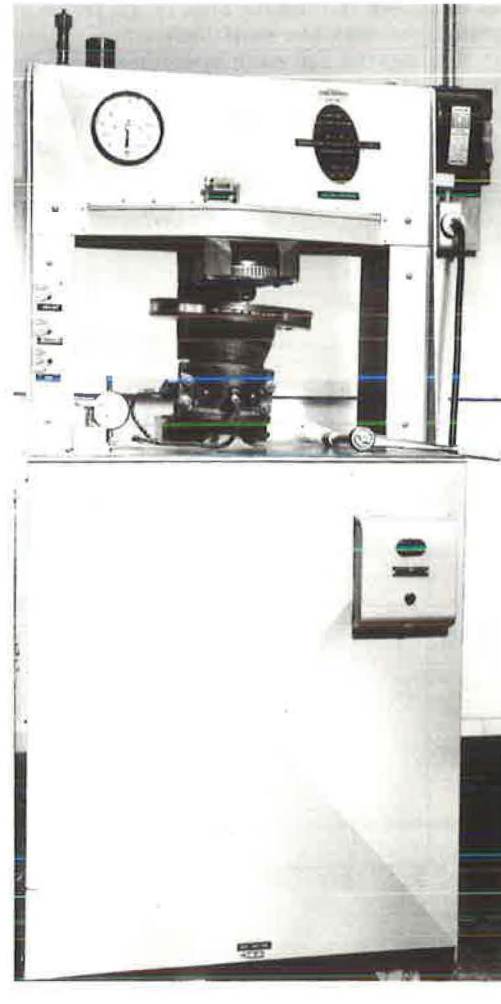

Figure 2. Gyratory testing machine.

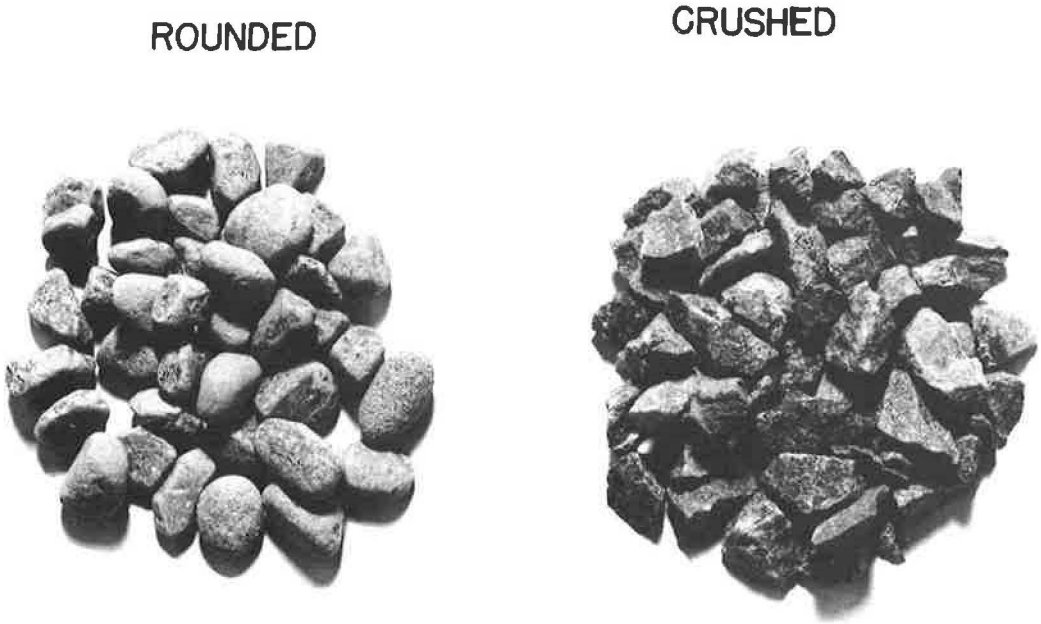

Figure 3. Rounded and crushed quartzite.

RESULTS

Of the several methods available to represent the degradation characteristics of aggregate, two were chosen: one was a simple gradation curve of percent smaller than certain sizes, and the other was based on surface-area concepts. Using the surface-area concept, measurements of the degradation were made on the basis of surface-area increase as determined by sieve analysis. The computing factors are given in Table 5 for an assumed specific gravity of 2.65. Values were calculated on the assumption that all material passing the No. 4 sieve was spherical and that retained was one-third cubes and two-thirds parallelepipeds with sides of 1:2:4 proportions.

It was decided that numerical increase in surface area, which is merely the difference between the final surface area and the original surface area, is not a satisfactory measure of aggregate degradation. For example, when a mixture with an original surface area of 2.2 cm^2/g has increased 2.2 cm^2/g in surface area after compaction, and another mixture with 67.3 cm^2/g has increased the same amount, it cannot be considered that the two mixtures have undergone equal degradation. The first mixture has gained 100 percent in surface area (its final surface area is twice the original), whereas the second mixture has increased only 3 percent.

TABLE 5

SURFACE-AREA FACTORS[a]

Fraction of Material		Factor (sq cm per g)
Passing	Retained	
1/2 In.	3/8 In.	2.2
3/8 In.	1/4 In.	3.2
No. 3	No. 4	4.5
No. 4	No. 6	5.7
No. 6	No. 8	7.9
No. 8	No. 16	12.7
No. 16	No. 50	30.0
No. 50	No. 100	100.0
No. 100	No. 200	205.0
No. 200	Pan	615.0

[a]Assumed specific gravity = 2.65; for values other than 2.65, multiply the above factors by 2.65/sp. gr.

Therefore, it was decided to express the data in percent increase in surface area rather than increase in surface area. Another advantage of the percentage method is the elimination of the necessity for correction of surface-area values for specific gravity.

Herein, the term degradation is used to include all of the aggregate breakdown due to mechanical action regardless of the type of mechanical action. Degradation can result from aggregate fracture or breakage through the piece, from chipping or corner breakage, and from the rubbing action of one piece or particle against another. In parts of this study, attempts were made to separate degradation into two parts: one due to fracture through the piece and designated as breakage, and the other due to corner breakdown and attrition which collectively have been designated as wear.

Degradation of One-Sized Aggregate

Size of particles and maximum size of particles are cited in the literature among the factors controlling degradation. To determine whether or not change of size will change the degradation characteristics of an aggregate and to investigate the effect of combinations of pieces of different sizes on degradation, specimens of one-sized aggregate were tested (Table 6).

Figure 4 shows the sieve analysis on specimens made of limestone aggregate; regardless of size of aggregate, all the curves approach a parabolic shape. Plots of the data in Table 6 for the other two aggregates would show that this conclusion obtains with respect to type of aggregate as well. As original size of particles decreases there is also a corresponding increase in fine material, which suggests that degradation increases as particle size decreases. Figure 5 shows the percent increase in surface area versus average size of original particles for the three aggregates. As the size of one-sized aggregate increases, the degradation under equal compactive effort (200 psi and 100 revolutions) increases.

At first glance it appears that the results of sieve analysis and percent increase in surface area are in conflict. However, sieve analysis indicates only what percent of material is of which size, without considering its original condition and the changes through which it has gone. A larger piece has to undergo more breakdown than a smaller particle to be reduced to a certain size. Therefore, although sieve analysis is an excellent way to study the pattern of degradation, it is by no means a measure of degradation. By relating the produced area to the original area, the concept of percent increase in surface area is a much better means of measuring degradation.

Figure 5 also shows that degradation increases from quartzite to limestone to dolomite, following the same pattern indicated by the Los Angeles rattler test. In other words, degradation of one-sized material increases as it becomes weaker and softer (higher Los Angeles value).

TABLE 6

RESULTS OF GYRATORY TESTS OF VARIOUS ONE-SIZED AGGREGATES
(200 psi; 100 revolutions)

Determination	Dolomite				Limestone				Quartzite			
Original Size	½ to ⅜ In.	⅜ In. to No. 3	No. 3 to 4	No. 4 to 6	½ to ⅜ In.	⅜ In. to No. 3	No. 3 to 4	No. 4 to 6	½ to ⅜ In.	⅜ In. to No. 3	No. 3 to 4	No. 4 to 6
(a) Total Percent Passing												
Sieve size:												
½ in.	100.0	--	--	--	100.0	--	--	--	100.0	--	--	--
⅜ in.	59.8	100.0	--	--	55.3	100.0	--	--	48.6	100.0	--	--
No. 3	37.3	53.6	100.0	--	32.0	58.4	100.0	--	23.2	43.8	100.0	--
No. 4	30.6	37.4	48.5	100.0	24.9	34.1	54.3	100.0	17.9	26.6	37.0	100.0
No. 6	25.2	29.6	32.5	46.5	20.2	25.7	33.7	53.6	14.0	19.2	19.3	38.1
No. 8	21.3	24.5	25.8	31.0	16.5	19.8	24.7	32.3	11.3	14.8	14.5	20.8
No. 16	14.2	16.4	16.7	18.7	10.7	12.1	14.7	17.0	7.0	8.8	8.3	10.6
No. 50	7.2	8.1	8.4	9.0	4.7	4.8	5.8	6.2	3.1	3.5	3.4	3.7
No. 100	5.4	6.0	6.1	6.8	2.9	3.1	3.6	3.8	1.8	2.1	2.2	2.4
No. 200	3.8	4.1	4.5	5.0	1.8	2.0	2.2	2.4	1.1	1.3	1.5	1.6
(b) Weight and Surface Area												
Total weight (g)	1,000.0	1,000.0	1,000.5	1,000.0	992.5	992.5	992.0	1,000.0	1,000.0	1,000.0	1,000.0	1,000.0
Surface area:												
Final (cm^2/g)	34.0	37.8	40.4	45.5	19.7	22.6	25.9	29.6	13.8	16.9	18.4	20.1
Original (cm^2/g)	2.2	3.2	4.5	5.7	2.2	3.2	4.5	5.7	2.2	3.2	4.5	5.7
Increase (cm^2/g)	21.8	34.6	35.9	39.7	17.5	19.4	21.4	23.9	11.6	13.7	13.9	14.4
Increase (%)	1,443.0	1,081.0	800.0	696.0	795.4	606.2	479.0	419.3	528.6	428.1	308.9	252.6

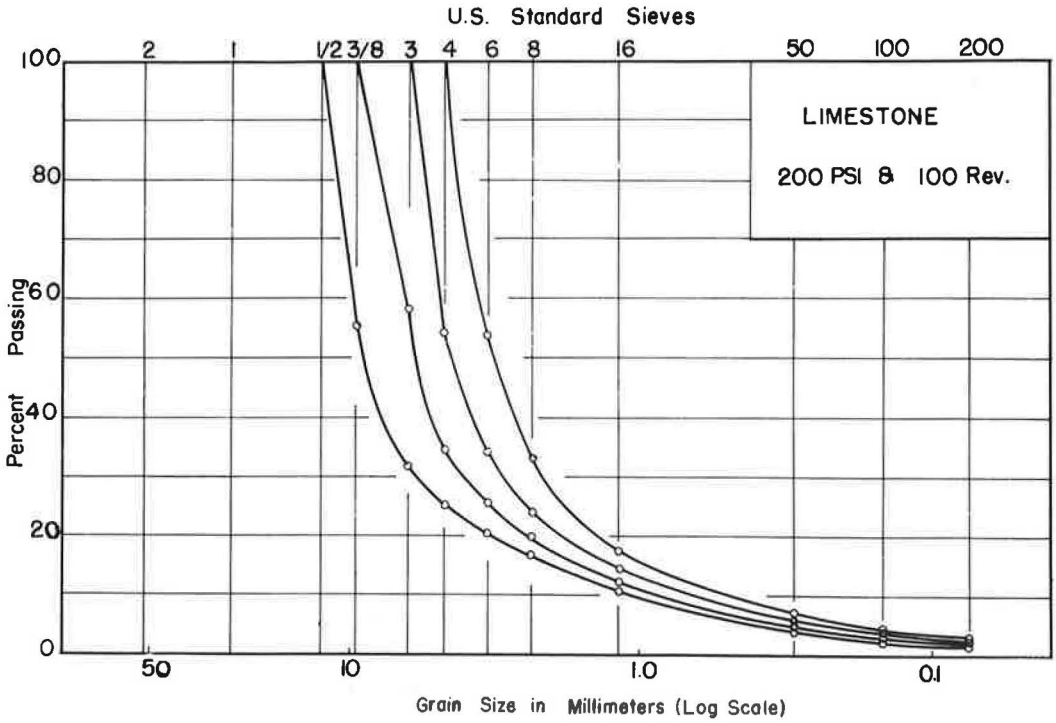

Figure 4. Sieve analysis of one-sized limestone aggregates after gyratory compaction.

