AGGREGATE DEGRADATION IN BITUMINOUS MIXTURES

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by

F. MOAVENZADEH

and

W. H. GOETZ

Joint Highway Research Project

PURDUE UNIVERSITY
LAFAYETTE INDIANA

Technical Paper

AGGREGATE DEGRADATION IN BITUMINOUS MIXTURES

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

January 30, 1963

FROM: H. L. Michael, Associate Director
Joint Highway Research Project

File: 2-8-3
Project: C-36-21C

Attached is a paper titled "Aggregate Degradation in Bituminous Mixtures" which has been authored by F. Moavenzadeh, formerly of our staff, and W. H. Goetz. The paper was presented at the 1963 Annual Meeting of the Highway Research Board in Washington, D.C., on January 10.

The paper is a summary of the research performed by Mr. Moavenzadeh under the direction of Professor Goetz which was presented to the Board several months ago. It is proposed that the paper be offered to the Highway Research Board for publication.

The paper is presented to the Board for the record and for approval of the proposed possible publication.

Respectfully submitted,

Harold L. Michael

Harold L. Michael, Secretary

HLM/lkc

Attachments

Copy: F. L. Ashbaucher
J. R. Cooper
W. L. Dolch
W. H. Goetz
F. F. Havey
F. S. Hill
G. A. Leonards
J. F. McLaughlin
R. D. Miles
R. E. Mills
M. B. Scott
J. V. Smythe
J. L. Waling
E. J. Yoder

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Purdue University
Lafayette, Indiana

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INTRODUCTION

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 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 ravelling. 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, by frictional resistance, and by 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

It was the purpose of this investigation, then, 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: (1) type of aggregate, (2) gradation of aggregate, (3) aggregate shape, (4) aggregate size, (5) asphalt content, and (6) compactive effort.

MATERIALS AND PROCEDURE

Three kinds of aggregates were used in this study, dolomite, limestone and quartzite. Their selection was based on a relatively wide range of Los Angeles values and on petrographic structure. Table 1 includes data on origin, specific gravity, Los Angeles value, and compressive strength, while Table 2 shows a summary of petrographic analysis results for the materials used.

An 85-100 penetration grade asphalt cement was used in this study. The results of tests on the asphalt are presented in Table 3.

The three gradations selected for this investigation are shown in Table 4. They 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 $\frac{1}{2}$ in. Figure 1 shows these three aggregate gradations graphically.

The aggregates used for each specimen were batched by component fractions according to the blend formula. A batch consisted of 1000 grams. The blended aggregates for specimens containing asphalt were heated to $275^{\circ} \pm 10^{\circ}$F. The asphalt was heated separately to 290° - 300°F. The mixing was accomplished using a Hobart electric mixer modified with a special mixing paddle and a scraper. The mixing continued for two minutes. For those cases in which the aggregate was tested without asphalt, the aggregate was not heated or subjected to the mixing operation with the Hobart mixer.

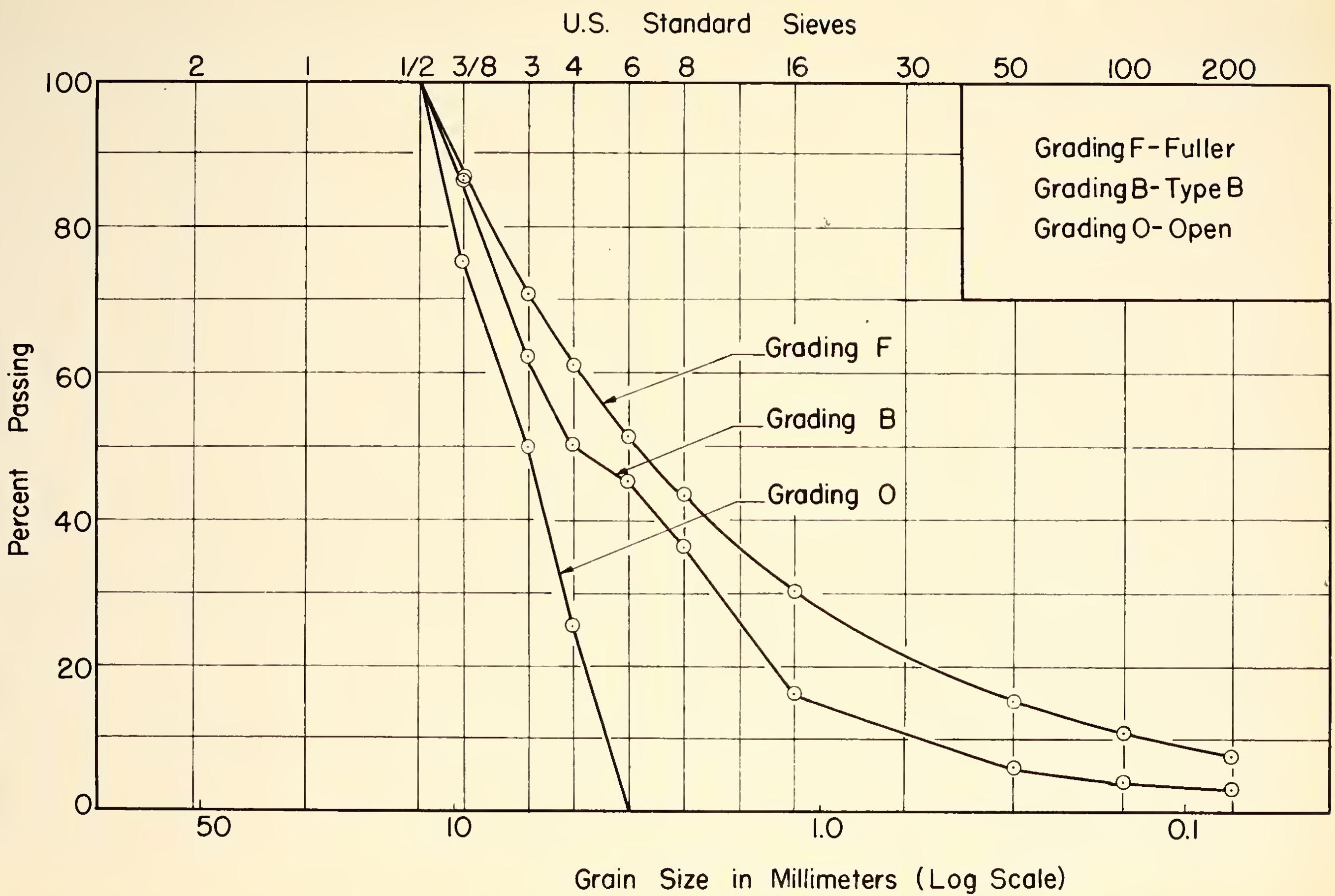

FIG. I GRADATION CURVES FOR ORIGINAL GRADATIONS

Due to the fact that this study was solely a laboratory investigation, a fundamental part of it was the selection of testing equipment which would produce specimens similar to the pavement with respect to density and structure. Many methods of compaction have been devised and used to simulate field compaction in the laboratory. Most of these methods are based principally upon 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 would 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 of the design shown in Figure 2 was used in this study. With this equipment it was possible to change the compactive effort in two different ways, (1) change in magnitude of load, and (2) 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 one thousand 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 were used to provide an elevated temperature throughout the test. After each mix had been subjected to the gyrating action, an extraction test was made on the whole specimen and the gradation of the extracted aggregate was determined for comparison with the gradation before mixing and compaction.

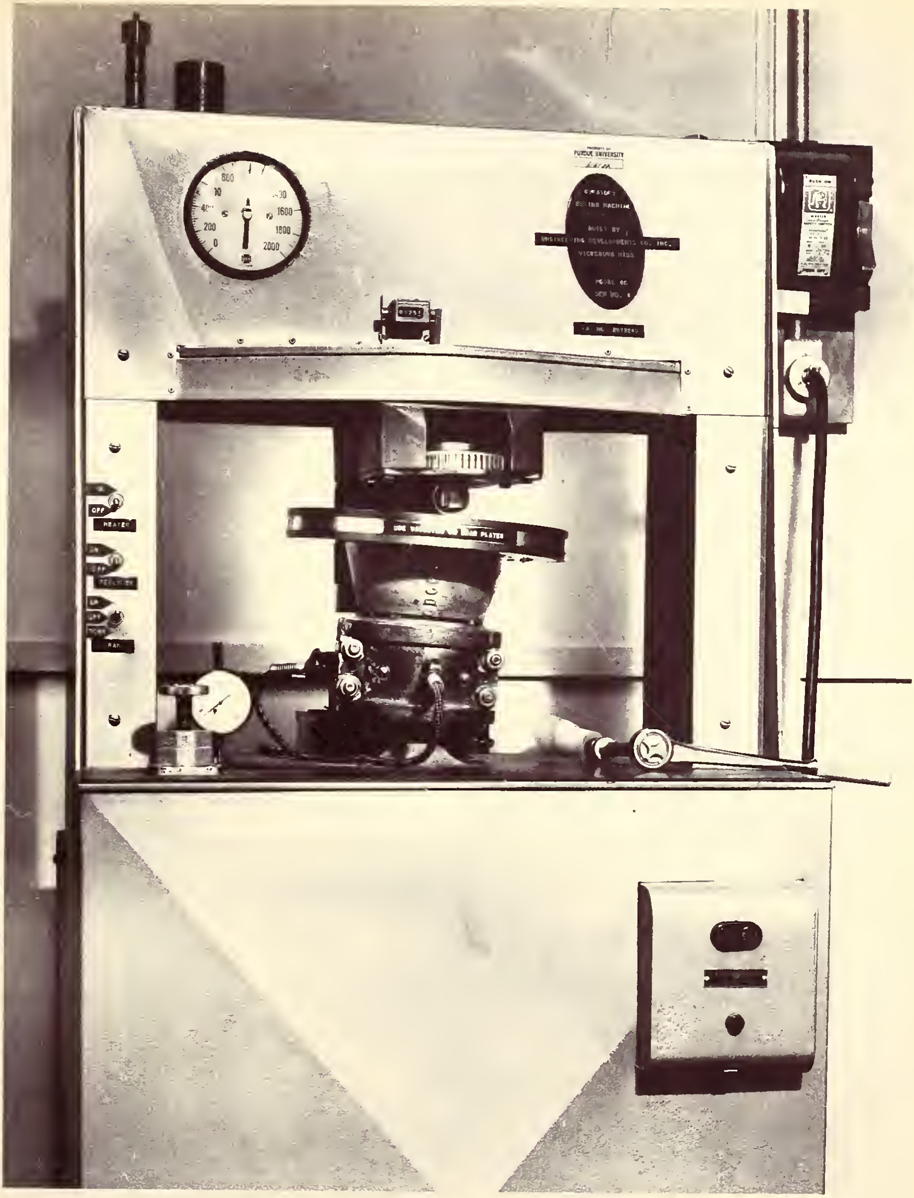

FIG. 2 GYRATORY TESTING MACHINE

In order to study the effect of shape of particles on degradation, it was desirable that the rounded pieces not differ from the crushed ones in their composition. Therefore, artifically rounded pieces were produced by subjecting angular pieces to a few thousand revolutions in a Los Angeles machine. See Figure 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: (1) Orseillin BB Red, (2) Crystal Violet, (3) Malachite Green Oxalate.

RESULTS

Of the several methods available to represent the degradation characteristics of aggregate, two were chosen for this study; 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 factors used for computing surface areas are given in Table 5 for an assumed specific gravity of 2.65. These 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/gr has increased 2.2 cm^2/gr

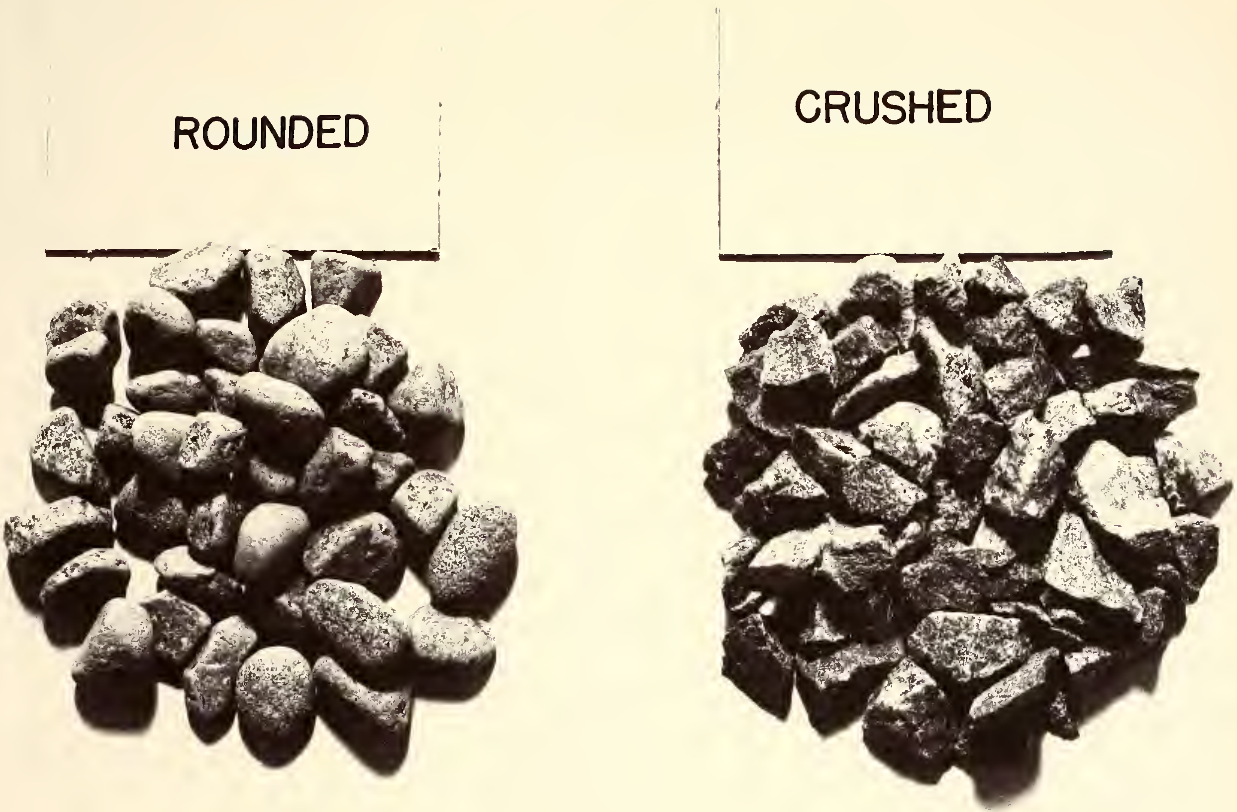

FIG. 3 CRUSHED AND ROUNDED QUARTZITE

in surface area after compaction, and another mixture with 67.3 cm^2/gr has increased the same amount, we cannot consider that the two mixtures have undergone equal degradation. The first mixture has gained 100 percent in surface area or, in other words, its final surface area is twice the original, while the second mixture has increased only 3 percent in surface area. 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.

The term degradation is used in this study to include all of the aggregate breakdown due to mechanical action regardless of the type of mechanical action causing it. 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 has 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. In order to determine whether or not change of size will change the degradation characteristics of an aggregate, and in order to investigate the effect of combinations of pieces of different sizes on degradation, specimens of one-sized aggregate were tested. The results are presented in Table 6. This table includes the results of sieve analysis together with percent increase in surface area for 12 specimens. Specimens containing one thousand grams of one-sized aggregate of ½" - 3/8", 3/8" - #3,

#3 - #4, and #4 - #6 of each of the three aggregates, dolomite, limestone and quartzite, were compacted in the gyratory compactor under 200 psi ram pressure and 100 revolutions.

Figure 4 shows the results of sieve analysis on specimens made of limestone aggregate. These results show that regardless of size of aggregate, all the curves appear to be approaching a parabolic shape. A plot of the data in Table 6 for the other two aggregates would show that this statement can be made with respect to type of aggregate as well. The results also indicate that as original size of particles decreases there is a corresponding increase in fine material, which might suggest that degradation increases as size of the particle decreases. Figure 5 presents the percent increase in surface area versus average size of original particles for the three kinds of aggregate. This figure shows that as the size of one-sized aggregate increases, the degradation under equal compactive effort (200 psi and 100 revolutions) increases.

Therefore, at first glance it appears that the results of the two methods, sieve analysis and percent increase in surface area, are in conflict. Clarification lies in the fact that sieve analysis representation only indicates what percent of material is of which size, without considering through what changes this material has gone and what was its original condition. A piece of larger size has to undergo more breakdown than a smaller particle to be reduced to a certain size. Therefore, it can be seen that sieve analysis representation, although it is an excellent means for studying the pattern of degradation, by no means can be used as a measure of degradation and the concept of percent increase in surface area, obtained by relating the produced area to the original area, is a much better means of measuring degradation.

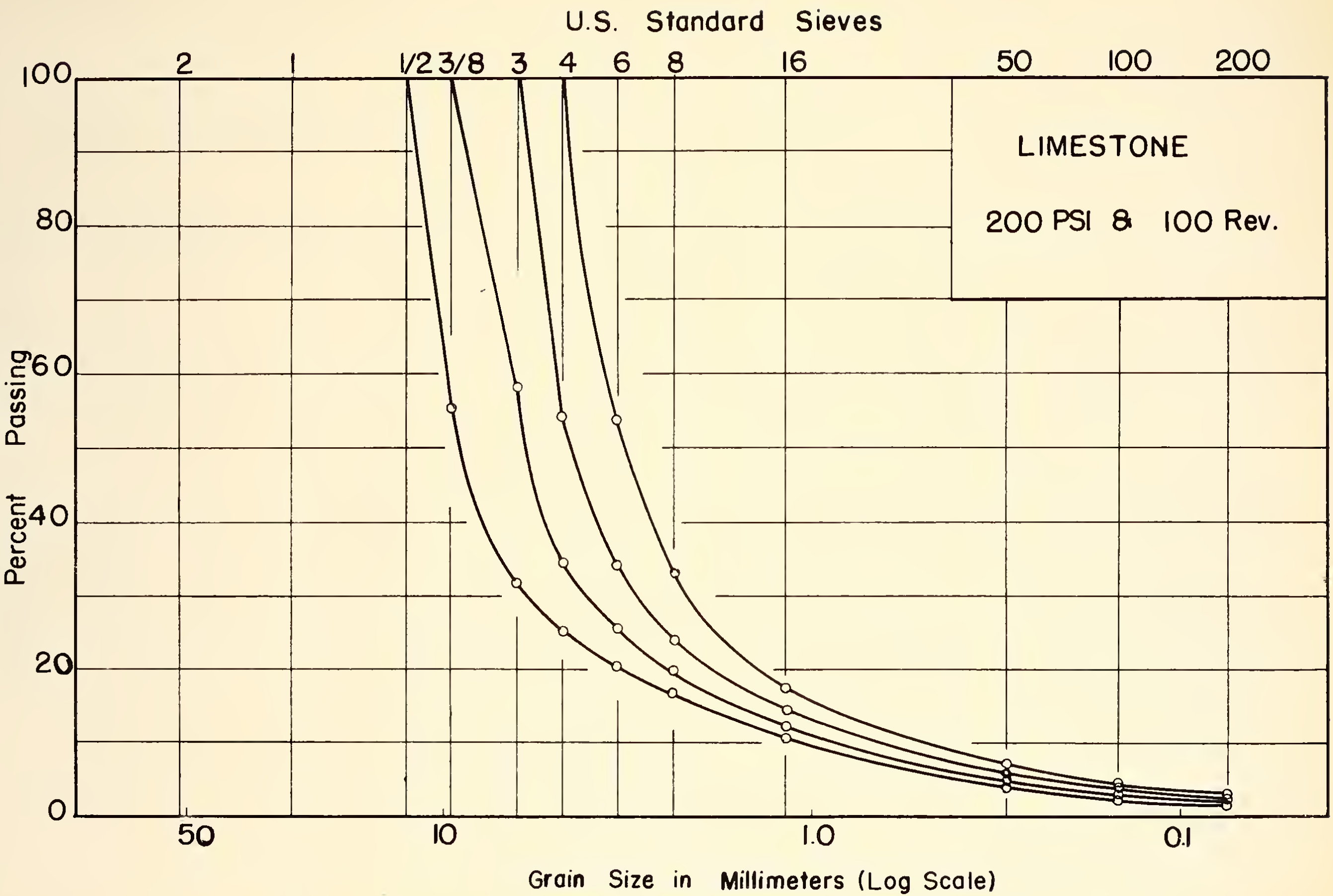

FIG.4 SIEVE ANALYSIS OF ONE-SIZED LIMESTONE AGGREGATES AFTER GYRATORY COMPACTION

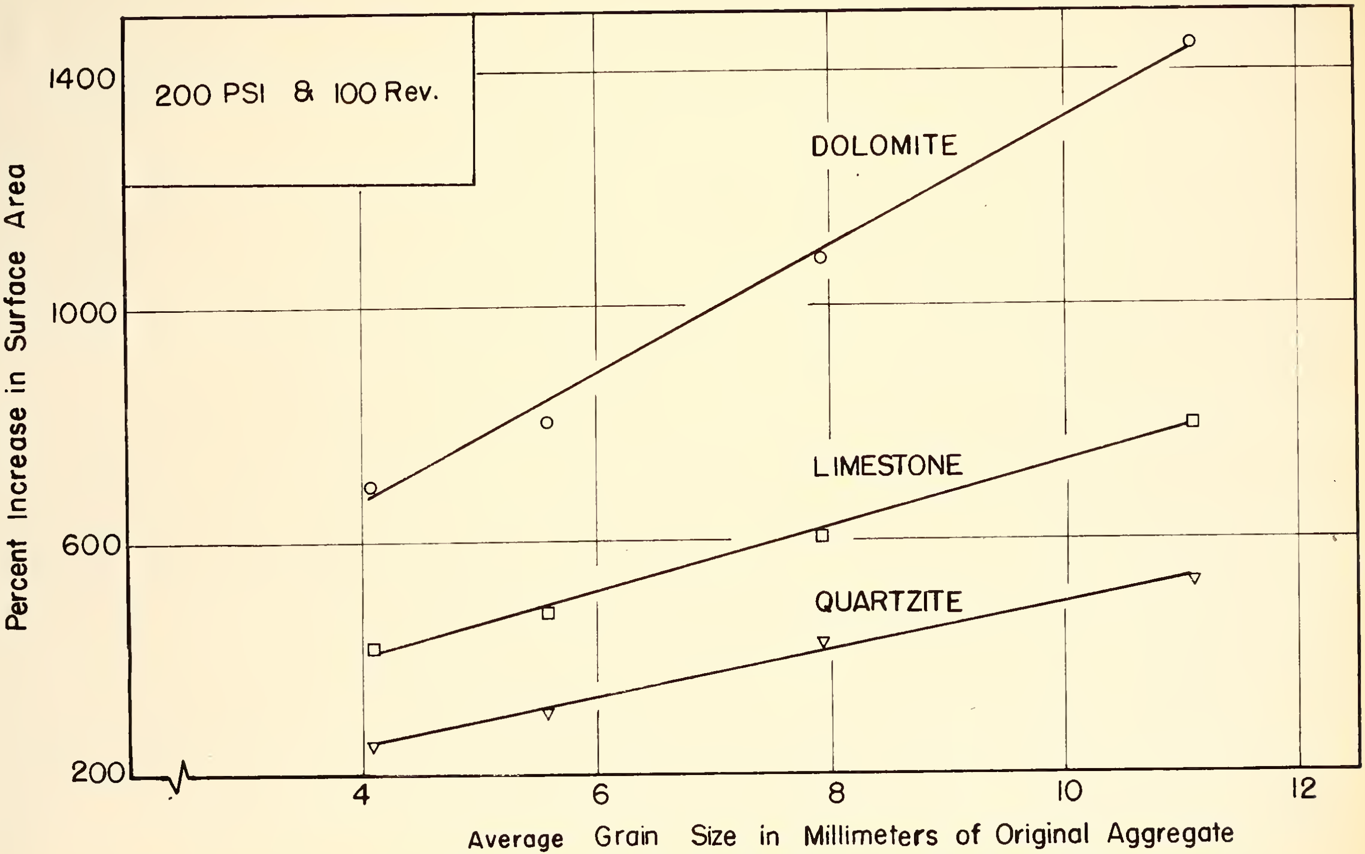

FIG. 5 DEGRADATION VS AGGREGATE SIZE - GYRATORY COMPACTION, ONE-SIZED AGGREGATES

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

Figure 6 shows the percent increase in surface area for different original one-sized fractions versus Los Angeles values of the three kinds of aggregate. This figure indicates that there is a linear relationship between the Los Angeles values of the three kinds of aggregate used in this study 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 having an original size of 3/8" - No. 3 were compacted under 100 psi ram pressure and five different numbers of revolutions in the gyratory machine. Table 7 gives the results of sieve analysis and percent increase in surface area for each specimen. Figure 7 shows the results of sieve analysis of dolomite aggregate after compaction. These results also 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. Figure 8 shows the degradation versus number of revolutions. It can be seen 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. The figure also indicates that as the material becomes softer or weaker, the slope of the latter part of the curves increases, which indicates that the degradation of such materials is more susceptible to change in compactive effort.