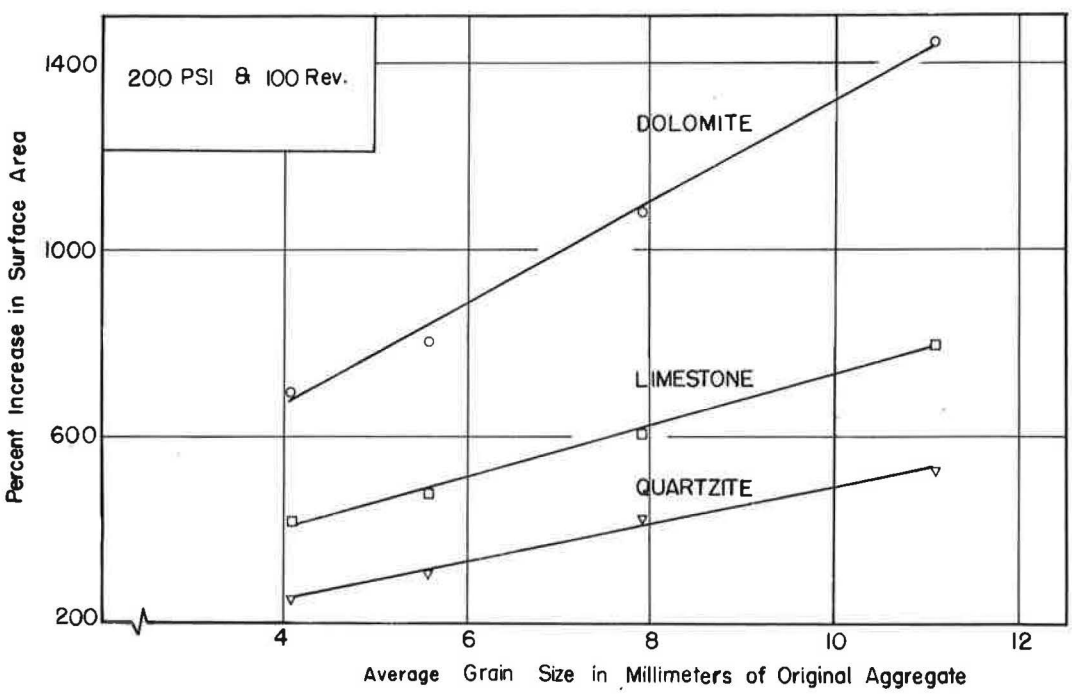

Figure 5. Degradation vs aggregate size; gyratory compaction, one-sized aggregate.

Figure 6 shows a linear relationship between the Los Angeles values of the three kinds of aggregate and the degradation of the one-sized aggregate when tested in the gyratory compactor and measured in percent increase in surface area.

The effect of change of compactive effort on the degradation of one-sized aggregate was studied by changing the number of revolutions of gyratory compaction. Five specimens of each kind of aggregate (original sieve size: $^3/_8$ in. to No. 3) were compacted under 100-psi ram pressure and five different numbers of revolutions (Table 7). The results of sieve analysis of dolomite aggregate after compaction indicate that the general shape of the gradation curve is not changed by a change in compactive effort; as compactive effort increases the curve shifts upward (Fig. 7).

Figure 8 shows that as compactive effort increases the degradation also increases, but generally a significant portion of the degradation occurs under the first few hundred revolutions and then the curves start leveling off. As the material becomes softer or weaker, the slope of the latter part of the curves increases, indicating that the degradation of such materials is more susceptible to change in compactive effort.

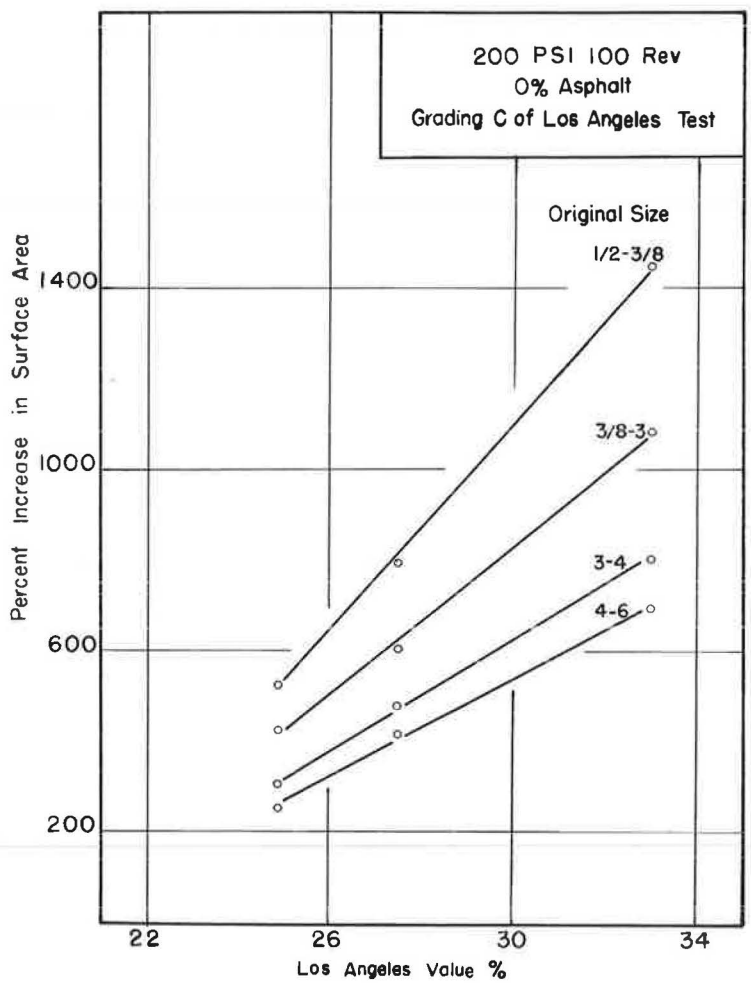

Figure 6. Degradation vs Los Angeles value; gyratory compaction, one-sized aggregate.

TABLE 7

RESULTS OF GYRATORY TESTS OF ONE-SIZED AGGREGATES
(100 psi)

Determination	3/8 In. to No. 3 Dolomite					3/8 In. to No. 3 Limestone					3/8 In. to No. 3 Quartzite				
No. of Rev.	50	100	250	500	1,000	50	100	250	500	1,000	50	100	250	500	1,000
(a) Total Percent Passing															
Sieve size:															
3/8 in.	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
No. 3	34.3	42.9	45.6	48.2	50.0	29.7	36.7	38.9	41.9	47.3	28.8	31.6	35.7	39.8	43.7
No. 4	19.5	22.0	25.8	30.7	32.1	16.8	21.2	23.3	27.4	30.5	15.2	17.1	20.0	23.8	27.5
No. 6	14.5	16.0	20.3	23.0	25.5	11.0	14.8	16.6	20.1	23.1	10.4	11.9	14.3	17.8	20.7
No. 8	11.1	12.5	15.5	18.5	20.6	8.5	11.6	13.4	16.6	19.8	7.6	8.8	10.9	14.0	16.5
No. 16	6.6	7.3	10.0	14.0	15.6	4.6	6.6	8.2	10.7	13.4	4.1	4.9	6.4	9.0	10.8
No. 50	3.2	3.6	5.5	7.3	8.3	1.8	2.7	3.5	4.7	6.2	1.5	1.9	2.6	4.1	4.9
No. 100	2.4	2.7	4.1	5.5	6.1	1.2	1.8	2.3	3.1	4.1	0.9	1.1	1.6	2.4	3.0
No. 200	1.7	2.0	2.8	3.9	4.3	0.8	1.3	1.5	2.1	2.7	0.5	0.7	1.0	1.5	1.8
(b) Weight and Surface Area															
Total weight (g)	1,000.0	999.5	1,000.0	1,000.0	1,000.0	1,000.0	1,000.0	995.0	1,000.0	1,000.0	1,000.0	999.5	999.0	1,000.0	1,000.0
Surface area:															
Final (cm^2/g)	18.0	19.8	27.2	34.0	38.3	11.5	15.3	17.8	22.4	27.9	9.6	11.3	13.7	18.3	21.2
Original (cm^2/g)	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2
Increase (cm^2/g)	14.8	16.6	24.0	30.8	35.1	8.3	12.1	14.6	19.2	24.7	6.4	8.1	10.5	15.1	18.0
Increase (%)	463.0	530.0	750.0	962.0	1,097.0	260.0	378.0	457.0	600.0	773.0	200.0	255.0	330.0	473.0	563.0

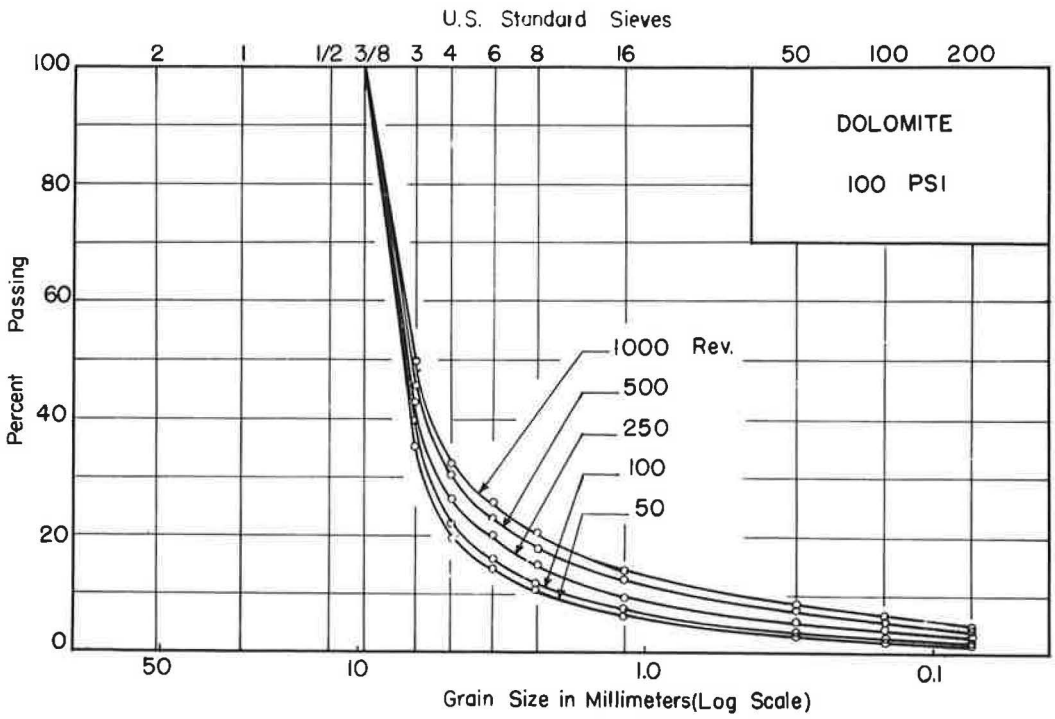

Figure 7. Sieve analysis of one-sized dolomite aggregates; varying number of revolutions of gyratory compactor.

Degradation of Individual Sizes in an Aggregation of Sizes

Before making a detailed analysis of the effect of variables on degradation of different mixtures, it was necessary to investigate the changes that occur in degradation characteristics of each particle size due to the presence of other sizes in the specimen. A dyeing process was used to determine the size fraction from which each particle was produced when degradation occurred. Because previous studies indicated that the kind of aggregate changes only the magnitude of degradation and has no effect on its pattern, it was decided to use only one kind of aggregate: the limestone, with the intermediate Los Angeles value, which could be satisfactorily dyed. Because separating

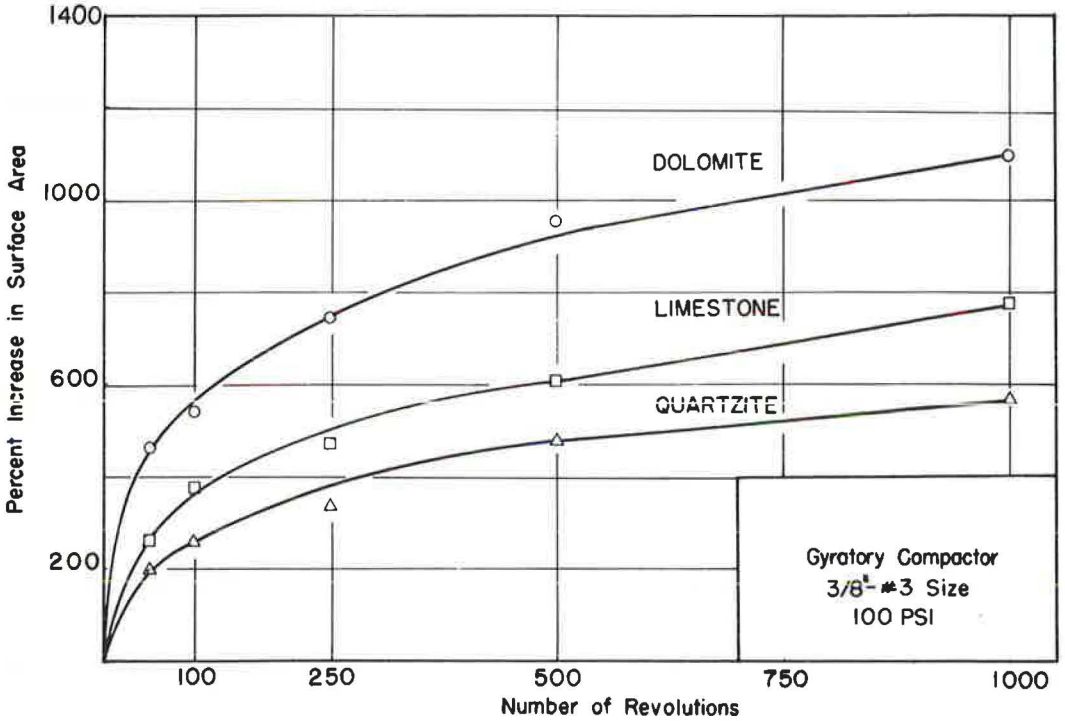

Figure 8. Degradation vs number of revolutions for one-sized aggregates.

the fractions of different colors by hand is time-consuming, it was decided to dye only the top three sizes—½ in. to ⅜ in., ⅜ in. to No. 3, and No. 3 to No. 4. Had a difference in pattern of degradation due to the size been noticed, then other sizes would have been dyed. The materials were separated only down to the No. 30 sieve. The factors considered as variables were gradation of aggregate, compactive effort, and presence or absence of asphalt.