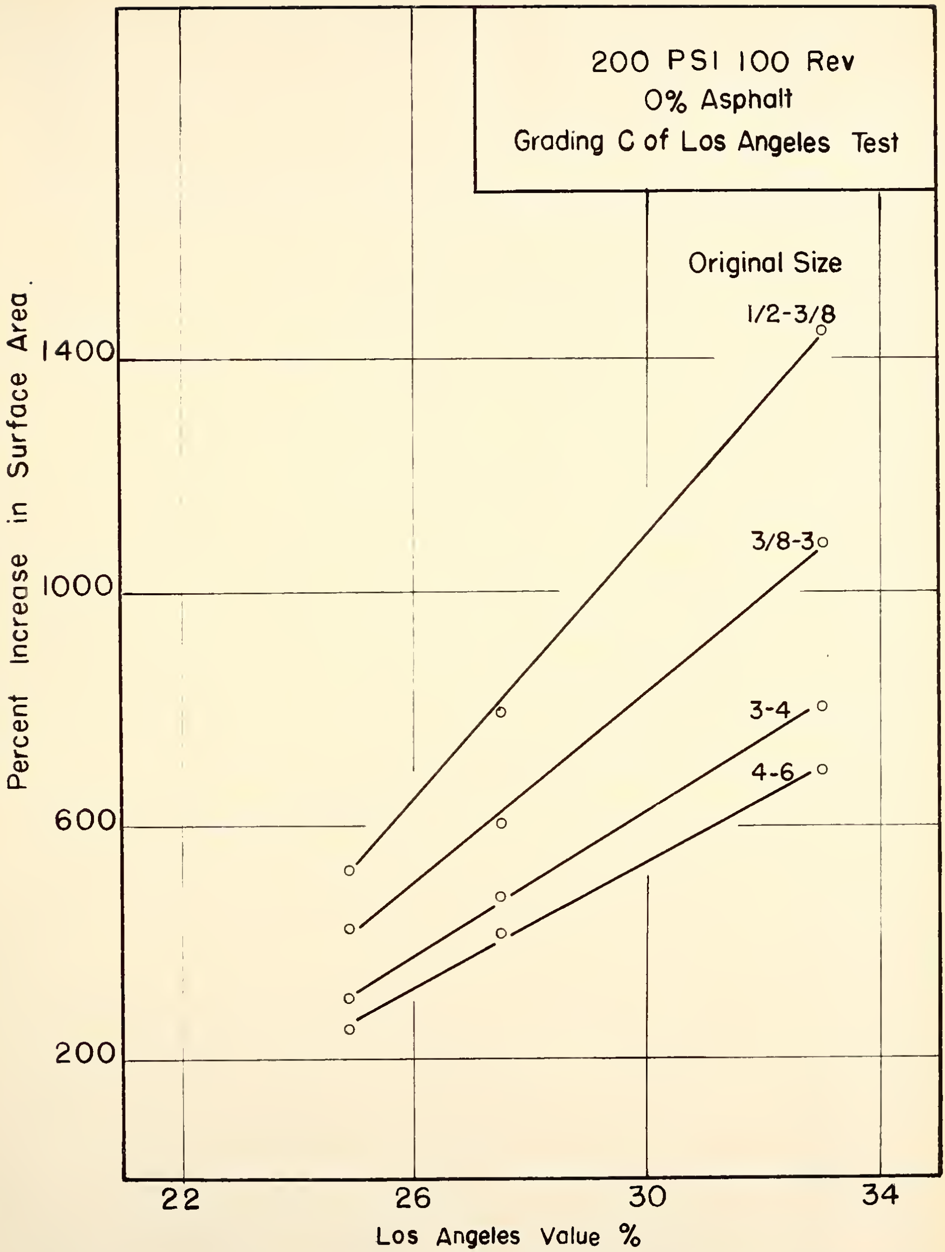

FIG. 6 DEGRADATION VS LOS ANGELES VALUE-GYRATORY COMPACTION, ONE-SIZED AGGREGATES

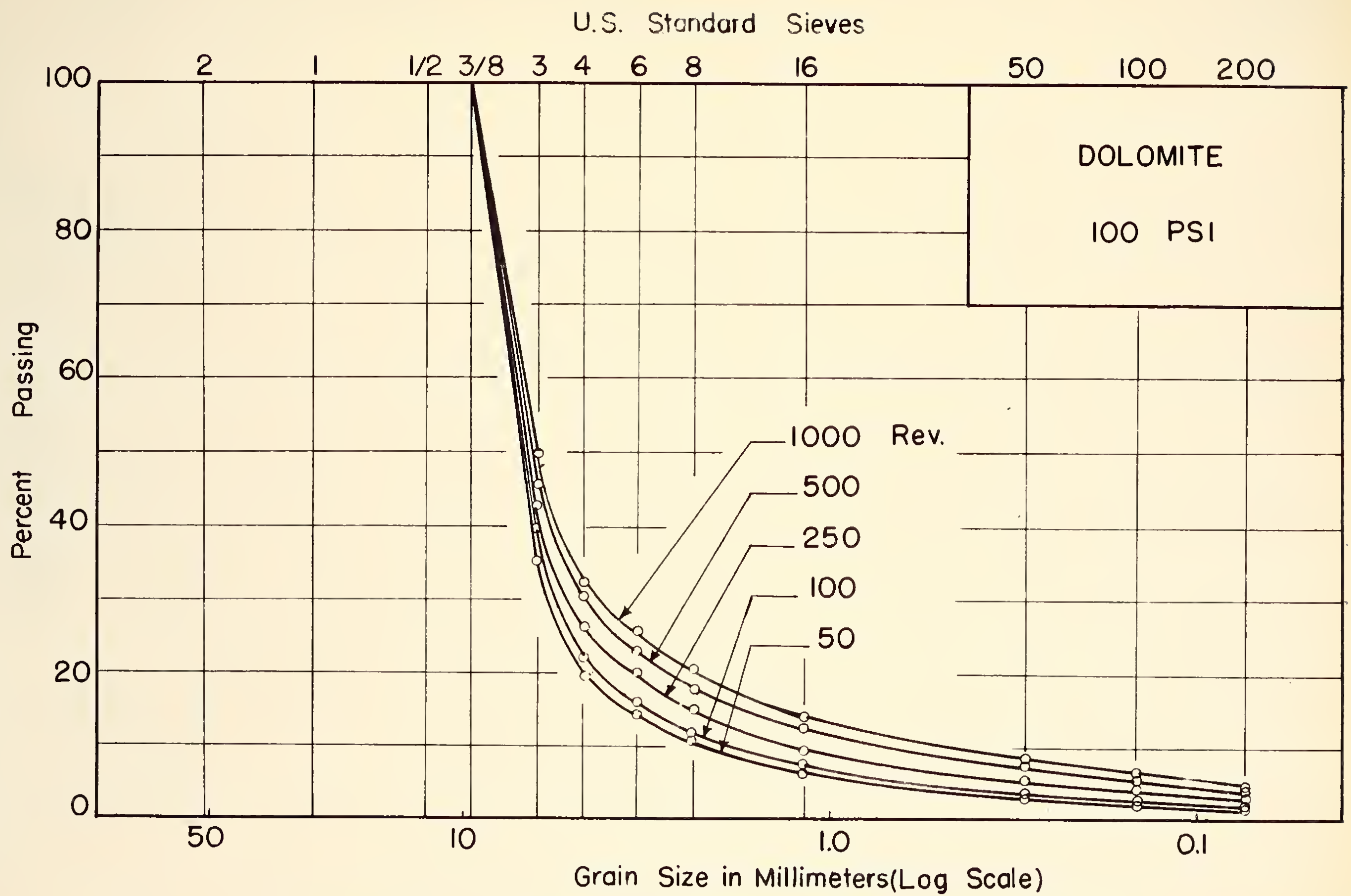

FIG. 7 SIEVE ANALYSIS OF ONE-SIZED DOLOMITE AGGREGATES-VARYING NUMBER OF REVOLUTIONS OF GYRATORY COMPACTOR

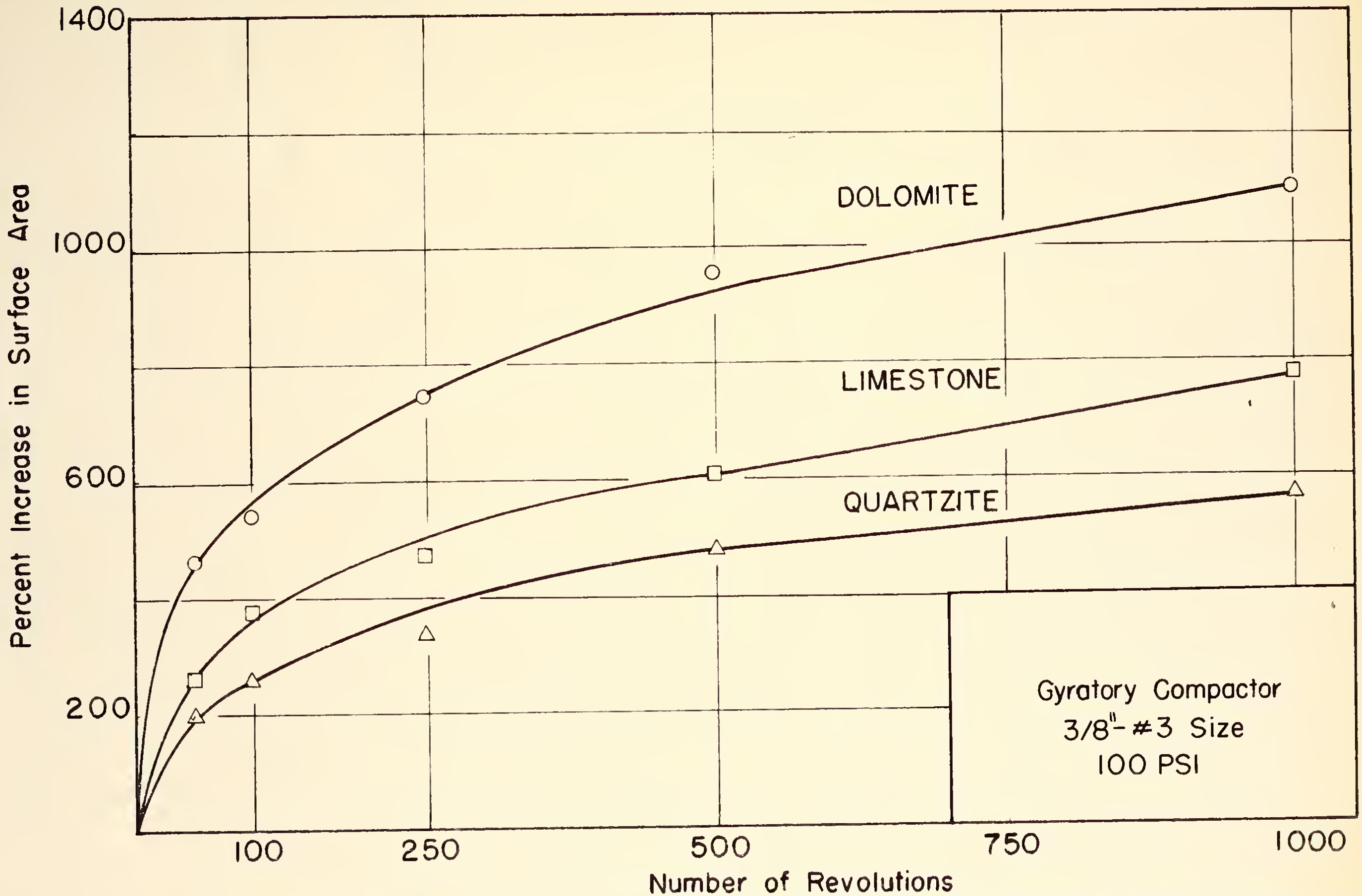

FIG. 8 DEGRADATION VS NUMBER OF REVOLUTIONS FOR ONE-SIZED AGGREGATES

Degradation of Individual Sizes in an Aggregation of Sizes

From the previous section it was found that degradation of one-sized aggregates when illustrated by sieve analysis curves has a constant pattern of a smooth curve approaching a parabolic one. It also was found that size of aggregate, kind of aggregate, and degree of compaction have no influence on the shape of the sieve analysis curve, while the magnitude of degradation is a function of these variables. In addition it was found that; the larger the size of particles, the greater the degradation; increase in compactive effort increases degradation; and aggregates with high Los Angeles values degrade more than those with low Los Angeles values.

Before making a detailed analysis of the effect of variables on degradation of different mixtures, it was necessary to investigate the changes which might occur in degradation characteristics of each size of particle due to the presence of other sizes in the specimen. For this purpose, a dyeing process was utilized to determine the size fraction from which each particle was produced when degradation occurred. Because it was found from studies on single-sized aggregates that kind of aggregate only changes the magnitude of degradation and has no effect on its pattern, it was decided to use only one kind of aggregate for this part of the study. The limestone which had the intermediate Los Angeles value and which could be satisfactorily dyed was used. Due to the time-consuming process of separating the fractions of different colors by hand, it was decided to dye only the top three sizes; namely 1/2" - 3/8", 3/8"-#3, and #3 - #4. If a difference in pattern of degradation due to the size was noticed, then other sizes would have been dyed also. The materials were separated only down to the #30 sieve. The factors which were considered as variables in this part of the study were gradation of aggregate, compactive effort, and presence or absence of asphalt.

The three gradations which are given in Table 3, gradings O, B, and F, were used in this part of the study. Twenty-four samples were used which were of three gradations, without asphalt and with 4 percent asphalt, and were tested under four different compactive efforts in the gyratory machine. The results of sieve analysis of each fraction (colored for identification), along with sieve analysis of the total specimen are presented in tabular form in Tables 8, 9, 10, 11, 12 and 13.

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. From left to right the curves show the degradation of particles of original sizes of 1/2"-3/8", 3/8" - #3, #3 - #4, and #4 - #6. These curves indicate that the degradation of each fraction has a constant pattern of a smooth curve approaching a parabolic one. Figures 10, 11, and 12 which show the sieve analysis of each fraction for specimens with four percent asphalt and original gradings O, B, and F, also indicate that the pattern of degradation of each fraction is a constant.

From the results obtained with the aid of colored aggregate it can be seen 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. The produced size distribution follows a curve which is smooth and approaches a parabolic one 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