The gradings O, B, and F given in Table 4 were used. Twenty-four samples of three gradations, without asphalt and with 4 percent asphalt, were tested under four different compactive efforts in the gyratory machine. The results of sieve analysis of each colored fraction, and sieve analysis of the total specimen are given in Tables 8, 9, and 10.

Figure 9 shows the sieve analysis of each fraction of a specimen without asphalt having an original open gradation and being subjected to 200-psi ram pressure and 100 revolutions in the gyratory compactor. The curves indicate that the degradation of each fraction has a constant pattern of a smooth curve approaching a parabola. Figures 10, 11, and 12 show the sieve analysis of each fraction for specimens with 4 percent asphalt and original gradings O, B, and F. The pattern of degradation of each fraction is also a constant.

The results obtained with colored aggregate showed that when particles of different sizes are mixed together and subjected to a certain compactive effort each size will break down into smaller particles whose new gradation has a characteristic size distribution. This size distribution follows a smooth curve and approaches a parabola similar to the curves obtained for specimens made of one-sized aggregates tested separately. Therefore, this portion of the study indicated that degradation of one-sized particles follows a definite pattern regardless of its size or the gradation with which it is associated, magnitude of compactive effort, or presence of asphalt. Also, from the first part of the study it was found that the degradation pattern is independent of kind of aggregate; hence, it can be concluded that when the pattern of degradation of

TABLE 8

RESULTS OF SIEVE ANALYSIS OF COLORED AGGREGATES, GRADING O_1

Sieve	Total Percent Passing									
	30 Rev.					100 Rev.				
	½ to ⅜ In. Violet	⅜ In. to No. 3 Red	No. 3 to 4 Green	No. 4 to 6 Natural	Total	½ to ⅜ In. Violet	⅜ In. to No. 3 Red	No. 3 to 4 Green	No. 4 to 6 Natural	Total
	(a) 100 Psi; 0% Asphalt									
½ In.	100.0				100.0	100.0				100.0
⅜ In.	25.5	100.0			81.4	27.7	100.0			83.3
No. 3	11.6	24.3	100.0		59.0	13.2	32.4	100.0		61.0
No. 4	8.2	10.0	31.1	100.0	37.3	10.0	14.7	40.4	100.0	40.8
No. 6	5.6	7.0	15.0	48.2	18.4	7.0	10.3	22.1	59.8	24.5
No. 8	4.0	5.2	10.4	23.7	10.8	5.2	8.1	15.5	32.4	15.2
No. 16	1.9	3.2	5.3	9.6	5.0	3.2	5.0	8.0	15.6	7.9
No. 50	0.9	1.6	2.0	2.2	1.6	2.0	2.5	3.0	4.0	2.8
No. 100					1.0					1.8
No. 200					0.7					1.1
Total Weight, g	250.0	251.0	251.0	251.0	1,003.0	251.5	251.5	251.5	251.5	1,006.0
	(b) 200 Psi; 0% Asphalt									
½ In.	100.0				100.0	100.0				100.0
⅜ In.	44.0	100.0			86.0	52.2	100.0			88.1
No. 3	19.4	45.6	100.0		66.8	23.6	49.4	100.0		68.3
No. 4	14.0	20.5	43.0	100.0	44.7	16.6	22.2	49.4	100.0	47.1
No. 6	10.8	13.9	24.5	69.1	29.6	12.8	16.4	28.4	77.2	33.7
No. 8	8.6	10.9	16.9	39.8	19.1	10.2	12.6	20.8	48.8	23.1
No. 16	5.4	6.1	9.5	17.3	9.6	7.1	8.2	11.9	24.0	12.0
No. 50	2.9	3.5	4.6	5.9	3.3	4.6	5.2	6.9	7.8	4.9
No. 100					2.1					3.1
No. 200					1.3					1.9
Total Weight, g	250.0	251.0	251.0	251.0	1,003.0	249.8	249.8	250.0	250.0	999.5
	(c) 100 Psi; 4% Asphalt									
½ In.	100.0				100.0	100.0				100.0
⅜ In.	19.6	100.0			79.9	25.0	100.0			79.4
No. 3	6.2	25.4	100.0		57.9	11.0	29.6	100.0		58.9
No. 4	4.4	8.4	28.4	100.0	35.3	8.0	11.0	36.2	100.0	38.0
No. 6	3.0	4.8	11.6	49.4	17.2	5.0	7.0	16.2	55.2	20.2
No. 8	2.2	3.4	7.2	24.6	9.4	3.0	4.8	10.8	30.8	11.9
No. 16	1.1	1.5	3.5	10.5	4.1	1.8	3.0	5.7	14.9	5.7
No. 30	0.5	0.7	2.0	5.8	2.2	1.0	2.0	4.3	9.1	3.4
No. 50					1.3					2.1
No. 100					0.8					1.5
No. 200					0.5					1.0
Total Weight, g	250.0	250.0	250.0	250.0	1,000.0	250.0	250.0	250.0	250.0	1,000.0
	(d) 200 Psi; 4% Asphalt									
½ In.	100.0				100.0	100.0				100.0
⅜ In.	30.5	100.0			84.1	34.0	100.0			83.0
No. 3	14.9	36.5	100.0		62.9	17.0	43.0	100.0		64.5
No. 4	10.1	14.5	45.6	100.0	42.6	12.0	20.2	48.0	100.0	44.8
No. 6	7.9	10.3	25.4	60.6	28.1	8.6	13.6	29.2	65.4	29.2
No. 8	5.7	6.9	18.0	35.2	18.0	7.1	10.0	21.2	39.7	19.5
No. 16	2.9	3.8	9.2	20.2	9.1	4.1	5.8	12.6	23.5	10.5
No. 30	1.8	2.8	6.9	13.0	5.4	2.6	3.5	9.2	17.0	6.3
No. 50					3.4					3.9
No. 100					2.2					2.5
No. 200					1.5					1.6
Total Weight, g	250.0	250.0	250.0	250.0	1,000.0	250.0	250.0	250.0	250.0	1,000.0

TABLE 9

RESULTS OF SIEVE ANALYSIS OF COLORED AGGREGATES, GRADING B

Sieve	Total Percent Passing									
	30 Rev.					100 Rev.				
	½ to ⅜ In. Violet	⅜ In. to No. 3 Red	No. 3 to 4 Green	No. 4 to 6 Natural	Total	½ to ⅜ In. Violet	⅜ In. to No. 3 Red	No. 3 to 4 Green	No. 4 to 6 Natural	Total
	(a) 100 Psi; 0% Asphalt									
½ In.	100.0				100.0	100.0				100.0
⅜ In.	20.1	100.0			89.4	22.5	100.0			88.3
No. 3	6.0	19.0	100.0		67.4	6.8	19.6	100.0		67.5
No. 4	3.4	4.4	23.7	100.0	54.5	5.0	7.3	25.4	100.0	55.2
No. 6	2.5	3.1	9.1	90.2	48.8	3.2	5.7	12.5	93.2	49.7
No. 8	1.4	2.1	4.5	75.1	40.7	1.8	3.7	7.8	78.8	41.8
No. 16	0.4	0.6	1.3	40.5	20.5	0.7	2.4	4.3	43.4	22.2
No. 30	0.1	0.3	0.5	26.8	13.4	0.2	1.6	2.5	28.6	14.8
No. 50					7.8					8.7
No. 100					5.4					5.9
No. 200					3.6					4.0
Total Weight, g	140.0	240.0	120.0	499.0	999.0	140.0	240.0	120.0	498.0	998.0
	(b) 200 Psi; 0% Asphalt									
½ In.	100.0				100.0	100.0				100.0
⅜ In.	24.7	100.0			89.6	26.1	100.0			89.6
No. 3	9.2	26.7	100.0		69.9	10.5	30.0	100.0		70.2
No. 4	6.4	9.4	31.7	100.0	57.0	7.2	11.6	32.9	100.0	57.4
No. 6	4.4	6.8	14.2	95.2	51.1	5.8	7.4	17.1	96.7	51.8
No. 8	2.2	4.4	9.2	82.2	43.3	2.8	5.7	11.3	84.7	44.2
No. 16	1.1	3.2	5.5	45.0	23.3	1.7	4.2	6.7	47.9	34.4
No. 30	0.4	2.3	3.0	30.6	15.6	0.7	3.2	3.5	32.4	16.3
No. 50					9.2					9.8
No. 100					6.3					7.1
No. 200					4.2					4.8
Total Weight, g	140.0	240.0	120.0	499.0	999.0	140.0	240.0	120.0	500.0	1,000.0
	(c) 100 Psi; 4% Asphalt									
½ In.	100.0				100.0	100.0				100.0
⅜ In.	16.8	100.0			88.0	18.5	100.0			88.4
No. 3	3.9	23.7	100.0		65.8	4.7	24.6	100.0		68.6
No. 4	2.1	4.1	15.8	100.0	53.1	3.3	6.7	20.0	100.0	54.5
No. 6	1.7	2.4	5.4	93.5	48.1	2.2	4.6	9.2	93.7	49.4
No. 8	1.3	1.6	3.3	77.7	39.7	1.5	2.9	5.0	78.7	40.9
No. 16	0.7	1.0	1.6	40.3	20.4	0.9	1.5	2.1	41.1	21.2
No. 30	0.2	0.4	0.8	26.8	13.4	0.4	0.8	1.2	27.3	14.0
No. 50					9.0					9.4
No. 100					5.7					5.9
No. 200					3.6					3.8
Total Weight, g	140.0	240.0	120.0	500.0	1,000.0	140.0	240.0	120.0	500.0	1,000.0
	(d) 200 Psi; 4% Asphalt									
½ In.	100.0				100.0	100.0				100.0
⅜ In.	19.7	100.0			89.0	21.4	100.0			89.9
No. 3	5.7	26.3	100.0		69.1	8.2	27.5	100.0		69.4
No. 4	4.0	8.6	27.1	100.0	56.4	6.0	10.7	35.5	100.0	56.8
No. 6	3.0	6.8	12.9	94.2	50.6	4.3	8.8	18.8	94.7	50.6
No. 8	2.4	3.7	7.5	80.2	42.3	3.2	6.0	13.8	81.7	43.2
No. 16	1.9	2.6	3.8	42.0	22.1	2.5	3.2	7.3	44.1	23.1
No. 30	1.0	1.9	2.6	28.5	15.0	1.5	2.3	5.5	29.3	15.4
No. 50					9.1					9.5
No. 100					6.4					6.6
No. 200					4.4					4.7
Total Weight, g	140.0	240.0	120.0	496.5	996.5	140.0	240.0	120.0	490.0	990.0

TABLE 10

RESULTS OF SIEVE ANALYSIS OF COLORED AGGREGATES, GRADING F

Sieve	Total Percent Passing									
	30 Rev.					100 Rev.				
	½ to ⅜ In. Violet	⅜ In. to No. 3 Red	No. 3 to 4 Green	No. 4 to 6 Natural	Total	½ to ⅜ In. Violet	⅜ In. to No. 3 Red	No. 3 to 4 Green	No. 4 to 6 Natural	Total
	(a) 100 Psi; 0% Asphalt									
½ In.	100.0				100.0	100.0				100.0
⅜ In.	15.7	100.0			86.7	18.9	100.0			87.7
No. 3	4.0	17.0	100.0		73.8	5.9	18.2	100.0		74.0
No. 4	2.6	4.7	16.8	100.0	63.9	3.9	5.7	21.1	100.0	64.2
No. 6	1.9	3.1	6.3	87.7	56.2	2.9	4.1	9.5	89.6	56.4
No. 8	1.2	2.2	3.7	74.1	47.4	1.8	2.8	6.3	76.5	47.8
No. 16	0.4	1.1	1.9	53.1	32.8	0.8	1.6	3.8	53.8	33.2
No. 30	0.1	0.7	1.1	37.5	23.0	0.5	0.9	2.3	38.5	23.6
No. 50					17.1					17.3
No. 100					13.3					14.3
No. 200					9.1					10.3
Total Weight, g	134.0	159.0	95.0	612.0	1,000.0	134.0	159.0	95.0	612.0	1,000.0
	(b) 200 Psi; 0% Asphalt									
½ In.	100.0				100.0	100.0				100.0
⅜ In.	21.7	100.0			89.5	32.1	100.0			90.9
No. 3	8.3	22.1	100.0		76.1	11.9	26.6	100.0		79.9
No. 4	4.9	9.8	25.3	100.0	65.8	8.5	12.3	38.9	100.0	68.4
No. 6	3.8	6.3	11.1	91.0	58.1	6.3	8.4	20.5	92.3	61.0
No. 8	2.4	4.8	7.8	79.0	49.7	4.1	5.5	12.1	81.7	52.9
No. 16	1.1	2.5	4.8	56.0	34.7	2.3	3.3	6.9	58.8	36.9
No. 30	0.8	1.7	3.0	40.5	25.0	1.4	2.5	4.3	43.5	26.9
No. 50					18.5					19.8
No. 100					15.6					16.3
No. 200					11.6					12.9
Total Weight, g	134.0	159.0	95.0	610.0	998.0	134.0	159.0	95.0	616.0	1,000.0
	(c) 100 Psi; 4% Asphalt									
½ In.	100.0				100.0	100.0				100.0
⅜ In.	11.2	100.0			88.0	15.4	100.0			89.6
No. 3	5.2	14.5	100.0		73.5	6.0	16.0	100.0		74.4
No. 4	3.7	7.3	25.3	100.0	64.1	4.1	8.2	28.9	100.0	64.4
No. 6	2.0	5.7	12.7	83.5	53.4	2.6	6.1	14.1	85.5	54.3
No. 8	1.9	4.0	9.0	73.2	46.5	2.1	4.4	11.9	75.4	47.7
No. 16	0.7	1.6	5.0	52.6	32.4	0.9	2.0	6.0	53.5	33.3
No. 30	0.2	0.6	1.2	38.0	23.1	0.4	1.0	2.0	38.9	24.0
No. 50					17.0					17.6
No. 100					12.4					12.8
No. 200					8.7					8.9
Total Weight, g	134.0	159.0	95.0	607.0	995.0	134.0	159.0	95.0	612.0	1,000.0
	(d) 200 Psi; 4% Asphalt									
½ In.	100.0				100.0	100.0				100.0
⅜ In.	18.3	100.0			89.9	26.5	100.0			90.1
No. 3	6.6	16.9	100.0		74.6	7.7	17.6	100.0		74.9
No. 4	4.8	8.8	36.3	100.0	65.4	5.4	9.6	47.9	100.0	65.9
No. 6	2.9	6.8	15.8	87.8	56.3	3.5	7.4	16.4	88.9	56.5
No. 8	2.4	5.0	12.6	77.9	49.6	3.0	5.8	13.1	78.2	50.5
No. 16	1.2	2.3	7.0	55.5	34.5	1.6	3.2	8.1	56.4	35.2
No. 30	0.7	1.2	2.9	40.5	24.8	1.1	1.8	3.6	42.0	25.4
No. 50					18.4					19.0
No. 100					13.4					14.1
No. 200					9.1					10.3
Total Weight, g	134.0	154.0	95.0	612.0	995.0	134.0	159.0	95.0	605.0	993.0

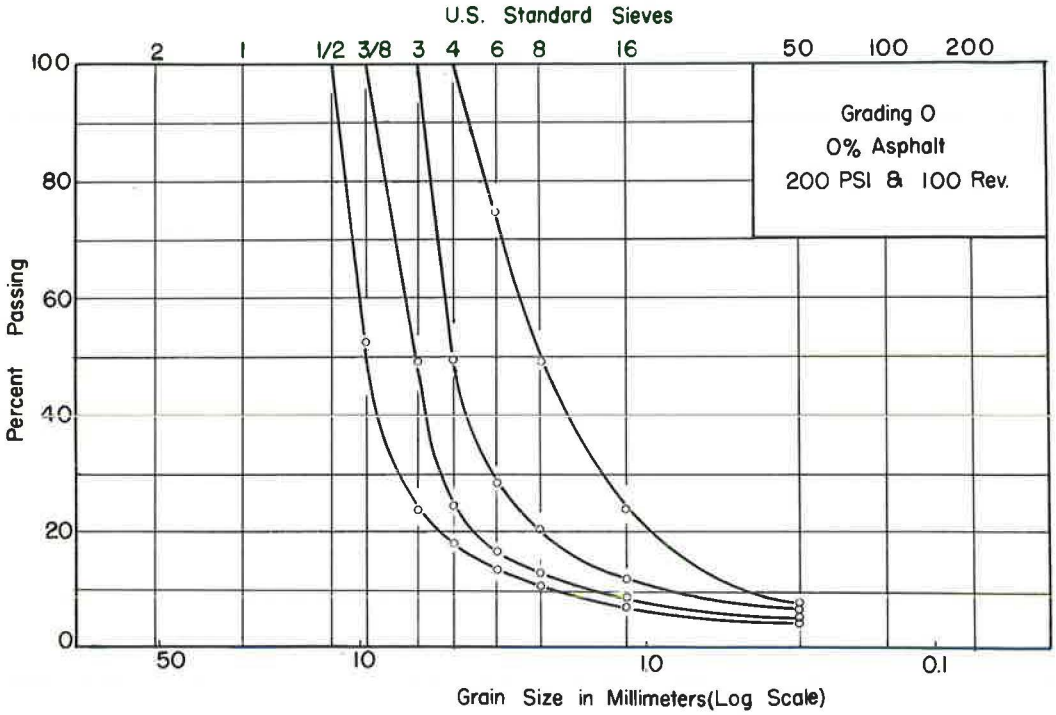

Figure 9. Sieve analysis of compacted colored aggregate.

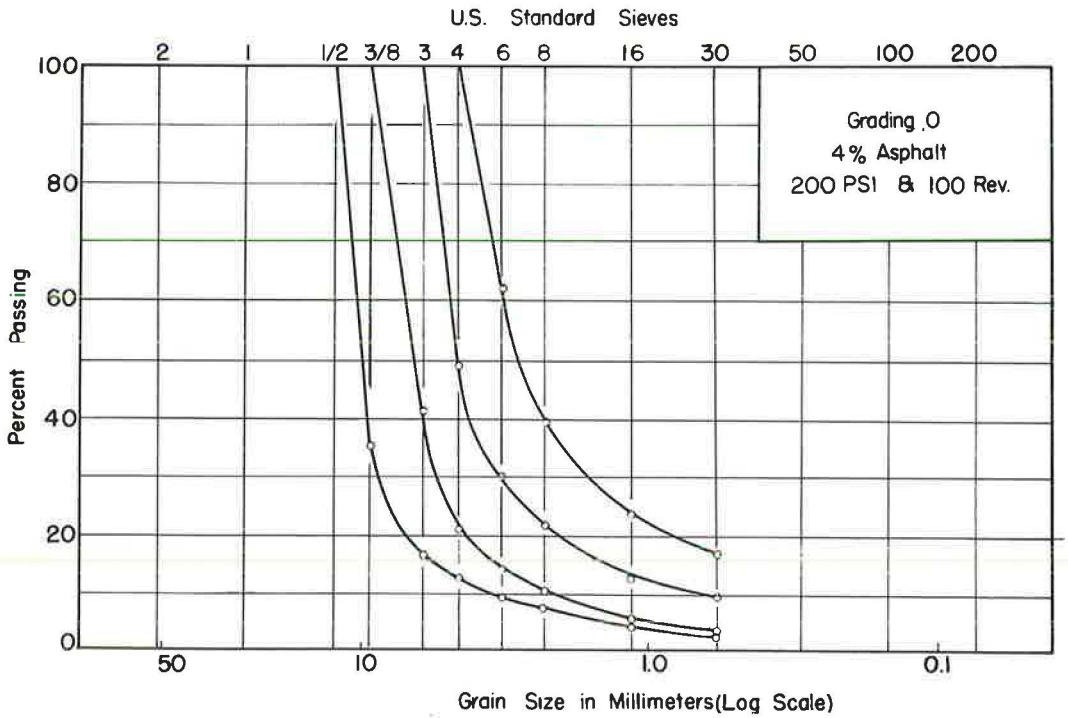

Figure 10. Degradation vs number of revolutions for one-sized aggregates.

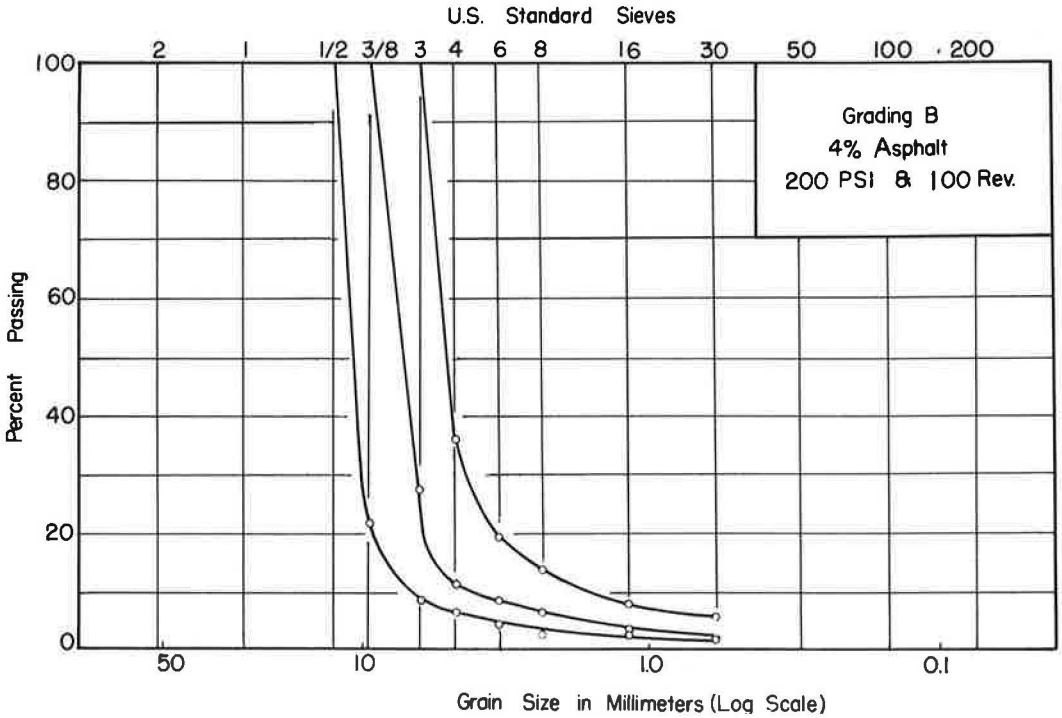

Figure 11. Degradation vs number of revolutions for one-sized aggregates.

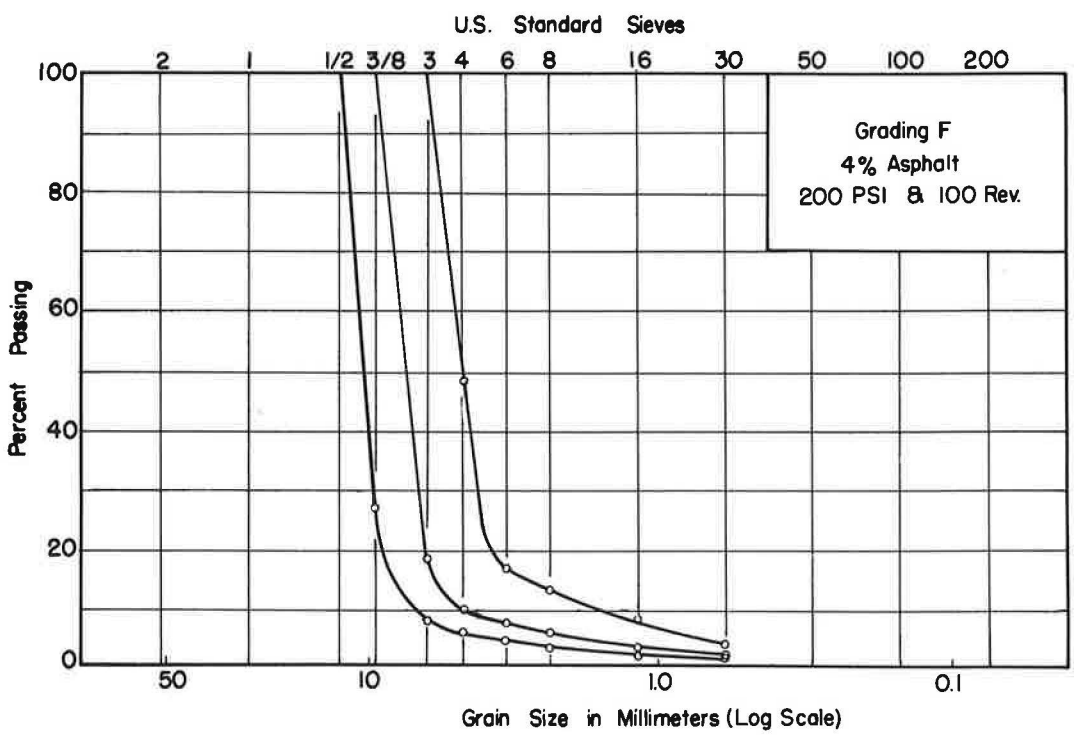

Figure 12. Degradation vs number of revolutions for one-sized aggregates.

each fraction is constant, then the combination of particles of different sizes will have a pattern which depends only on the blending ratios of these sizes rather than on type of aggregate or magnitude of compactive effort.

Thus, it can be stated that if pattern of degradation is a matter of concern, which is the case in ore treatment and in mining and metallurgical engineering, then this pattern can be predicted beforehand by knowing the gradation of feed material. But if magnitude of degradation is a matter of concern, additional variables have to be investigated thoroughly before any prediction can be made concerning this factor. In other words, in addition to gradation, the magnitude of degradation in a degradation process is dependent upon compactive effort, shape of particles, and type of rock even though these factors do not affect its pattern. For example, a change of gradation will not eliminate production of a certain size of particles when particles of larger size than this size are produced. The change in gradation will reduce or increase each size in such a proportion that the final gradation of each fraction will follow a smooth curve approaching a parabolic one. However, this change of gradation will change the magnitude of degradation, because the magnitude of degradation depends on energy consumed for breakage. So any factor affecting the breakage energy will affect the magnitude of degradation. For example, higher compactive effort corresponds to higher breakage energy and thus has to result in higher degradation. But the pattern of degradation is not energy dependent and can be considered as a constant.