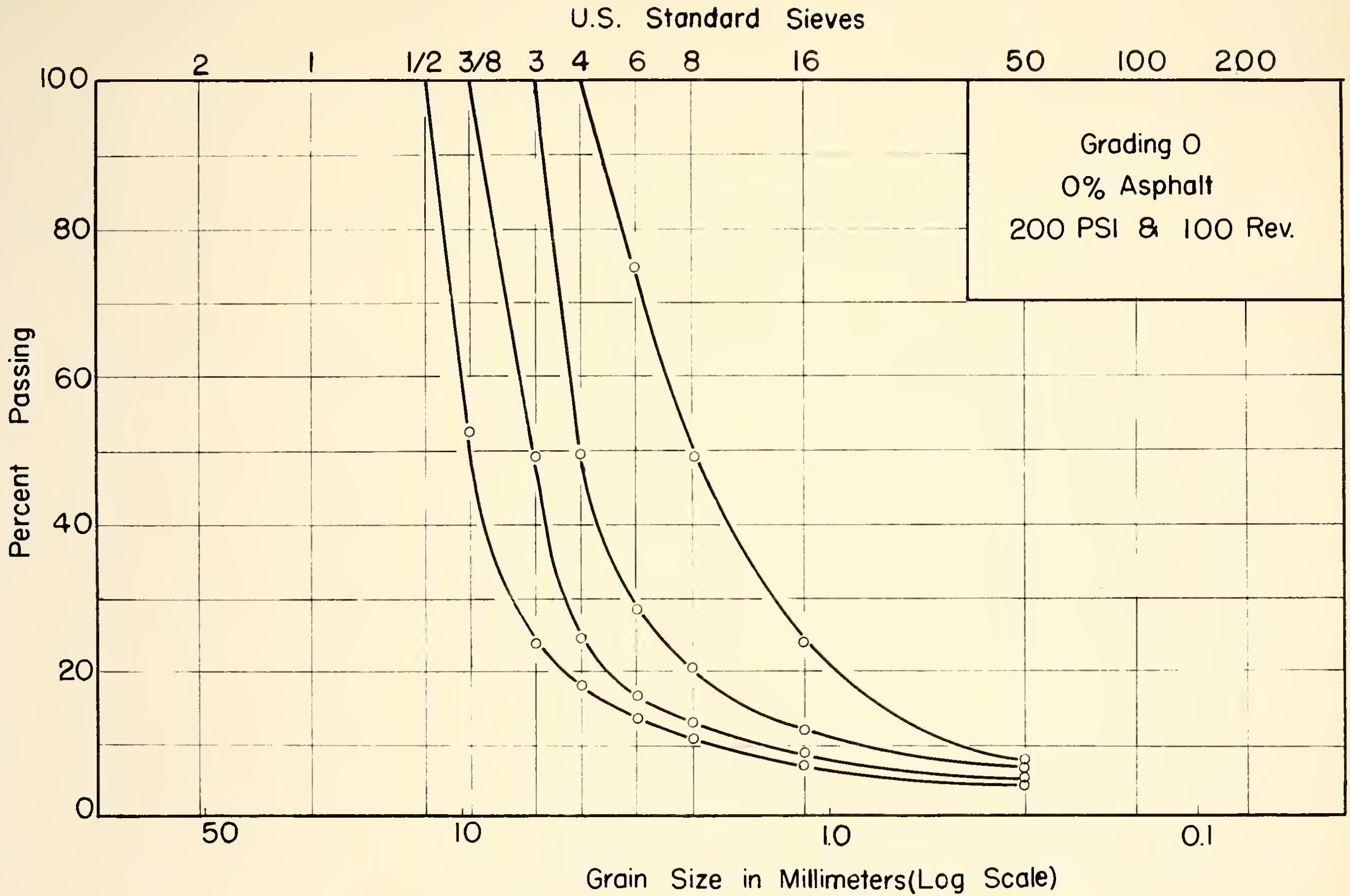

FIG. 9 SIEVE ANALYSIS OF COMPACTED COLORED AGGREGATE- GRADING O, 0% ASPHALT, 200 PSI, 100 REVOLUTIONS

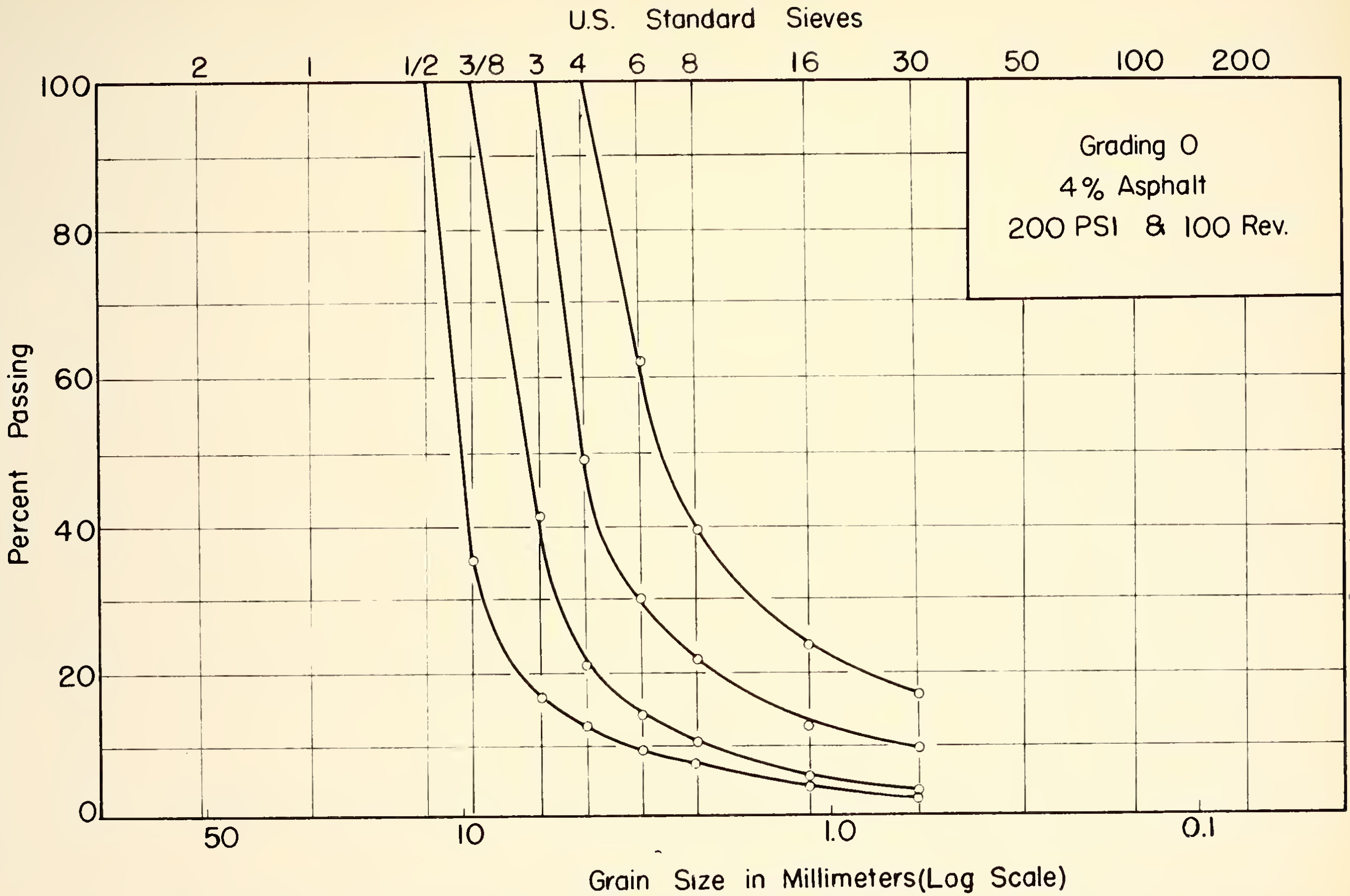

FIG.10 SIEVE ANALYSIS OF COMPACTED COLORED AGGREGATE–GRADING O, 4% ASPHALT, 200PSI, 100REVOLUTIONS

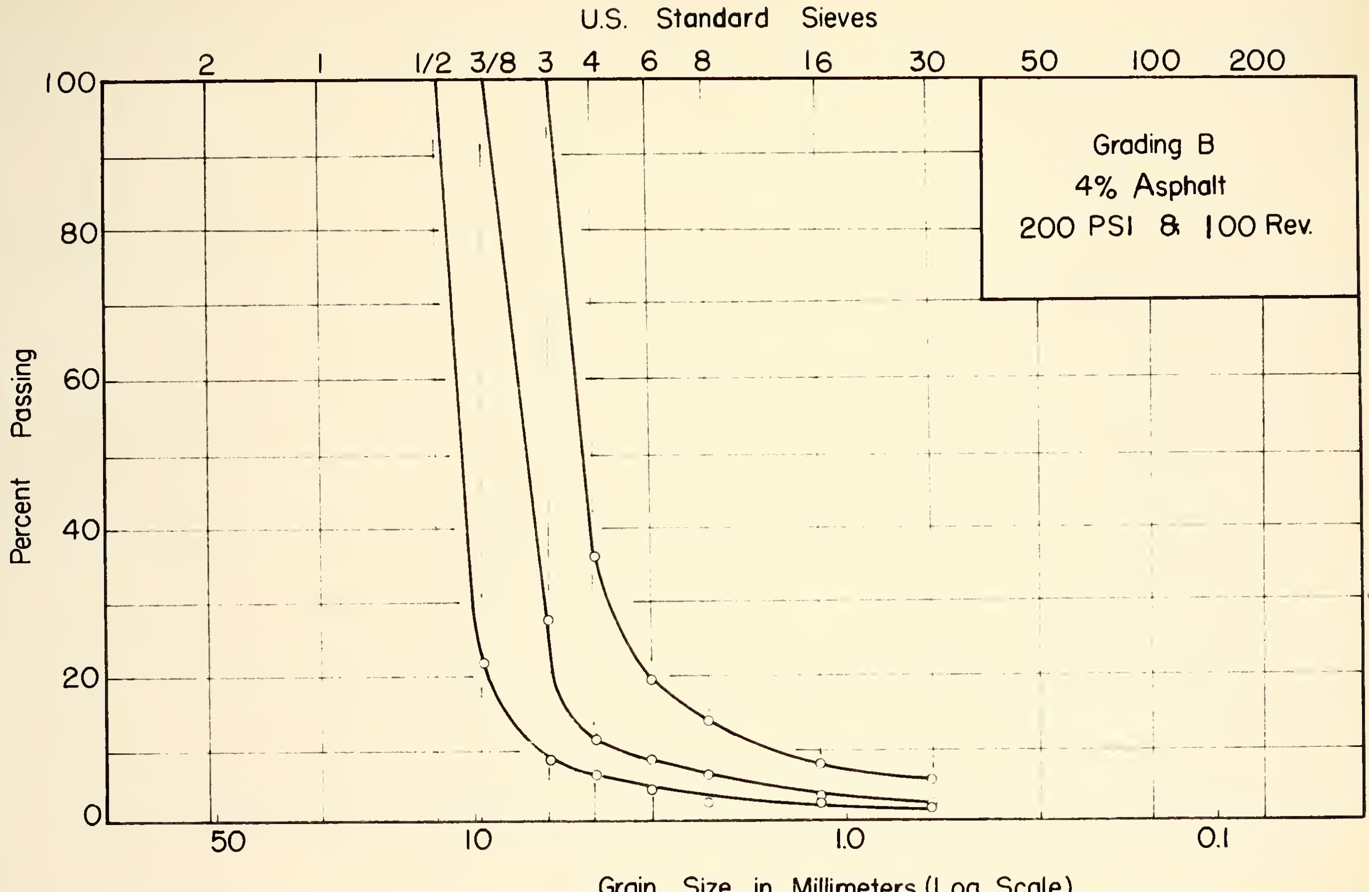

FIG. 11 SIEVE ANALYSIS OF COMPACTED COLORED AGGREGATE-GRADING B, 4% ASPHALT, 200 PSI, 100 REVOLUTIONS

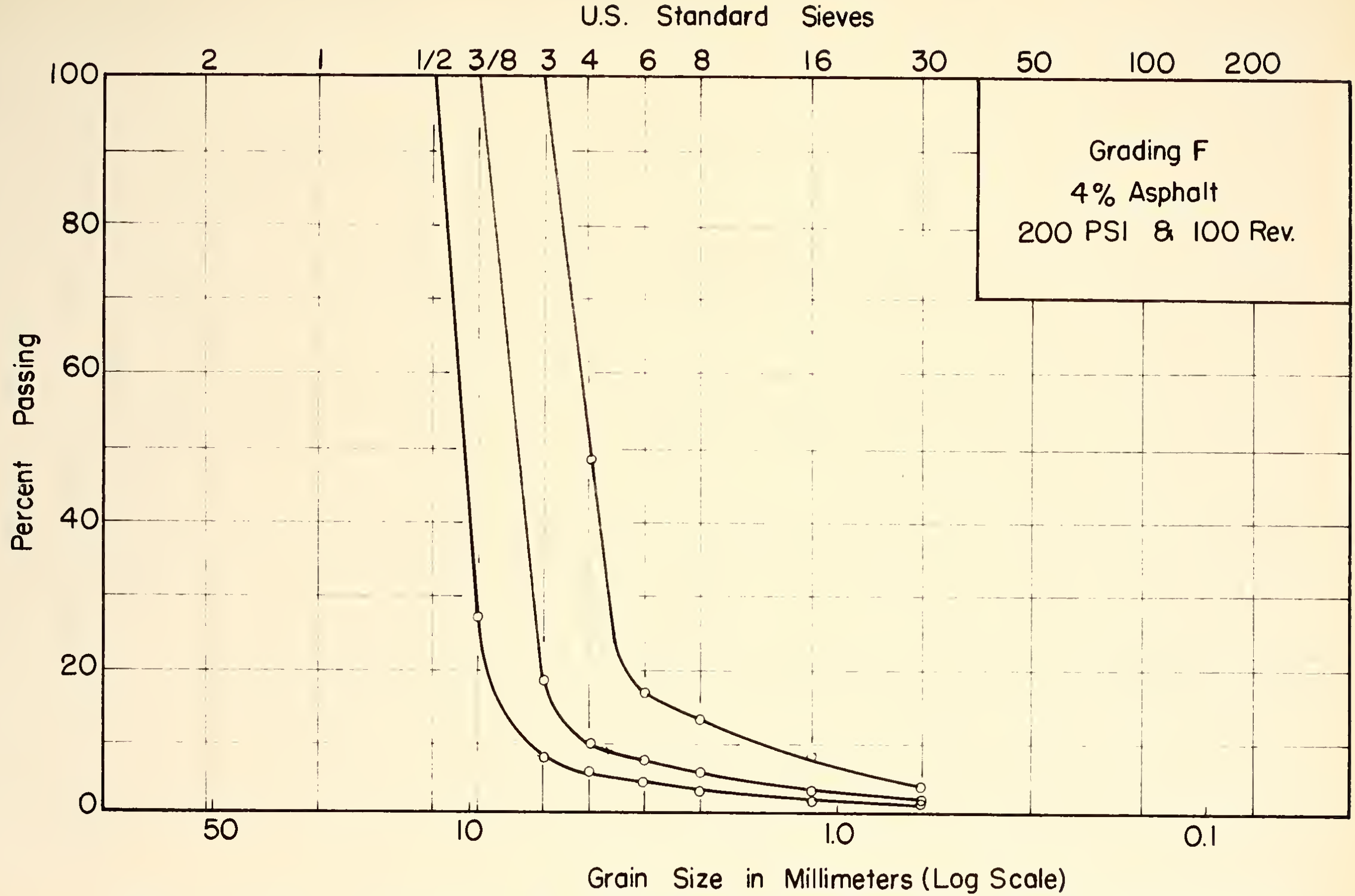

FIG. 12 SIEVE ANALYSIS OF COMPACTED COLORED AGGREGATE-GRADING F, 4% ASPHALT, 200 PSI, 100 REVOLUTIONS

pattern of degradation of 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, we can deduce 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

In this portion of the investigation, 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.

Tables 14, 15 and 16 present data for the percent increase in surface area for each of the three kinds of aggregate. Each value is for a specimen whose original gradation, percent asphalt, and effort used in testing it can be read from the table. Similar data for specimens made of rounded quartzite are given in Table 17.

Ram Pressure and Number of Revolutions

Figure 13 illustrates the percent increase in surface area versus number of revolutions for specimens made of limestone with zero and 4 percent asphalt. All specimens were made of grading O. The ram pressures are indicated on each curve. This figure shows that degradation increases very rapidly in the first part of the test and then continues to increase at a decreasing rate until

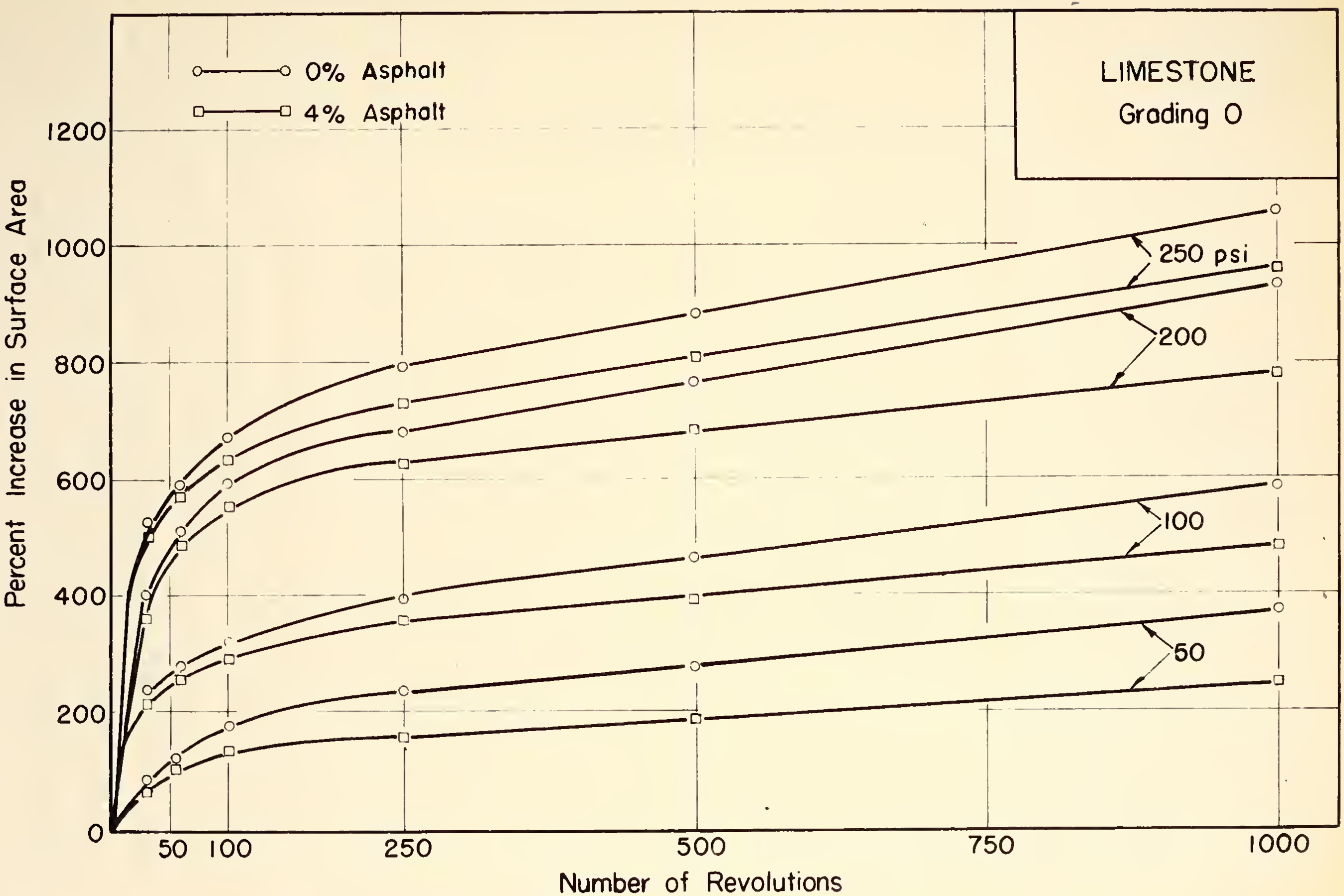

FIG. 13 DEGRADATION VS. NUMBER OF REVOLUTIONS–VARIABLE RAM PRESSURE

about 250 revolutions after which the rate of increase remains constant in each case. It can also be noticed that 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 1000 revolutions had occurred in the first hundred revolutions, while 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 zero and 4 percent asphalt. In this case the results for all three gradings are shown. Degradation on the ordinate is plotted on a log scale, while 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. These figures indicate that degradation increases both with increase in ram pressure and increase in number of revolutions. This means that degradation increases with increase in compactive effort.

In Figures 16 and 17 degradation is plotted versus number of revolutions. Each curve is for a single ram pressure as indicated on the curve. In these figures degradation for each gradation is plotted on different scales, and from left to right the results are for gradings O, B, and F, respectively. These figures also indicate that as compactive effort increases degradation also increases.

It can be seen that 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 Angles value) the aggregate the less was the increase in degradation from