Since, for any original gradation, the pattern of degradation is constant, and it is only the magnitude of degradation which varies with other factors, it can be deduced that the effects of degradation on the properties of a given bituminous mixture have to be due to the magnitude of degradation. Therefore, in the detailed study which follows, only the magnitude of degradation has been considered, and attempts are made to find which factors are more effective in reducing the magnitude of degradation and what protective measures can be taken against degradation of aggregate in bituminous mixtures.

Effect of Mixture and Compaction Variables

The magnitude of degradation, measured by percent increase in surface area, was determined for the three types of aggregate, dolomite, limestone, and quartzite. Three gradations, grading O, grading B, and grading F, were used. Compactive effort applied by the gyratory compactor was changed both in ram pressure and number of revolutions. For this purpose 450 specimens were formed and tested, the asphalt was extracted, and a sieve analysis made on the dry aggregate from which the percent increase in surface area for each specimen was calculated.

Table 11 gives data for the percent increase in surface area for each of the three kinds of aggregate.

Ram Pressure and Number of Revolutions.—Figure 13 shows the percent increase in surface area versus number of revolutions for specimens made of limestone with 0 and 4 percent asphalt. All specimens were made of grading O. The ram pressures are indicated on each curve. Degradation increases very rapidly in the first part of the test and then continues to increase at a decreasing rate until about 250 revolutions after which the rate of increase remains constant in each case. Also, as ram pressure increases the degradation in the first few revolutions increases drastically. For a ram pressure of 250 psi, almost 70 percent of the degradation that occurred at 1,000 revolutions had occurred in the first hundred revolutions, whereas at 50-psi ram pressure only 50 percent of the degradation had occurred in the first hundred revolutions.

Figures 14 and 15 show degradation versus ram pressure for specimens made of limestone with 0 and 4 percent asphalt; the results for all three gradings are shown. Degradation on the ordinate is plotted on a log scale; ram pressure on the abscissa is plotted to an arithmetic scale. Gradation designations of original mixtures are shown at the left side of the curves. Degradation increases both with increase in ram pressure and increase in number of revolutions; therefore, degradation increases with increase in compactive effort.

Figures 16 and 17 plot degradation versus number of revolutions. Each curve is for a single ram pressure, as indicated. Degradation for each gradation is plotted on a

TABLE 11

PERCENT INCREASE IN SURFACE AREA

Psi	Rev.	Grading O, % Asphalt				Grading B, % Asphalt				Grading F, % Asphalt			
		0	2	4	6	0	2	4	6	0	2	4	6
						(a) Dolomite							
50	30	258.0				24.0				11.2			
	100	321.0				35.5				16.3			
	250	420.0				44.0				20.0			
	500	500.0				72.2				23.9			
100	30	334.2	309.0	308.0	395.0	41.7	39.7	40.0	47.2	14.4	15.1	12.4	13.1
	60	422.0	382.0	370.0	408.0	52.3	44.5	46.8	51.5	21.0	16.5	14.2	16.3
	100	500.0	410.0	416.0	419.0	61.0	49.5	53.0	59.4	24.5	17.5	17.0	18.9
	250	660.0	470.0	485.0		74.0		60.5		32.8		22.0	
	500	740.0		600.0		105.0		65.5		37.0		25.5	
200	30	628.0	571.0	594.0	563.0	62.3	52.0	62.3	63.4	25.4	19.0	17.5	24.3
	60	805.0	655.0	680.0	734.0	77.1	61.0	68.2	68.3	30.0	22.2	22.7	28.8
	100	937.0	706.0	752.0	757.0	90.0	66.7	75.0	72.0	32.3	25.5	26.5	30.7
	250	1,250.0	890.0	915.0		120.0		84.5		39.0		33.0	
	500	1,440.0		1,070.0		146.0		92.0		44.0		37.0	
250	30	730.0	646.0	648.0	698.0		60.5	69.6	70.6		21.1	20.0	25.3
	60	881.0	775.0	780.0	840.0		70.3	79.3	76.5		25.2	23.9	31.7
	100	1,058.7	859.0	892.0	919.0		80.0	82.0	78.2		29.0	28.6	38.1
	250	1,480.0	1,000.0	1,050.0				95.0				36.2	
	500	1,700.0		1,230.0				102.0				41.5	
						(b) Limestone							
50	30	85.0		68.4		19.6				5.2			
	60	120.5		105.3									
	100	175.5		134.0		30.5				7.4			
	250	220.0		158.0									
	500	275.0		185.0		45.1				14.1			
	1,000	378.0		249.0									
100	30	238.0	204.0	180.0		31.1	25.6	39.7	37.9	11.0	10.5	10.2	11.2
	60	278.0	275.0	255.0		40.6	31.9	45.5	40.3	15.4	14.2	11.2	15.0
	100	320.0	310.0	290.0		47.0	35.0	49.0	42.1	16.9	16.0	13.3	17.5
	250	390.0	365.0	355.0		58.5		54.5		21.6		16.8	
	500	462.0		390.0		72.0		64.0		25.6		18.4	
	1,000	580.0		484.0									
200	30	430.0	374.0	380.0		51.5	43.1	54.8	52.7	15.3	17.0	17.8	17.5
	60	510.0	440.0	493.0		57.9	47.5	60.6	57.3	20.5	21.0	20.0	20.5
	100	594.0	510.0	552.0		64.1	52.5	64.0	64.0	24.5	24.0	22.5	25.5
	250	678.0	600.0	625.0		72.0		76.0		30.0		26.5	
	500	765.0		681.0		90.0		83.6		32.5		30.0	
	1,000	929.0		776.0									
250	30	526.3	427.0	502.0			46.7	59.5	54.0		18.1	19.3	20.6
	60	588.6	559.0	570.0			50.0	66.0	62.1		23.0	22.2	25.8
	100	678.9	639.0	630.0			55.0	71.6	66.0		28.5	26.2	31.2
	250	779.0	720.0	726.3				80.0				30.7	
	500	900.0		807.9				88.0				32.8	
	1,000			955.3									
						(c) Quartzite							
50	30					11.2				2.0			
	100					18.1				4.8			
	250					25.0				7.9			
	500					28.8				13.5			
100	30	126.0	154.0	149.0		15.0	12.6	15.7	21.4	4.3	2.3	3.6	4.3
	60	179.0	202.0	164.0		20.0	20.7	21.5	23.9	7.0	5.3	5.2	6.5
	100	196.0	236.0	198.0		24.9	22.8	30.0	25.9	8.6	8.8	7.0	7.9
	250	230.0	284.0	229.0		33.9		37.5		15.0		9.5	
	500	300.0		270.0		39.0		44.0		18.0		12.5	
200	30	261.0	245.0	250.0		28.4	26.2	27.5	39.1	7.5	7.0	7.0	8.6
	60	334.0	280.0	300.0		37.0	35.6	34.6	42.5	10.3	8.9	9.3	12.1
	100	364.0	338.0	335.0		43.4	37.9	41.2	49.2	13.5	12.0	12.1	15.8
	250	440.0	400.0	405.0		53.8		49.0		18.9		15.5	
	500	530.0		460.0		61.8		58.0		23.8		18.6	
250	30	292.0	300.0	300.0			34.1	32.5	45.0		11.4	9.3	10.2
	60	380.0	325.0	352.0			38.0	38.4	49.6		12.4	11.3	13.6
	100	420.0	370.0	420.0			42.8	45.0	54.5		14.5	15.0	17.0
	250	511.0	444.0	500.0				52.0				17.5	
	500	610.0		560.0				60.0				21.1	

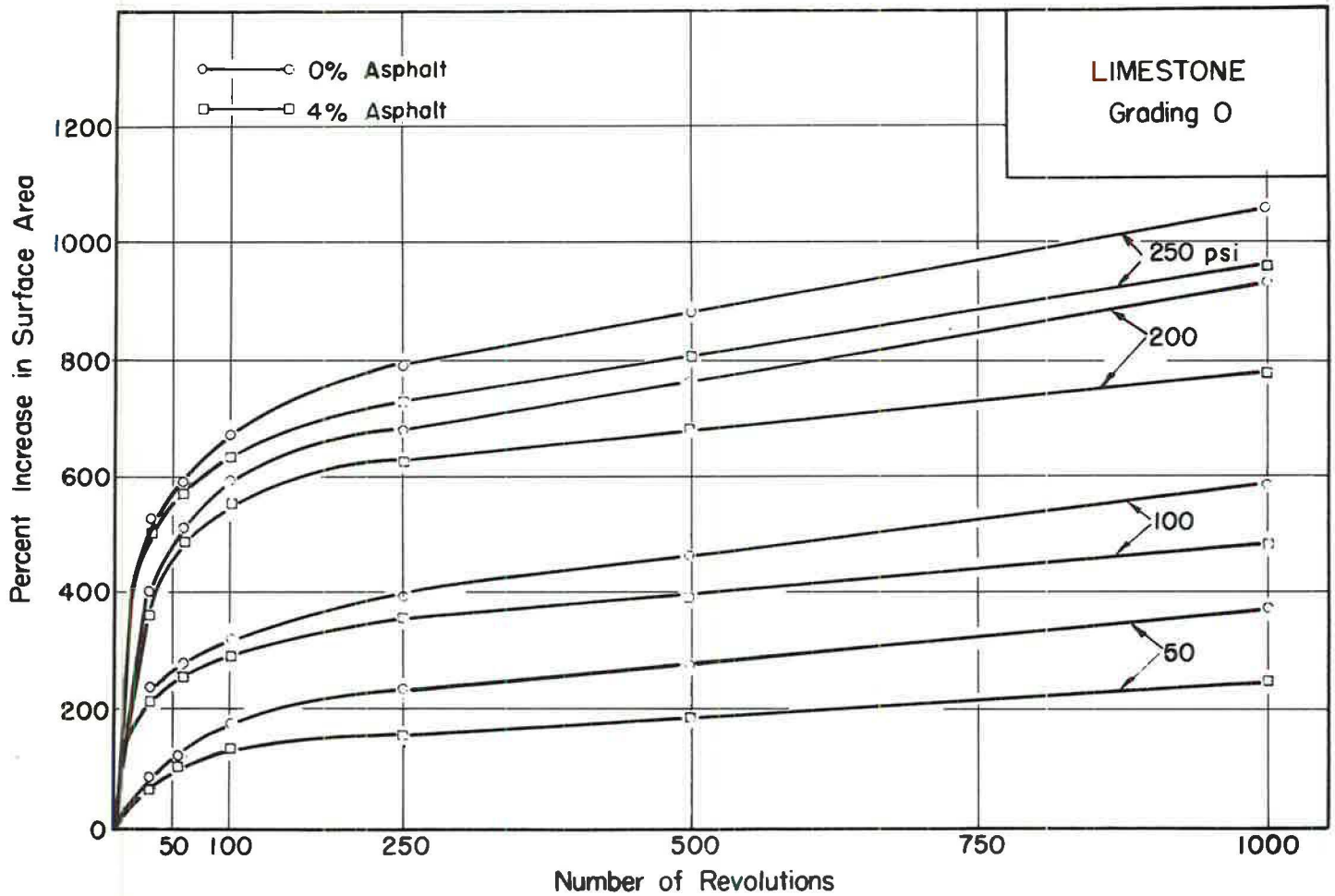

Figure 13. Degradation vs number of revolutions; variable ram pressure.