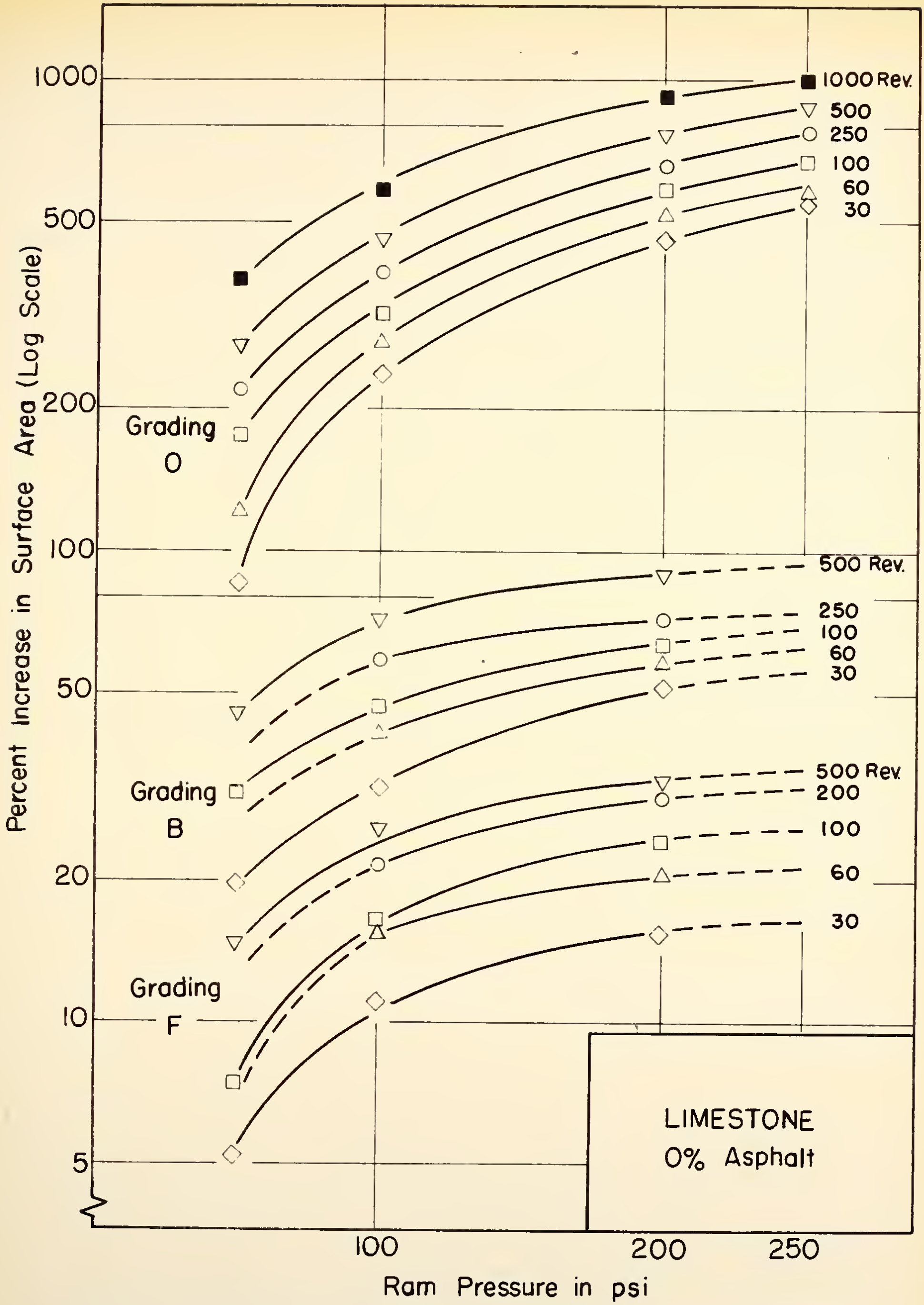

FIG. 14 DEGRADATION VS RAM PRESSURE FOR LIMESTONE - 0% ASPHALT

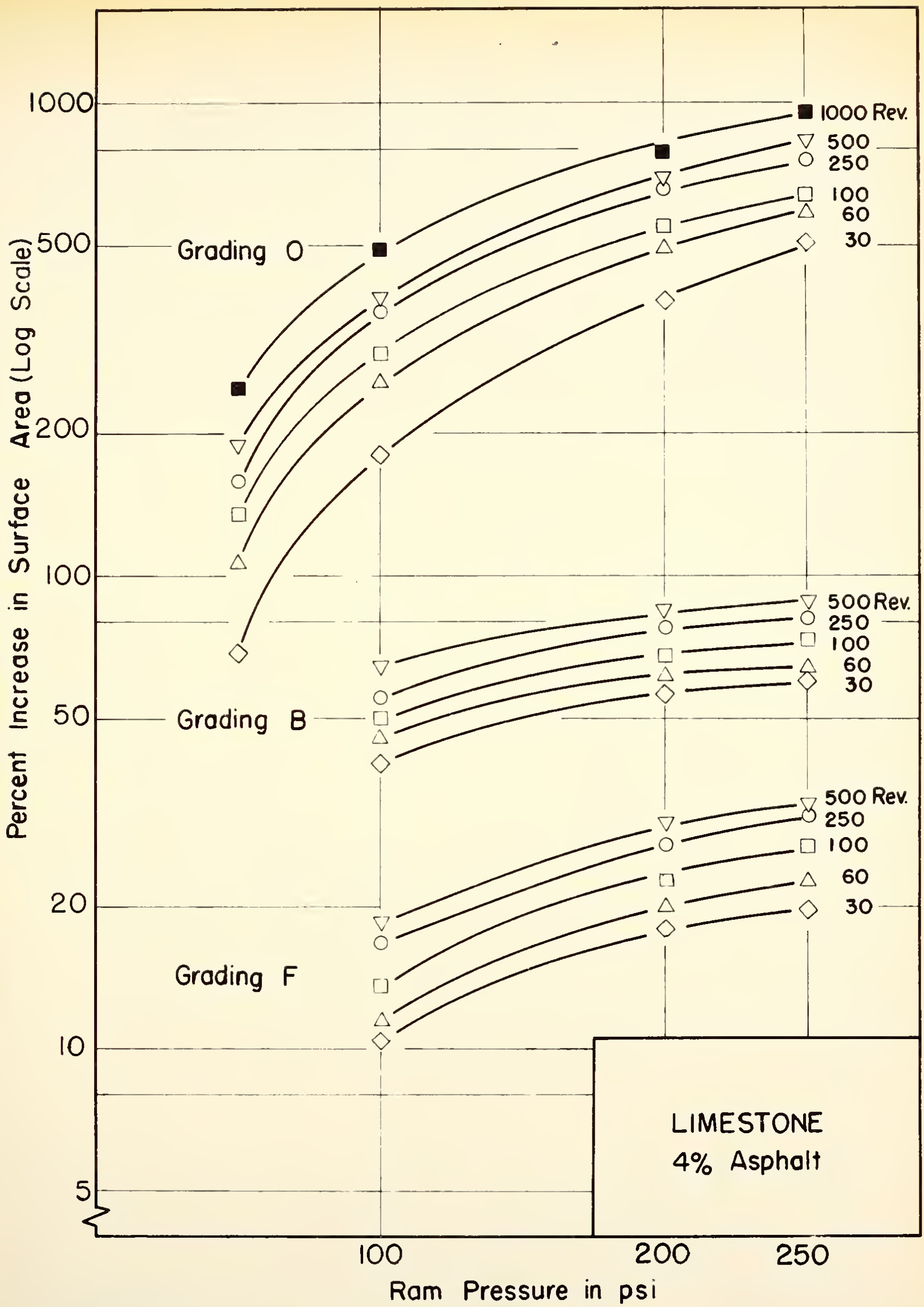

FIG. 15 DEGRADATION VS RAM PRESSURE FOR LIMESTONE-4 % ASPHALT

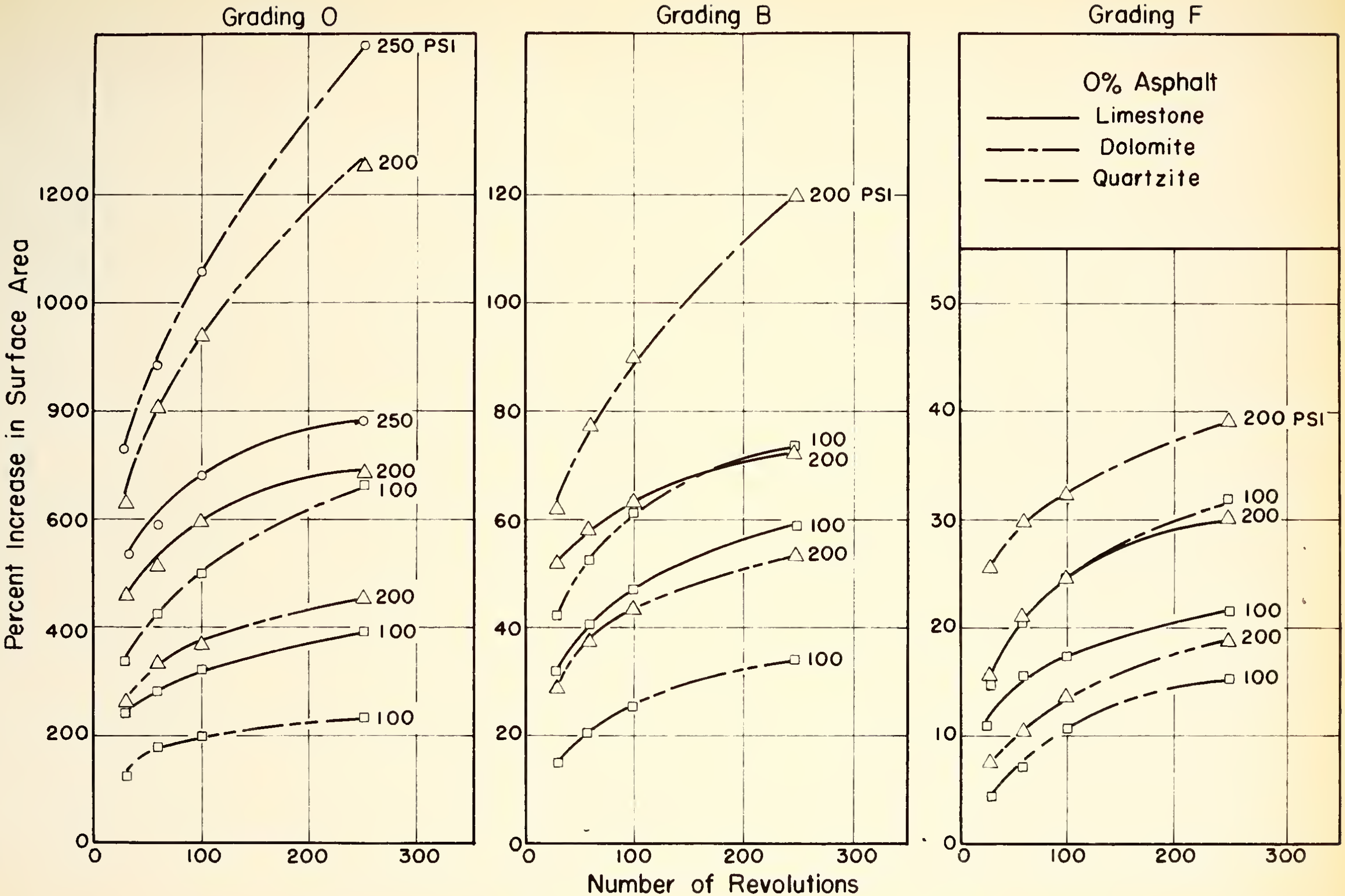

FIG. 16 DEGRADATION VS NUMBER OF REVOLUTIONS-0% ASPHALT

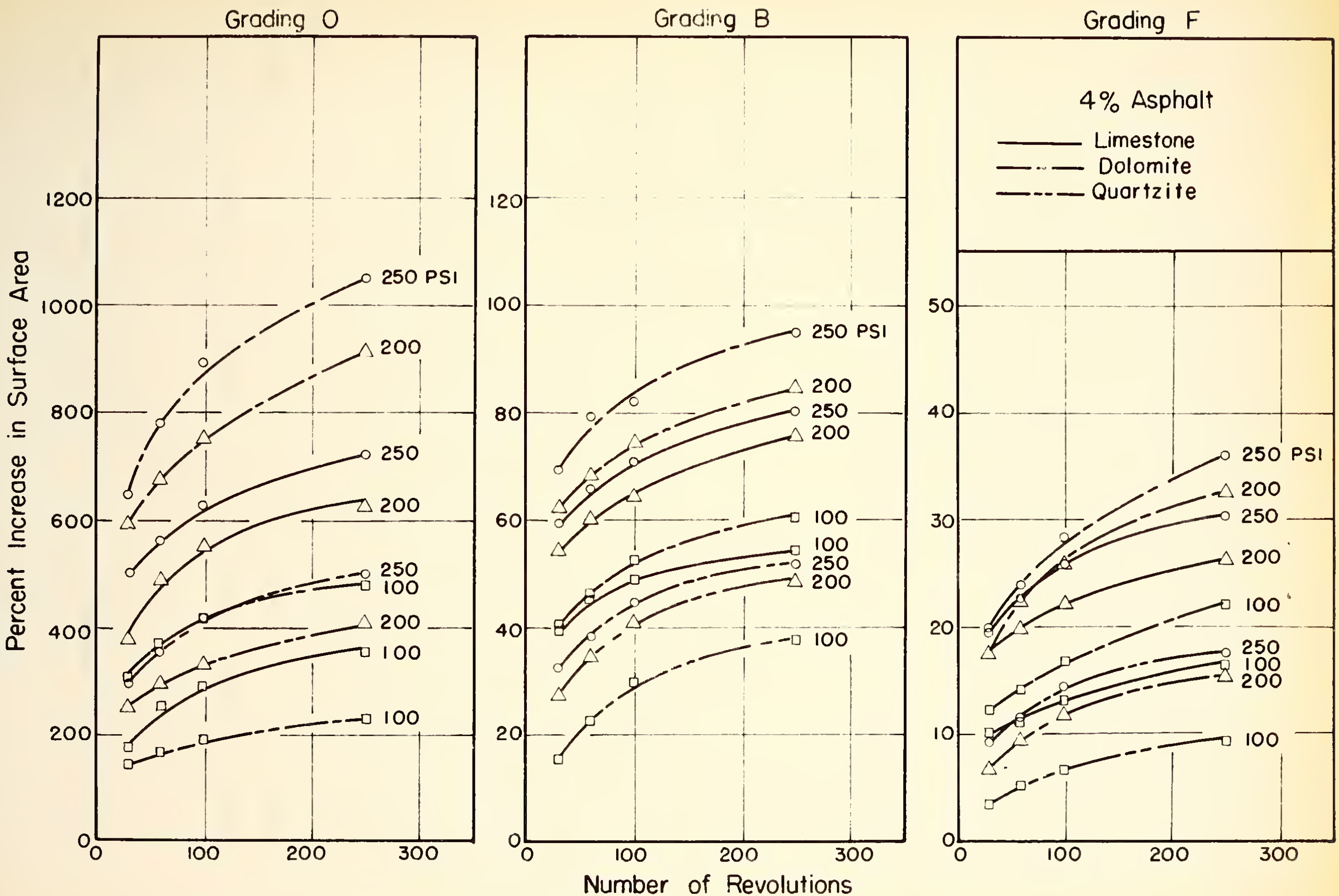

FIG. 17 DEGRADATION VS NUMBER OF REVOLUTIONS- 4% ASPHALT

this cause. These figures also show that increase in degradation caused by increase in number of revolutions depends upon 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. It can be noted from Figures 14 and 15 that as gradation becomes more dense, degradation decreases. 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 isn't 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, in Figure 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 in Figures 16 and 17 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 1400 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, changes in kind of aggregate, or changes 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. In a previous section 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 Content

Figure 18 illustrates the effect of change in asphalt content on degradation for the three gradings of limestone aggregate. This figure, as well as the results for the other two kinds of aggregate, indicates that depending on compactive effort, kind of aggregate, and gradation of aggregate there is in general an asphalt content for which the degradation is minimum. The results also indicate 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

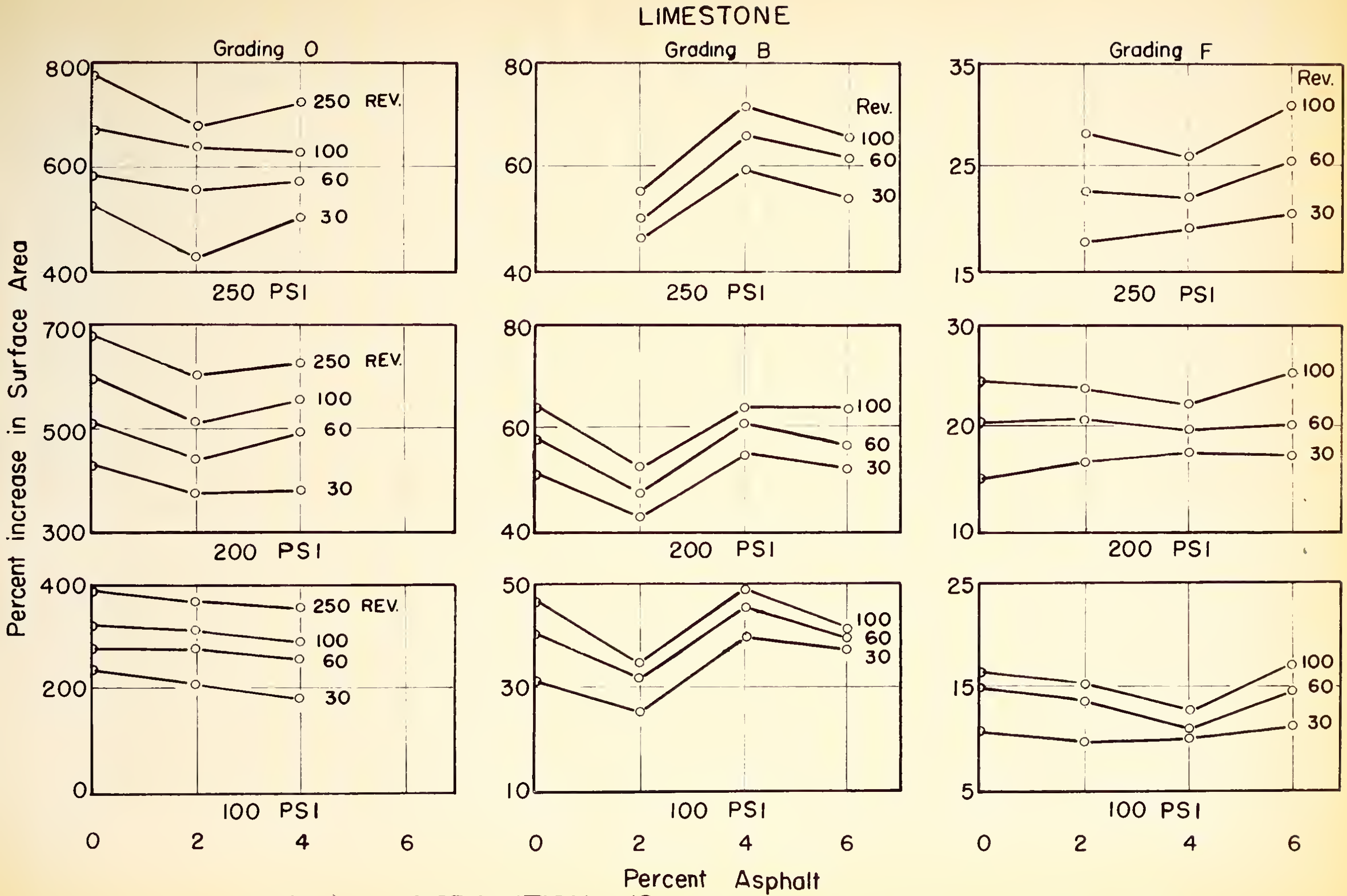

FIG. 18 DEGRADATION VS ASPHALT CONTENT - LIMESTONE

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 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

In order 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 17 contains the percent increase in surface area for such specimens. The same gradings (O, B, and F) as used before were used in this part of the study. The levels of compactive effort used were 100, 200, and 250 psi ram pressure, and 30, 100, and 250 revolutions. Eighteen specimens of each grading were tested, half of them without asphalt and the other

half with 4 percent asphalt. Therefore, a total of 54 specimens were used. Figure 19 presents the results obtained from specimens with 4 percent asphalt. The degradation of rounded and angular quartzite are compared.

This figure shows that 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 phenomena 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 phenomenon 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 we should be able to eliminate that portion of degradation due to wear. Practically, however, we can only reduce this portion rather than eliminate it, because when particles start to break, the newly produced pieces are no longer rounded and wear starts to occur.

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

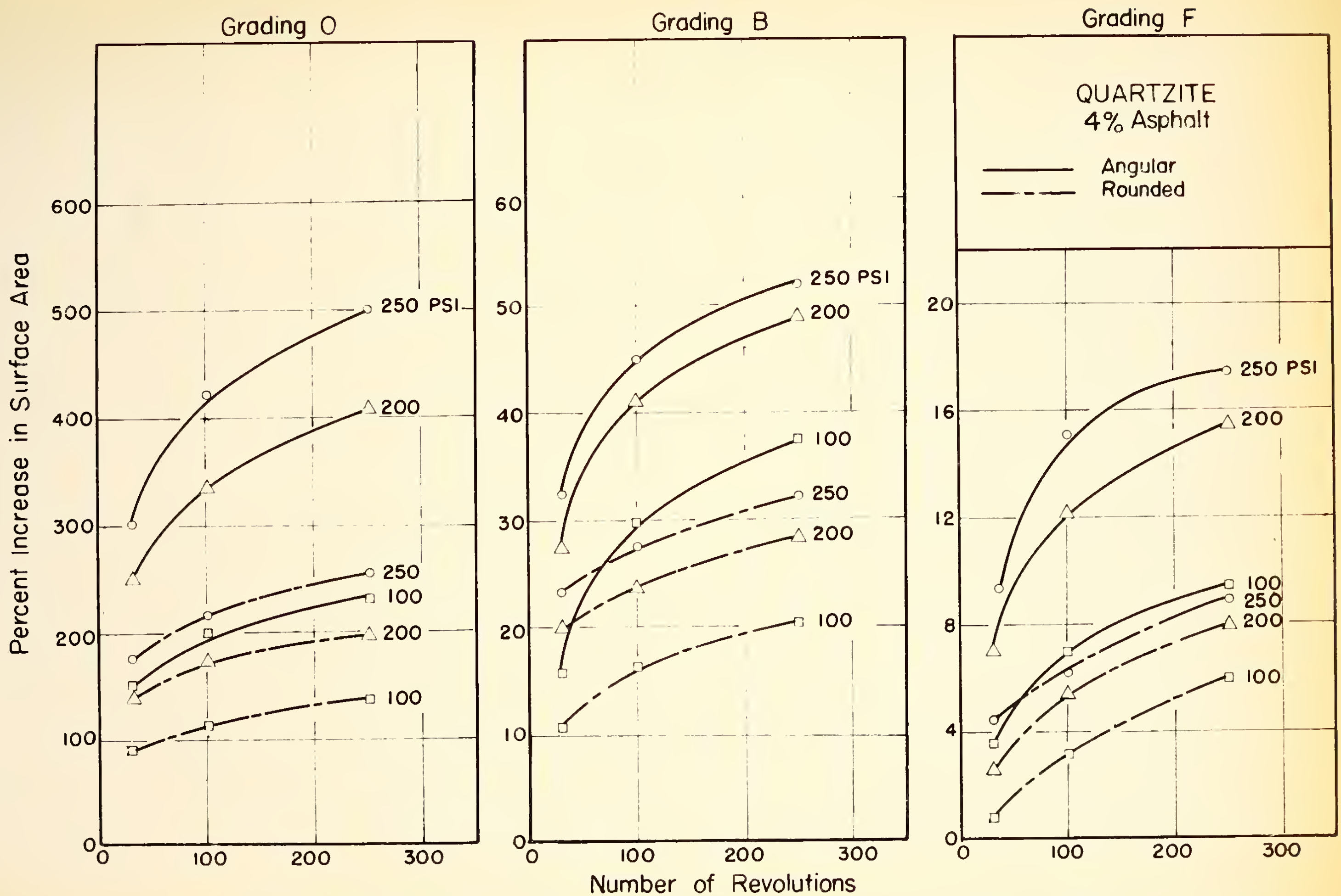

FIG.19 DEGRADATION VS NUMBER OF REVOLUTIONS-ANGULAR AND ROUNDED QUARTZITE, 4% ASPHALT

Degradation Versus Los Angeles Value

In order to see whether there is any relationship between the Los Angeles value and degradation of aggregate, degradation values were plotted versus the Los Angeles values for the three kinds of aggregate used in this investigation. Among the three gradings used for the Los Angeles test (Table 1), 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 testing gradings O, B, and F respectively. Each curve is for a certain number of revolutions which can be read on the curve. 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 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, while above 250 revolutionr more degradation is experienced by the less resistant material in the gyratory compactor than in 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, while Figure 22 shows that such linearity was not reached for specimens with grading F under compactive efforts used in this study.