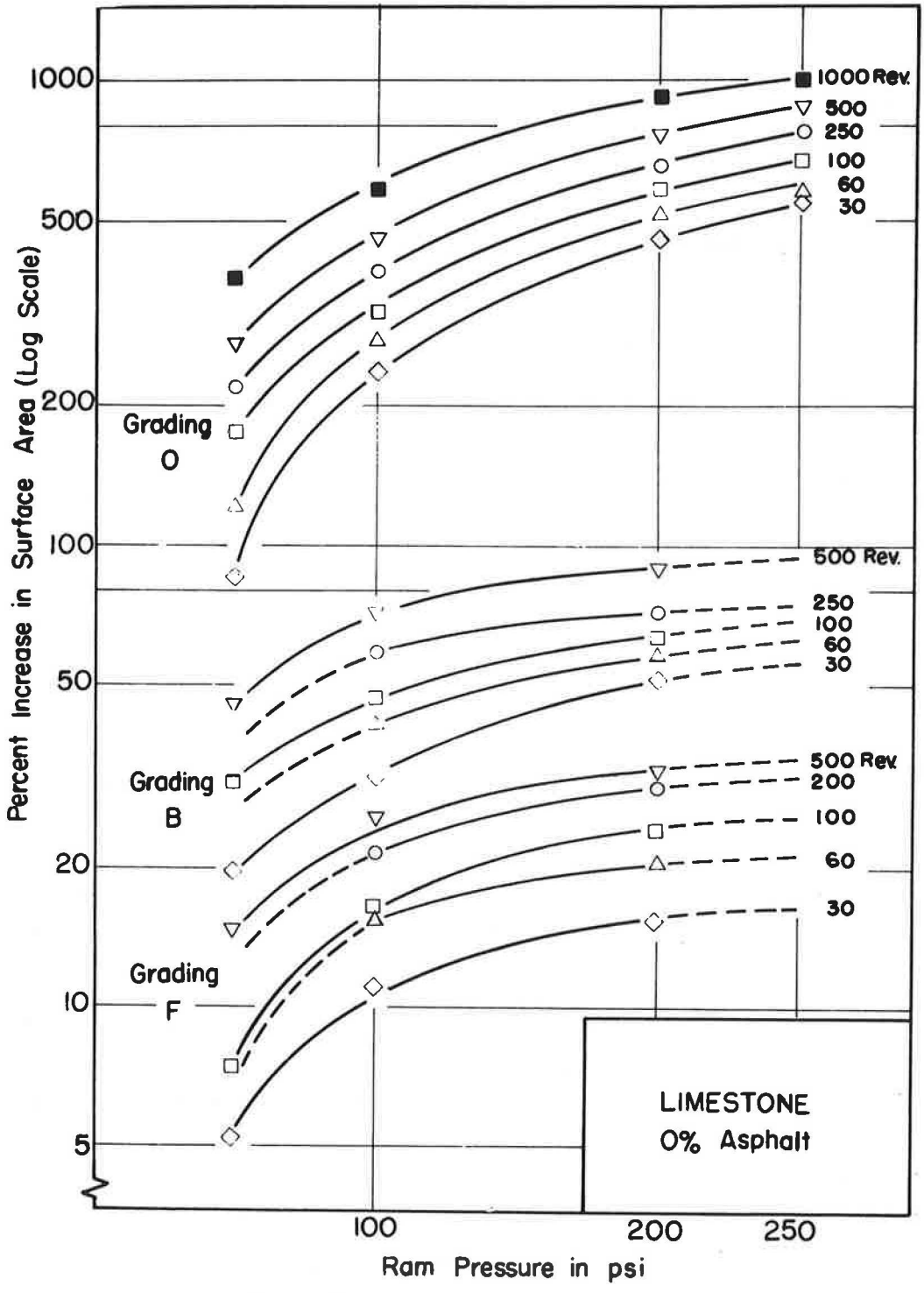

Figure 14. Degradation vs ram pressure.

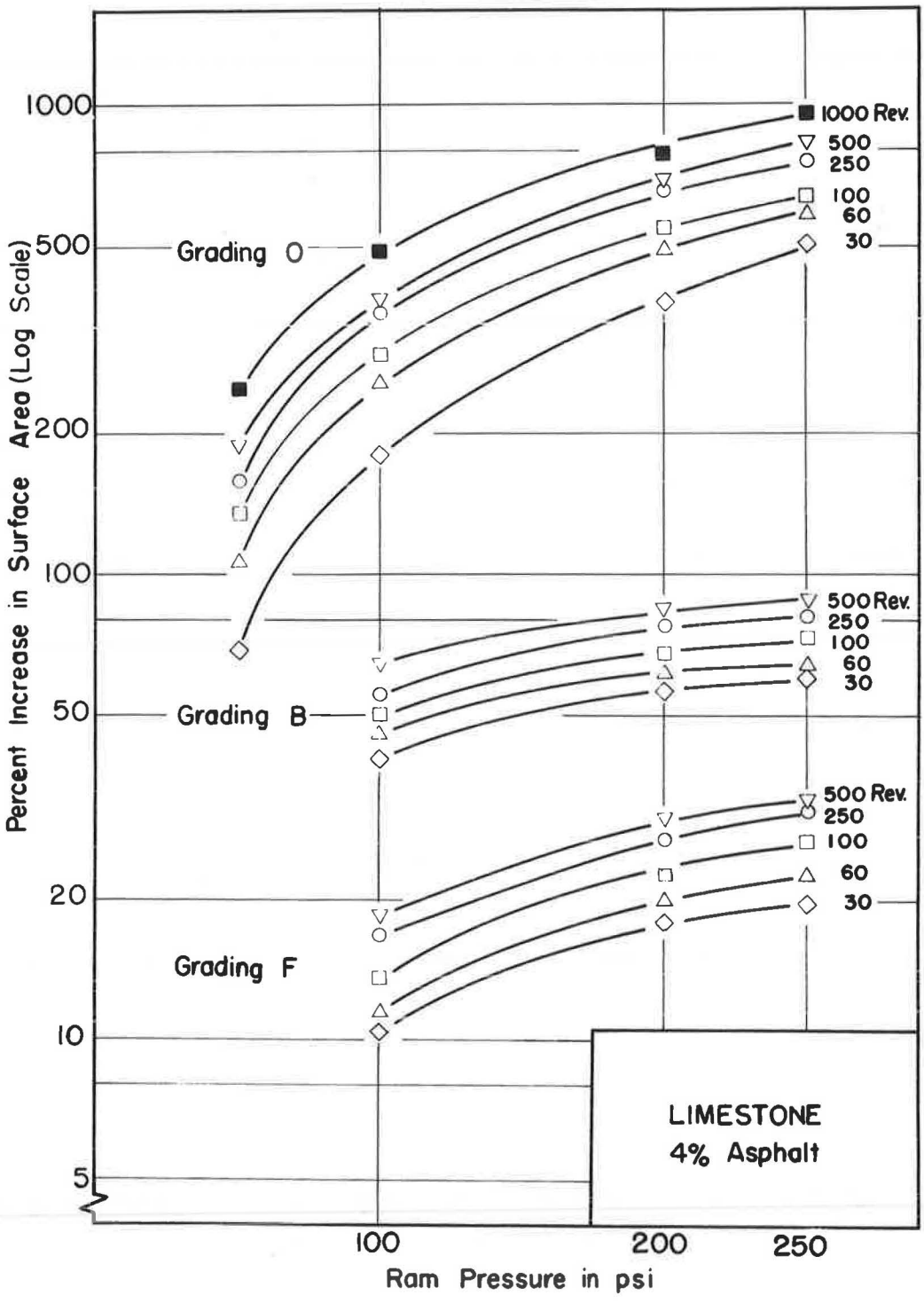

Figure 15. Degradation vs ram pressure.

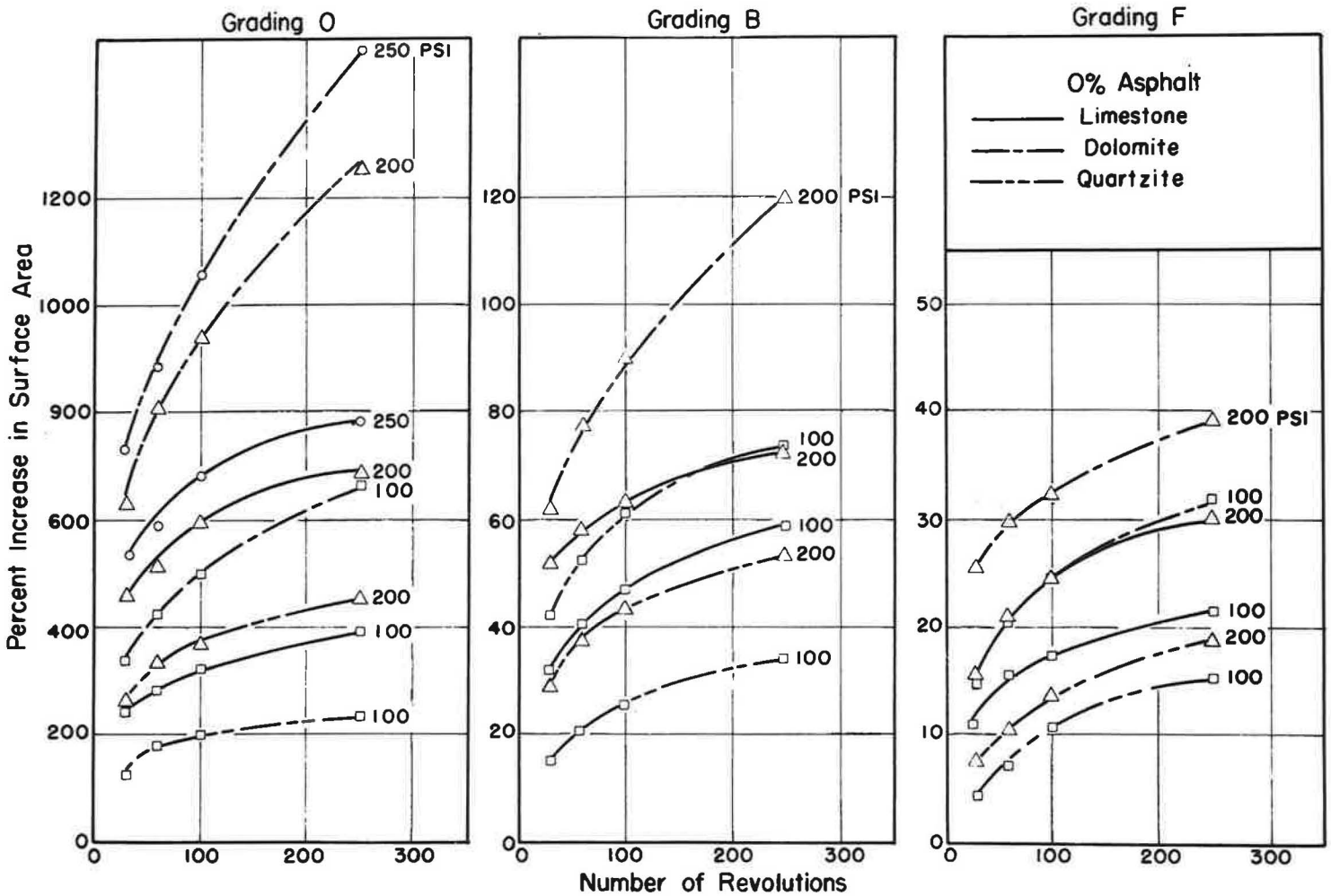

Figure 16. Degradation vs number of revolutions.

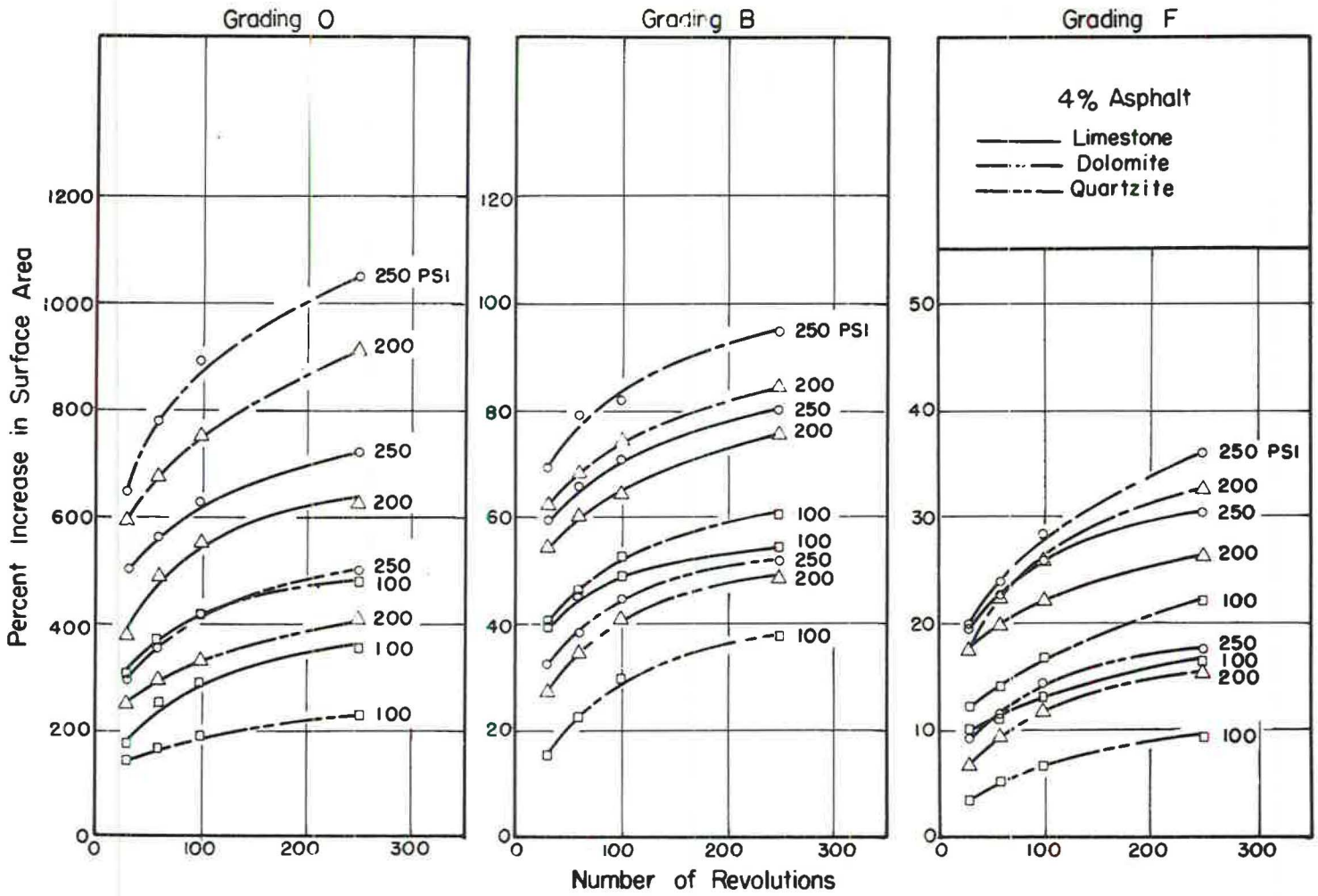

Figure 17. Degradation vs number of revolutions.

different scale. These figures also indicate that as compactive effort increases degradation also increases.

When ram pressure was kept constant and compactive effort was increased only by the number of revolutions, the increase in degradation depended on type of aggregate and gradation of aggregate. The softer and weaker the aggregate (higher Los Angeles value) the greater was the increase in degradation caused by increase in number of revolutions, while the harder (lower Los Angeles value) the aggregate the less was the increase in degradation. Figures 16 and 17 also show that increase in degradation caused by increase in number of revolutions depends on gradation. The slopes of curves for open-graded mixtures are much steeper than those for dense-graded ones.

Type and Gradation of Aggregate.—Even more pronounced than the effect of compactive effort is the effect of the original gradation of the mixture on the degradation of aggregate. As gradation becomes more dense, degradation decreases (Figs. 14 and 15). Open-graded mixtures which contain only the four top sizes of aggregate produced the highest degradation for all three kinds of aggregate, at all compactive levels, and for all asphalt contents. At the same time, grading F which corresponds to Fuller's gradation for maximum density gave the lowest values of degradation under the same conditions. Although it is not at once apparent because a log scale has been used to plot degradation, it should be noted that open-graded mixtures experienced some twenty times more degradation than dense-graded mixtures under the same conditions.

Figures 16 and 17 indicate that the amount of degradation also depends on kind of aggregate. The softer and weaker (higher Los Angeles value) the aggregate the more the degradation. The curves for dolomite always lie above the curves for the other two kinds of aggregate. However, the effect of aggregate softness and strength on degradation also depends on gradation of the mixtures. For example (Fig. 16), the change in degradation due to kind of aggregate is a matter of a few hundred percent for the case of the open-graded mixtures, while for the dense-graded mixtures this change is around 50 percent at most.

Cognizance of the scale of degradation for each gradation makes one aware that original gradation of aggregate has a very pronounced effect on magnitude of degradation. Degradation for open-graded mixtures (grading O) ranges from 100 percent to 1,400 percent depending on the type of aggregate and compactive effort; while for dense-graded mixtures (grading F) this range is between 5 and 40 percent, or only about $1/20$ to $1/35$ of the values obtained for open-graded mixtures. This indicates that the original aggregate gradation is the most important factor in degradation, because the results indicate that changes in compactive effort, in kind of aggregate, or in aggregate shape (as discussed later) did not produce as much change in degradation as changes in original gradation.

This point can easily be related to the previous finding with regard to mechanism of degradation. It was said that magnitude of degradation depends on distribution and magnitude of forces applied to the specimen. When a dense mixture is used the number of contact points is numerous and any applied force will be distributed to many more points in much less intensity than for more open mixtures, which in turn produces much less breakage. In open mixtures the number of contact points are few, and particles are subjected to much higher contact pressures, which in turn causes much more breakage than in dense-graded mixtures.

Asphalt Cement.—Figure 18 shows the effect of change in asphalt content on degradation for the three gradings of limestone aggregate. Depending on compactive effort, kind of aggregate, and gradation of aggregate there is in general an asphalt content for which the degradation is minimum. It is also indicated that asphalt content is not an independent variable with respect to degradation as was shown to be the case for kind of aggregate and aggregate gradation. For an independent factor, such as kind of aggregate, it could be said that when aggregates become softer and weaker the degradation increases regardless of other variables, but for the asphalt content variable there is no such trend.

This result may be viewed with respect to the role of asphalt in the mechanism of degradation. It was found that magnitude of degradation depends on distribution of load and intensity of contact pressure. Considering asphalt as a viscous material which

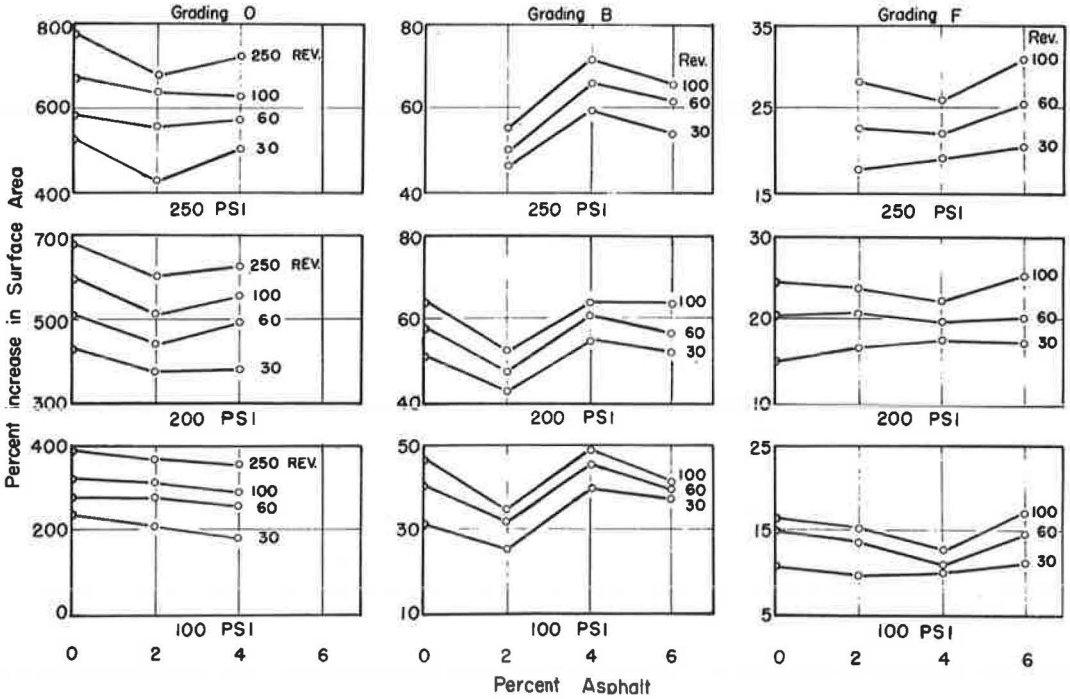

Figure 18. Degradation vs asphalt content, limestone.

covers the particles, its effect on degradation may be influenced by the effect of its viscosity on magnitude of contact pressure. Also, for a particular arrangement of particles and a particular condition of load the asphalt may help the particles to rotate and slip over each other. Rotation and slippage of particles will increase the probability of wear of corners of particles and will also increase the probability of obtaining a denser mixture. If these effects result in an increase in contact pressure, degradation will increase, but if the effect is to reduce contact pressure, degradation will be decreased. Since these effects of asphalt change as the specimen undergoes densification, the net result is a complex one in which no definite pattern for effect of asphalt on degradation is apparent.

Aggregate Shape. —To investigate the effect of aggregate shape on degradation, a limited number of tests were performed on specimens made of rounded pieces of quartzite. Table 12 contains the percent increase in surface area for such specimens. The same gradings (O, B, and F) were used in this part of the study. Eighteen specimens of each grading were tested, nine without asphalt and nine with 4 percent asphalt; therefore, a total of 54 specimens were used.

Figure 19 shows the results obtained from specimens with 4 percent asphalt, comparing rounded and angular quartzite. Curves for rounded aggregate lie below those for the angular material. Also, both the flatness and spacing of the curves for rounded pieces are less than those for angular ones, indicating that increase in compactive effort produces less degradation in the case of rounded aggregate regardless of whether the increase is due to pressure or number of revolutions. The cause of this phenomenon can be attributed to the reduction, in the case of rounded aggregate, of that part of degradation which is due to wear rather than breakage. Wear occurs due to the rounding off of corners of particles when they rotate or slip over each other. Breakage occurs when the contact pressure between two particles exceeds their strength, resulting in fracture or splitting. Theoretically, by using rounded particles that portion of degradation due to wear should be eliminated. Practically, however, this portion can only be reduced rather than eliminated, because when particles start to break, the newly produced pieces are no longer rounded and wear begins.

TABLE 12

PERCENT INCREASE IN SURFACE AREA, ROUNDED QUARTZITE

Psi	Rev.	Grading O, % Asphalt		Grading B, % Asphalt		Grading F, % Asphalt	
		0	4	0	4	0	4
100	30	67.8	82.9	7.2	10.8	1.0	0.7
	100	116.0	110.0	14.0	16.5	1.9	3.2
	250	138.0	135.0	19.0	20.5	4.2	6.0
200	30	114.0	142.4	12.2	20.0	2.6	2.5
	100	178.0	173.4	21.5	23.5	4.8	5.5
	250	212.0	198.0	28.0	28.5	7.7	8.0
250	30	128.0	175.0	13.3	23.3	2.9	4.5
	100	185.0	215.0	23.0	27.5	5.7	6.2
	250	231.0	250.0	29.0	32.0	8.6	9.0

This reasoning leads to the conclusion that the major part of the difference between degradation of rounded and angular particles can be considered as reduction of wear. Figure 19 shows that the rounded aggregate experienced almost 50 percent less degradation than the angular one, which then can be considered as almost 50 percent less wear. This reduction of degradation due to the shape of particles should decrease as softer

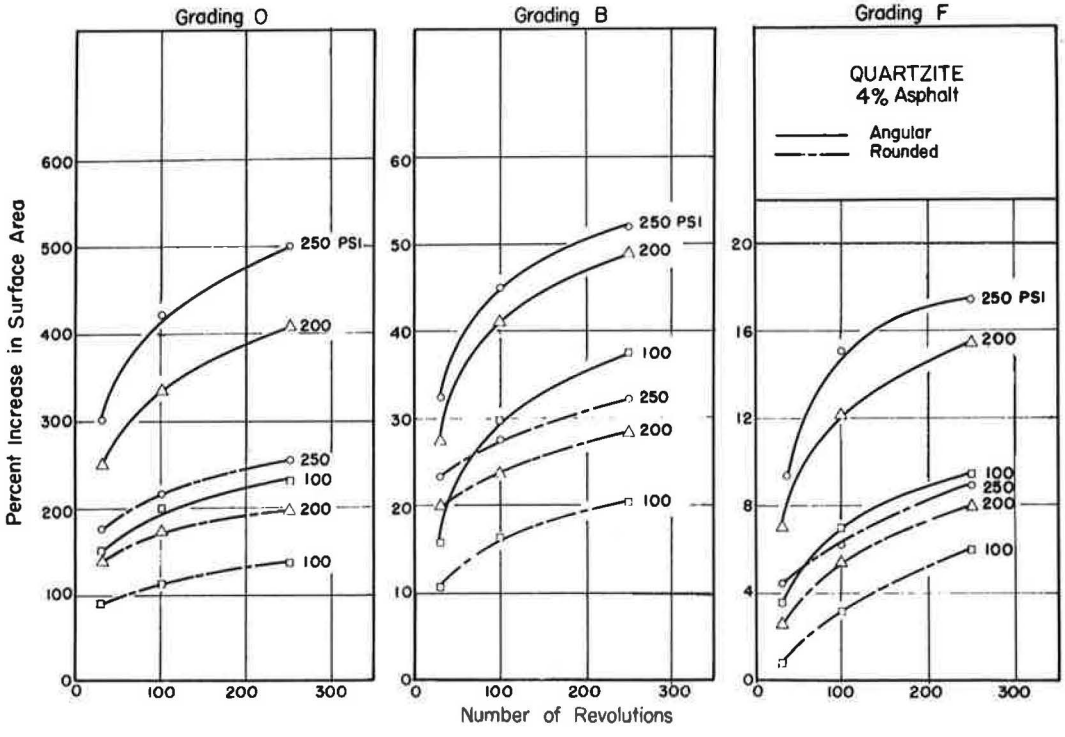

Figure 19. Degradation vs number of revolutions.

material is used, because in soft aggregates probability of breakage is high. Thus, after a few applications of load, the amount of angular pieces should increase and wear should start. This was one reason for using the quartzite with the lowest Los Angeles value in this portion of the study.

Degradation vs Los Angeles Value

Degradation values were plotted against the Los Angeles values for the three kinds of aggregate to determine any relationship. Grading C was used to determine the correlation between Los Angeles value and degradation merely because the maximum size of grading C is the closest to the maximum size used in this investigation.

Figures 20, 21, and 22 show the results obtained from gradings O, B, and F, respectively. Each curve is for the indicated number of revolutions. The three points on each curve are the results obtained from specimens made of the three kinds of aggregate tested under equal efforts.

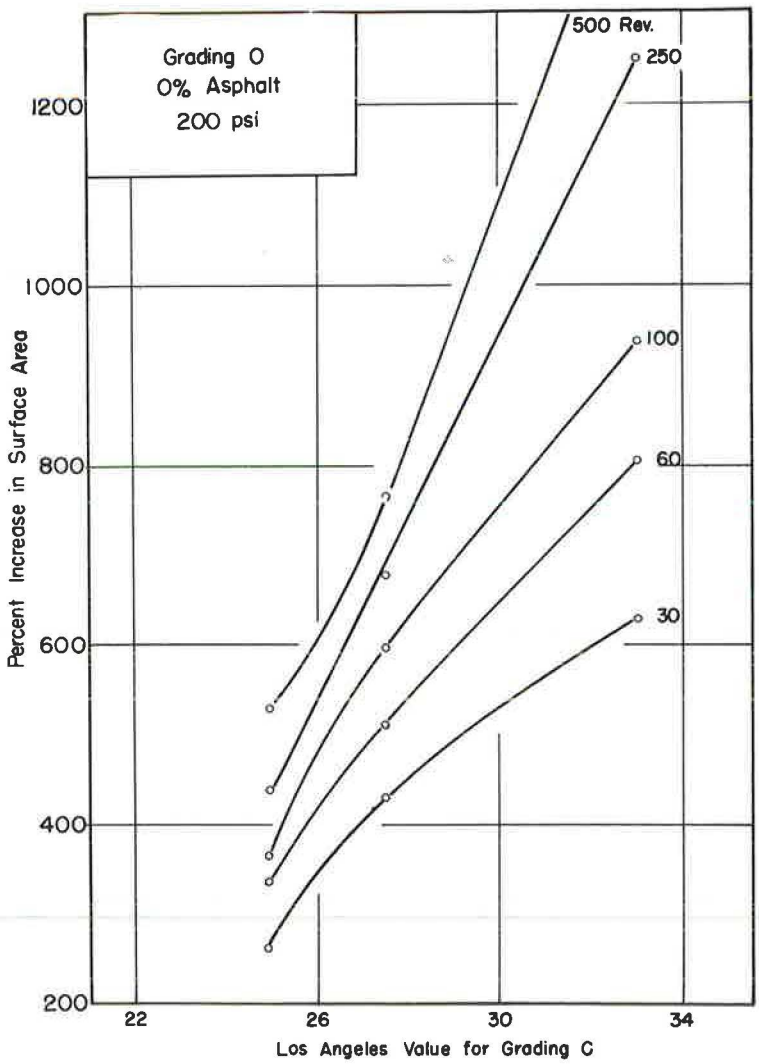

Figure 20. Degradation vs Los Angeles value.

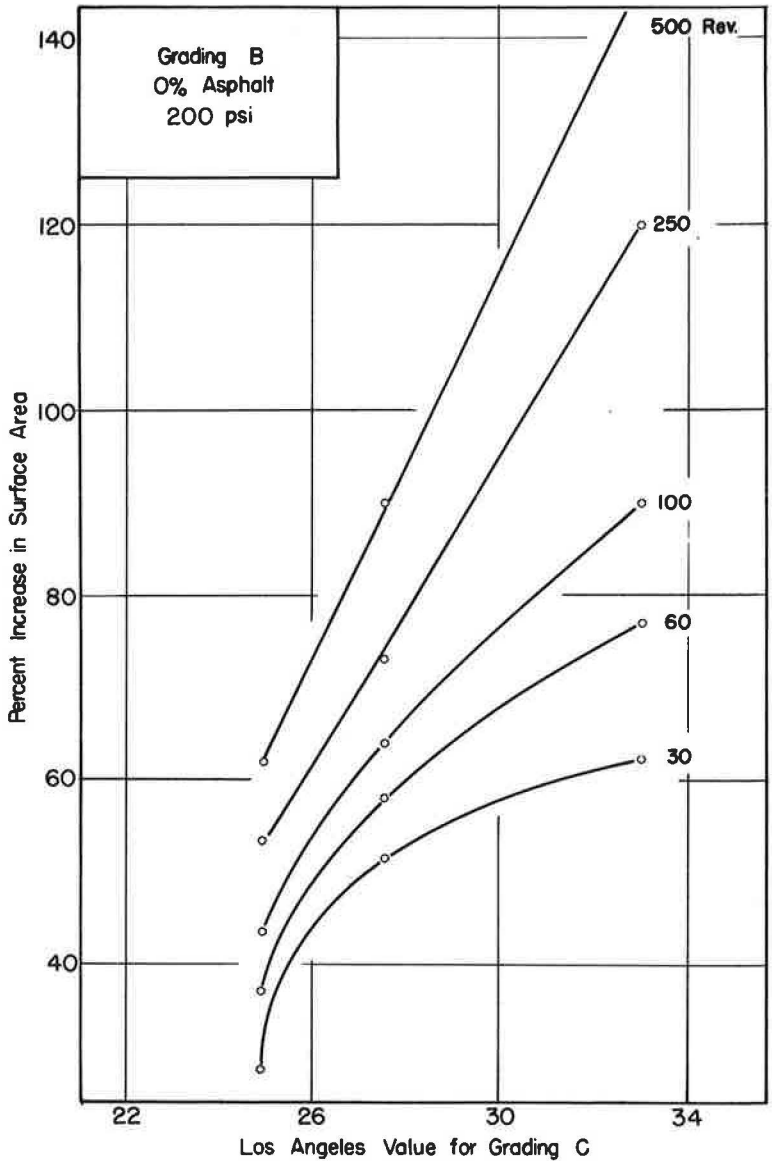

Figure 21. Degradation vs Los Angeles value.

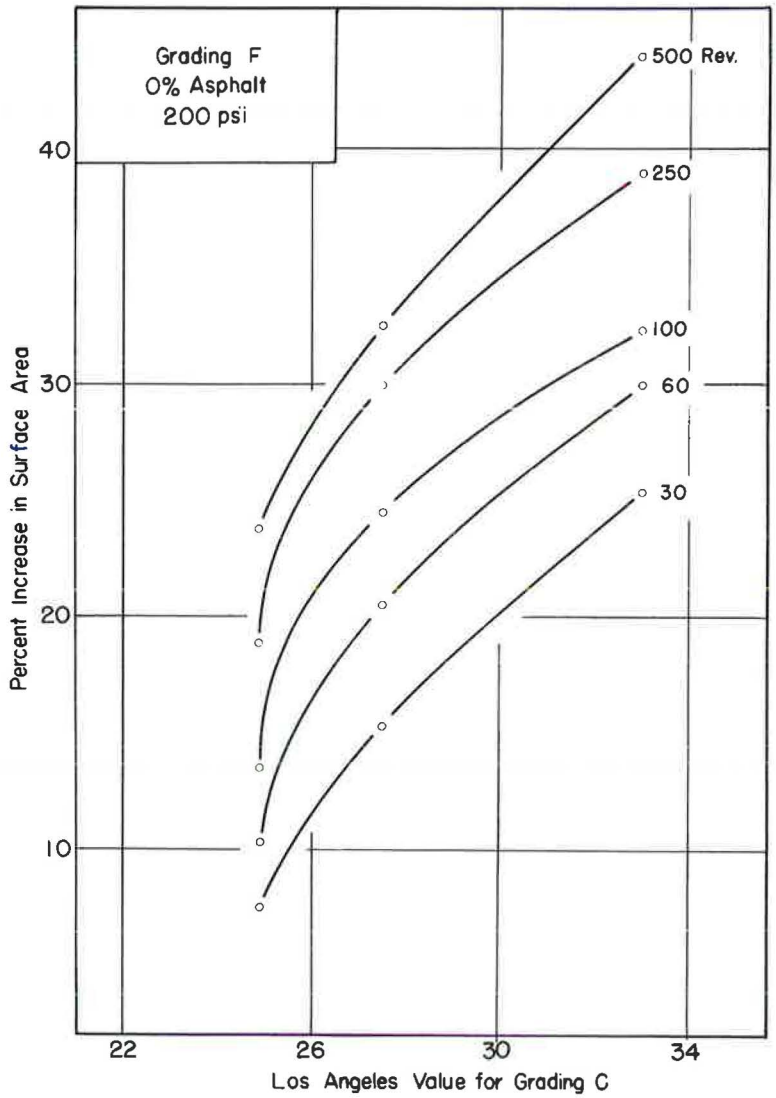

Figure 22. Degradation vs Los Angeles value.

Figure 20 shows that as the Los Angeles value increases the degradation value also increases, but the rate of increase is not constant, and the relationships are not linear until the compactive effort is about 200-psi ram pressure and 250 revolutions. Below this level of compactive effort the Los Angeles machine produces more degradation for soft or weak aggregate than the gyratory machine. Above 250 revolutions more degradation is experienced by the less resistant material in the gyratory compactor than in the Los Angeles machine because the curve for 500 revolutions is concave rather than convex.

Figure 21 shows that for grading B this linearity occurs somewhere between 200-psi ram pressure and 250 revolutions, and 200-psi ram pressure and 500 revolutions; Figure 22 shows that such linearity was not reached for specimens with grading F under compactive efforts used in this study.

It is therefore indicated that, depending on gradation of the aggregate, there is a certain level of compaction for which the plot of degradation versus Los Angeles value of the aggregate is a straight line. For compactive efforts higher than that, soft and

weak aggregates experienced more degradation in the gyratory machine than in the Los Angeles machine, and for compactive efforts below that, soft and weak materials experienced more degradation in the Los Angeles machine. Therefore, as far as degradation is concerned, depending on the gradation of the material, the Los Angeles test corresponds only to a certain level of compaction. This level of compaction increases as gradation of material becomes more dense. Inasmuch as these levels of compaction, especially in dense-graded materials, are much higher than those normally found in the field, some doubts are imposed on the validity of the Los Angeles test as a measure of quality of aggregate with respect to degradation. This becomes especially apparent when it is noted that the dolomite aggregate with a high Los Angeles value (Figs. 16 and 17) when tested in a Fuller gradation produced less than one-tenth of the degradation under equal compactive effort of that produced by the low Los Angeles value quartzite when tested in the open gradation.

It was mentioned before that degradation occurs due to two phenomena, wear and breakage. Wear was considered responsible for that portion of degradation which is caused by rotation and slippage of particles over each other; breakage was considered to occur when the contact pressure exceeds the strength of the particle in a certain direction. Thus, under traffic compaction the particles either break or rotation wears off their corners. In either case the result is production of particles of smaller sizes. Rotation and breakage will result in a denser packing, producing a mat whose particles have more contact points and less chance for rotation. This reduces the rate of degradation under further compaction. But in the Los Angeles rattler test the particles do not experience this dense packing or cushioning effect which occurs in a road mat and consequently the material is subjected to a more severe degradation condition than actually exists in the field.

Petrographic Analysis

A comparison of petrographic analysis (Table 2) with degradation and Los Angeles values of the materials indicates that the nature of grain boundaries, cementation, and percent of voids influence the resistance of aggregates to degradation. Good interlocking between the grains in limestone results in a low Los Angeles value and low degradation. Loose interlocking in dolomite results in a high Los Angeles value and high degradation. Quartzite's strength is due to silica cementation that results in a comparatively strong and resistant rock. If the material had not been highly stressed, this strong cementation would have resulted in a very low Los Angeles value. However, the directional weakness due to cracking and fracturing makes the material susceptible to impact breakage, which may be the reason for its high Los Angeles value as compared to the nature of its cementation. The results also show that degradation increases as percent voids of the material increases.

CONCLUSIONS

The results obtained from this study led to the following conclusions, which are specifically applicable only to the particular kinds of aggregate used. Furthermore, all the tests were performed in the laboratory, and there exists no field correlation study specifically to evaluate the field behavior of the materials. All conclusions and recommendations deal with degradation characteristics of mineral aggregate. Suggested protective measures are made only with respect to the reduction of aggregate degradation without considering their effects on other properties of mixtures.

1. Within the range of the materials and procedures, there appears to be a unique pattern for degradation of each aggregate fraction of a bituminous mixture. This pattern does not vary with kind of aggregate, compactive effort, presence of asphalt, or original gradation of the mixture.
2. The magnitude of degradation of a bituminous mixture, as measured by percent increase in aggregate surface area, depends on the following factors: kind of aggregate, aggregate gradation, compactive effort, and particle shape. The effect of asphalt on the magnitude of degradation depends on other factors and cannot be considered as an independent variable.

3. Physical characteristics of the aggregate, as reflected by its Los Angeles value or by petrographic analysis, have a dominant effect on degradation. Mineral aggregates with low Los Angeles values will produce less degradation than those with high Los Angeles values. Rocks with good interlocking or cementation between grains are more resistant to degradation than others.

4. From the results of tests on mixtures ranging in gradation from open to dense and tested with compactive efforts ranging from low to high, it can be concluded that some aggregates having a Los Angeles loss greater than the minimum commonly specified may, from the standpoint of degradation, be satisfactory materials especially if used in dense gradings subjected to low compactive effort.

5. Gradation of the mixture is the most important factor controlling degradation. As the gradation becomes denser, degradation decreases. The magnitude of this decrease is much greater than that brought about by changes in other variables. Soft or weak materials with high Los Angeles values can produce much less degradation than hard and strong materials if the former are used in dense-graded mixtures and the latter in open mixtures. Therefore, from a degradation point of view, dense-graded mixtures offer the best use of local aggregates with high Los Angeles values.

6. Increase in compactive effort results in increase in degradation of the mixture regardless of the form of this increase in effort, but degradation is more susceptible to change in magnitude of load than to change in repetition of load. The rate of change in degradation is high during the initial part of the application of compactive effort, and thereafter becomes less as the compactive effort is increased.

7. When the degradation of rounded particles is compared with that of angular particles of the same kind of aggregate, the rounded aggregate can be expected to produce less degradation because of a reduction of that portion of degradation which is due to wear. Use of rounded material will be helpful in reduction of degradation providing its use does not impair other properties of the mixtures.

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