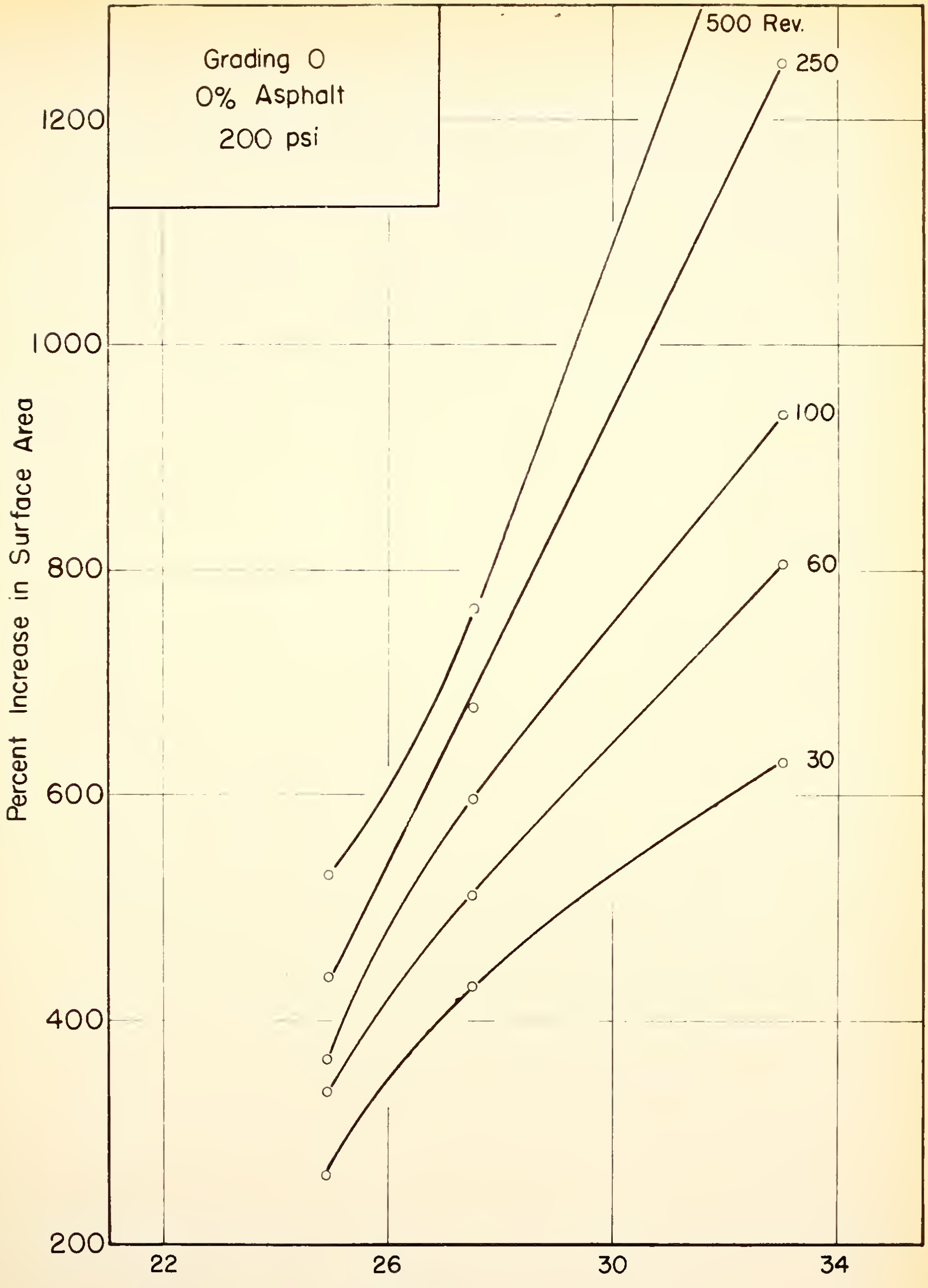

FIG. 20 DEGRADATION VS LOS ANGELES VALUE, GRADING O, 200 PSI

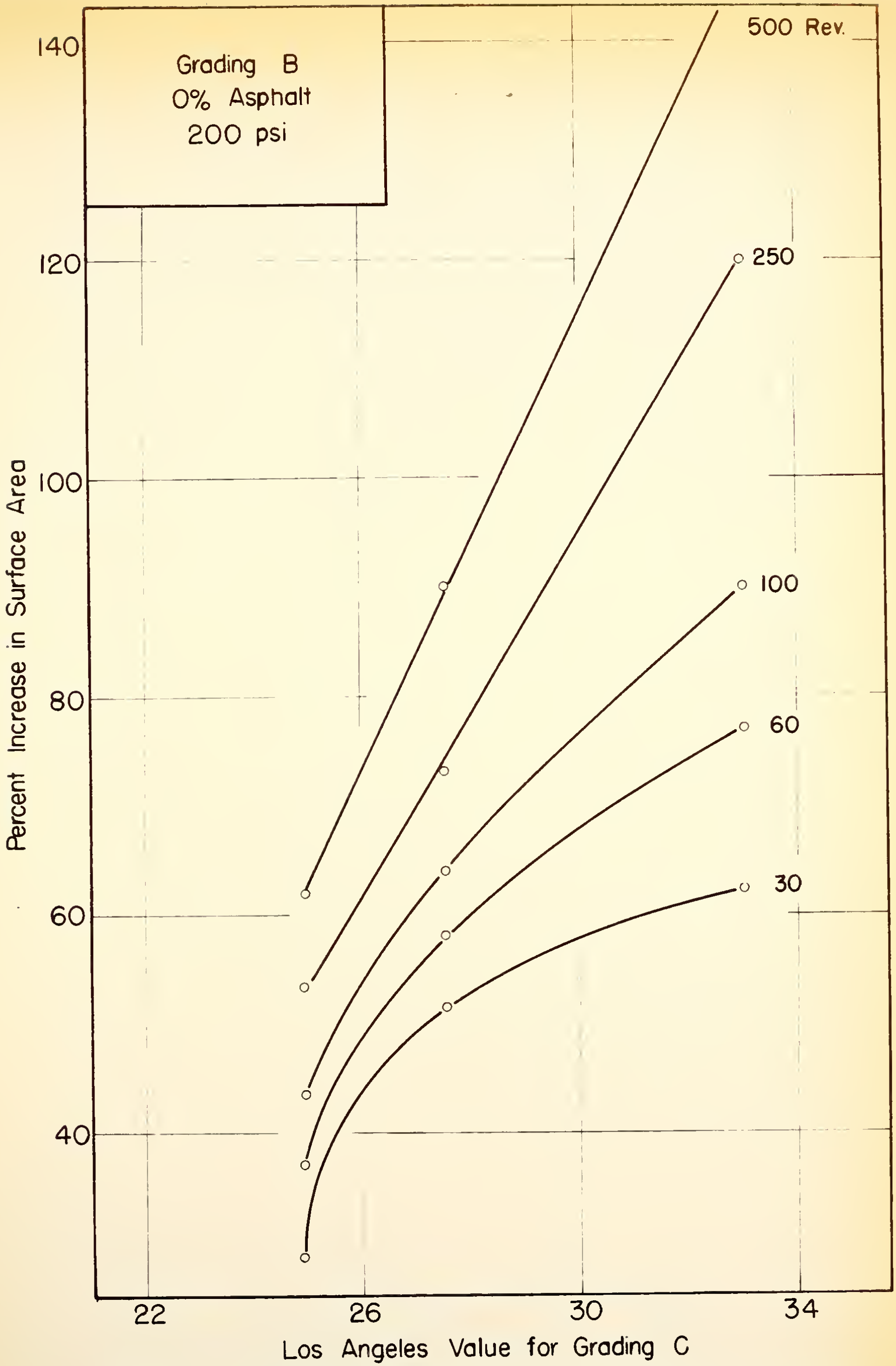

FIG. 21 DEGRADATION VS LOS ANGELES VALUE, GRADING B, 200 PSI

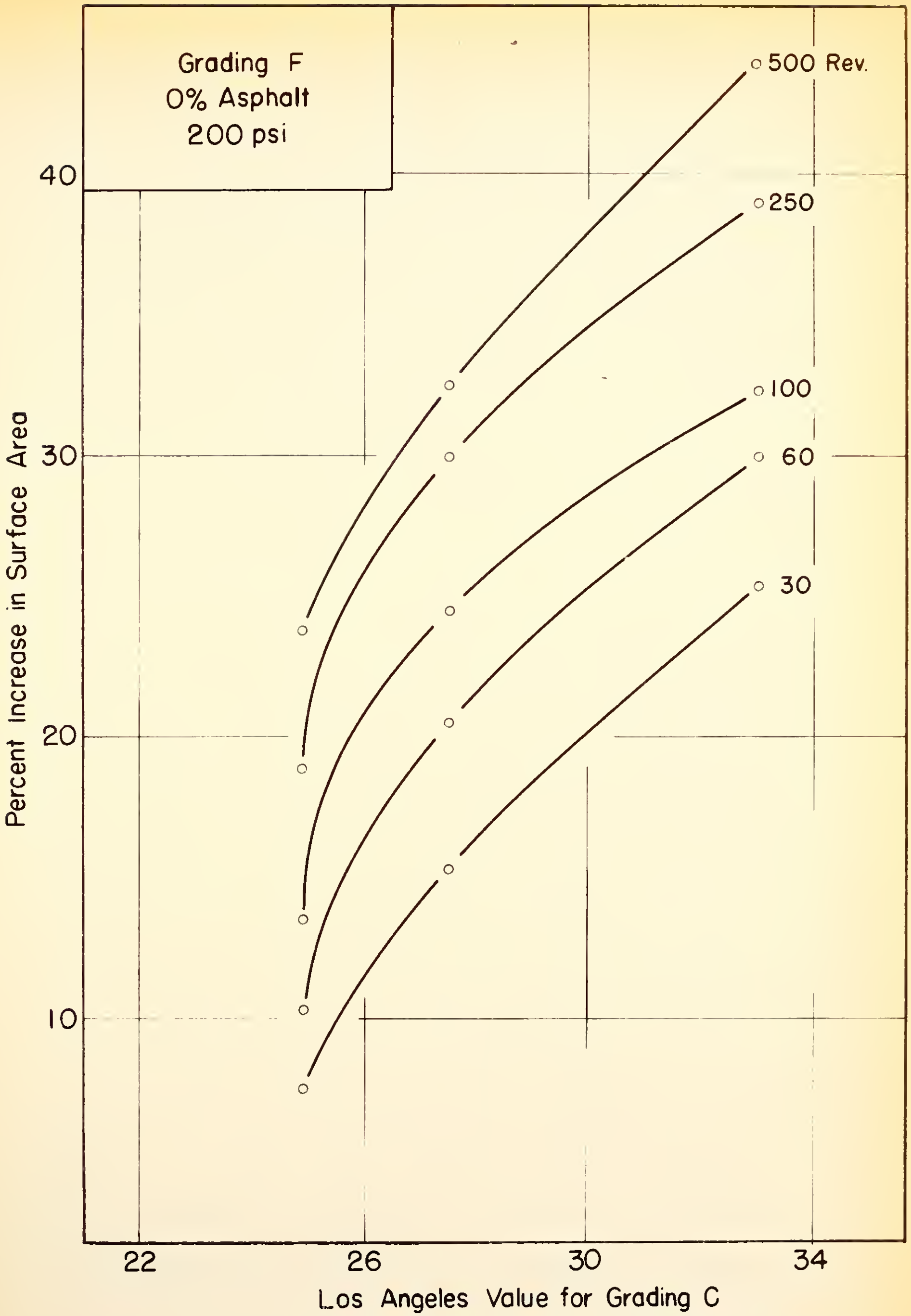

FIG. 22 DEGRADATION VS LOS ANGELES VALUE
GRADING F, 200 PSI

The foregoing discussion indicates 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, as can be seen in Figures 20, 21, and 22 increases as gradation of material becomes more dense. Noting that these levels of compaction, especially in dense-graded materials, are much higher than those the material is normally subjected to in the field, imposes some doubts 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 (Figures 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, while 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. These two actions, rotation and breakage will result in a denser packing, thus 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 reveals that nature of grain boundaries, cementation, and percent of voids influence the resistance of aggregates to degradation. Good interlocking between the grains present in limestone, results in a low Los Angeles value and low degradation. Loose interlocking, present in dolomite, results in a high Los Angeles value and high degradation. In quartzite strength is due to silica cementation, which 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. But 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 appear to justify the following conclusions. It should be realized that they are specifically applicable only to the particular kinds of aggregate used in this study. Furthermore, it should be noted that all the tests were performed in the laboratory, and there exists no field correlation study to specifically evaluate the field behavior of the materials. Also, it has to be noted that all conclusions and recommendations deal with degradation characteristics of mineral aggregate. Protective measures suggested in this study 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 used in this study, 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, gradation of the aggregate, compactive effort, and shape of particles. The effect of asphalt on the magnitude of degradation is dependent 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, has 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, 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 more dense, 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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TABLE 1

RESULTS OF LOS ANGELES ABRASION
AND COMPRESSIVE STRENGTH TESTS*

Los Angeles Abrasion

Type of Aggregate	Grading **		
	A	B	C
Dolomite	40.0	41.0	33.0
Limestone	26.7	25.0	27.5
Quartzite	22.0	23.7	24.9

Compressive Strength PSI***

Type of Aggregate	Size of Specimen Inches	
	1.0 x 1.0 x 1.0	1.0 x 1.0 x 2.0
Dolomite	10,100	8,500
Limestone	15,000	14,300
Quartzite	25,200	29,600

* Each value is the average of three tests
** According to ASTM Method C 131
*** Rate of loading .025 in/min

TABLE 2

PETROGRAPHIC ANALYSIS

	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
Av. grain size, mm.	.2	.5; .2	.8; <.1
Range, mm.	.1-.4	.1-1; .1-.3	.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 wavy 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

ORIGINAL GRADATIONS

Percent Passing

Sieve	Grading O	Grading B	Grading F
1/2"	100.0	100.0	100.0
3/8"	75.0	86.0	86.6
#3(1/4")	50.0	62.0	70.7
#4	25.0	50.0	61.2
#6	0.0	45.0	51.4
#8		36.0	43.3
#12		25.0	36.3
#16		16.0	30.0
#30		11.0	22.0
#50		6.0	15.0
#100		4.0	10.9
#200		3.0	7.7

TABLE 4

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, 100 grams, 5 sec., 77°F	90
Penetration, 100 grams, 5 sec., 32°F	20
Flash Point, Cleveland Open Cup, °F	600
Solubility in CCl_4, percent	99.8

TABLE 5

SURFACE AREA FACTORS

Fraction of Material		Factor
Passing	Retained	Sq. cm. per gram
1/2"	3/8"	2.2
3/8"	1/4"(#3)	3.2
#3	#4	4.5
#4	#6	5.7
#6	#8	7.9
#8	#16	12.7
#16	#50	30.0
#50	#100	100.0
#100	#200	205.0
#200	Pan	615.0

Note: Assumed sp. gr. = 2.65. For values other than 2.65, multiply the above factors by $\frac{2.65}{\text{sp. gr.}}$

TABLE 6

RESULTS OF GYRATORY TESTS OF VARIOUS ONE-SIZED AGGREGATES
200 PSI - 100 Revolutions

Total Percent Passing

	Dolomite				Limestone				Quartzite			
Original Size	1/2-3/8	3/8-#3	#3-#4	#4-#6	1/2-3/8	3/8-#3	#3-#4	#4-#6	1/2-3/8	3/8-#3	#3-#4	#4-#6
Sieve Size												
1/2"	100.0	-	-	-	100.0	-	-	-	100.0	-	-	-
3/8"	59.8	100.0	-	-	55.3	100.0	-	-	48.6	100.0	-	-
#3	37.3	53.6	100.0	-	32.0	58.4	100.0	-	23.2	43.8	100.0	-
#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
#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
#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
#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
#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
#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
#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
Total Weight gr	1000.0	1000.0	1000.5	1000.0	992.5	992.5	993.0	1000.0	1000.0	1000.0	1000.0	1000.0
Final S.A. cm^2/gr	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 S.A. cm^2/gr	2.2	3.2	4.5	5.7	2.2	3.2	4.5	5.7	2.2	3.2	4.5	5.7
S.A. Increase cm^2/gr	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 in S.A.	1443.0	1081.0	800.0	696.0	795.4	606.2	479.0	419.3	528.6	428.1	308.9	252.6

TABLE 7

RESULTS OF GYRATORY TESTS OF ONE-SIZED AGGREGATES
100 PSI

Total Percent Passing

	3/8"-#3 Dolomite					3/8"-#3 Limestone					3/8"-#3 Quartzite				
No. of Rev.	50	100	250	500	1000	50	100	250	500	1000	50	100	250	500	1000
Sieves															
3/8"	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
#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
#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
#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
#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
#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
#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
#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
#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
Total Weight gms	1000.0	999.5	1000.0	1000.0	1000.0	1000.0	1000.0	995.0	1000.0	1000.0	1000.0	999.5	999.0	1000.0	1000.0
Final S.A. cm^2/gr	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 S.A. cm^2/gr	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 in S.A. cm^2/gr	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 in S.A.%	463.0	530.0	750.0	962.0	1097.0	260.0	378.0	457.0	600.0	773.0	200.0	255.0	330.0	473.0	563.0

TABLE 8

RESULTS OF SIEVE ANALYSIS OF COLORED AGGREGATES
GRADING O, 0% ASPHALT

Total Percent Passing

Compactive Effort	100 psi, 30 Rev.					100 psi., 100 Rev.				
Size Fraction	1/2"-3/8"	3/8"-#3	#3-#4	#4-#6	Total	1/2"-3/8"	3/8"-#3	#3-#4	#4-#6	Total
Sieves / Color	Violet	Red	Green	Natural		Violet	Red	Green	Natural	
1/2"	100.0				100.0	100.0				100.0
3/8"	25.5	100.0			81.4	27.7	100.0			83.3
#3	11.6	24.3	100.0		59.0	13.2	32.4	100.0		61.0
#4	8.2	10.0	31.1	100.0	37.3	10.0	14.7	40.4	100.0	40.8
#6	5.6	7.0	15.0	48.2	18.4	7.0	10.3	22.1	59.8	24.5
#8	4.0	5.2	10.4	23.7	10.8	5.2	8.1	15.5	32.4	15.2
#16	1.9	3.2	5.3	9.6	5.0	3.2	5.0	8.0	15.6	7.9
#50	0.9	1.6	2.0	2.2	1.6	2.0	2.5	3.0	4.0	2.8
#100					1.0					1.8
#200					0.7					1.1
Total Weight, gms	250.0	251.0	251.0	251.0	1003.0	251.5	251.5	251.5	251.5	1006.0

Compactive Effort	200 psi, 30 Rev.					200 psi, 100 Rev.				
Size Fraction	1/2"-3/8"	3/8"-#3	#3-#4	#4-#6	Total	1/2"-3/8"	3/8" #3	#3-#4	#4-#6	Total
Sieves / Color	Violet	Red	Green	Natural		Violet	Red	Green	Natural	
1/2"	100.0				100.0	100.0				100.0
3/8"	44.0	100.0			86.0	52.2	100.0			88.1
#3	19.4	45.6	100.0		66.8	23.6	49.4	100.0		68.3
#4	14.0	20.5	43.0	100.0	44.7	16.6	22.2	49.4	100.0	47.1
#6	10.8	13.9	24.5	69.1	29.6	12.8	16.4	28.4	77.2	33.7
#8	8.6	10.9	16.9	39.8	19.1	10.2	12.6	20.8	48.8	23.1
#16	5.4	6.1	9.5	17.3	9.6	7.1	8.2	11.9	24.0	12.0
#50	2.9	3.5	4.6	5.9	3.3	4.6	5.2	6.9	7.8	4.9
#100					2.1					3.1
#200					1.3					1.9
Total Weight, gms	250.0	251.0	251.0	251.0	1003.0	249.8	249.8	250.0	250.0	999.5

TABLE 9

RESULTS OF SIEVE ANALYSIS OF COLORED AGGREGATES
GRADING O, 4% ASPHALT

Total Percent Passing

Compactive Effort	100 psi, 30 Rev.					100 psi, 100 Rev.				
Size Fraction	1/2"-3/8"	3/8"-#3	#3-#4	#4-#6	Total	1/2"-3/8"	3/8"-#3	#3-#4	#4-#6	Total
Color / Sieves	Violet	Red	Green	Natural		Violet	Red	Green	Natural	
1/2"	100.0				100.0	100.0				100.0
3/8"	19.6	100.0			79.9	25.0	100.0			79.4
#3	6.2	25.4	100.0		57.9	11.0	29.6	100.0		58.9
#4	4.4	8.4	28.4	100.0	35.3	8.0	11.0	36.2	100.0	38.0
#6	3.0	4.8	11.6	49.4	17.2	5.0	7.0	16.2	55.2	20.2
#8	2.2	3.4	7.2	24.6	9.4	3.0	4.8	10.8	30.8	11.9
#16	1.1	1.5	3.5	10.5	4.1	1.8	3.0	5.7	14.9	5.7
#30	0.5	0.7	2.0	5.8	2.2	1.0	2.0	4.3	9.1	3.4
#50					1.3					2.1
#100					0.8					1.5
#200					0.5					1.0
Total Weight, gms	250.0	250.0	250.0	250.0	1000.0	250.0	250.0	250.0	250.0	1000.0

Compactive Effort	200 psi, 30 Rev.					200 psi, 100 Rev.				
Size Fraction	1/2"-3/8"	3/8"-#3	#3-#4	#4-#6	Total	1/2"-3/8"	3/8"-#3	#3-#4	#4-#6	Total
Color / Sieves	Violet	Red	Green	Natural		Violet	Red	Green	Natural	
1/2"	100.0				100.0	100.0				100.0
3/8"	30.5	100.0			84.1	34.0	100.0			83.0
#3	14.9	36.5	100.0		62.9	17.0	43.0	100.0		64.5
#4	10.1	14.5	45.6	100.0	42.6	12.0	20.2	48.0	100.0	44.8
#6	7.9	10.3	25.4	60.6	28.1	8.6	13.6	29.2	65.4	29.2
#8	5.7	6.9	18.0	35.2	18.0	7.1	10.0	21.2	39.7	19.5
#16	2.9	3.8	9.2	20.2	9.1	4.1	5.8	12.6	23.5	10.5
#30	1.8	2.8	6.9	13.0	5.4	2.6	3.5	9.2	17.0	6.3
#50					3.4					3.9
#100					2.2					2.5
#200					1.5					1.6
Total Weight, gms	250.0	250.0	250.0	250.0	1000.0	250.0	250.0	250.0	250.0	1000.0

TABLE 10

RESULTS OF SIEVE ANALYSIS OF COLORED AGGREGATES
GRADING B, 0% ASPHALT

Total Percent Passing

Compactive Effort	100 psi, 30 Rev.					100 psi, 100 Rev.				
Size Fraction	1/2"-3/8"	3/8"-#3	#3-#4	#4-#6	Total	1/2"-3/8"	3/8"-#3	#3-#4	#4-#6	Total
Color / Sieves	Violet	Red	Green	Natural		Violet	Red	Green	Natural	
1/2"	100.0				100.0	100.0				100.0
3/8"	20.1	100.0			89.4	22.5	100.0			88.3
#3	6.0	19.0	100.0		67.4	6.8	19.6	100.0		67.5
#4	3.4	4.4	23.7	100.0	54.5	5.0	7.3	25.4	100.0	55.2
#6	2.5	3.1	9.1	90.2	48.8	3.2	5.7	12.5	93.2	49.7
#8	1.4	2.1	4.5	75.1	40.7	1.8	3.7	7.8	78.8	41.8
#16	0.4	0.6	1.3	40.5	20.5	0.7	2.4	4.3	43.4	22.2
#30	0.1	0.3	0.5	26.8	13.4	0.2	1.6	2.5	28.6	14.8
#50					7.8					8.7
#100					5.4					5.9
#200					3.6					4.0
Total Weight, gms	140.0	240.0	120.0	499.0	999.0	140.0	240.0	120.0	498.0	998.0

Compactive Effort	200 psi, 30 Rev.					200 psi, 100 Rev.				
Size Fraction	1/2"-3/8"	3/8"-#3	#3-#4	#4-#6	Total	1/2"-3/8"	3/8"-#3	#3-#4	#4-#6	Total
Color / Sieves	Violet	Red	Green	Natural		Violet	Red	Green	Natural	
1/2"	100.0				100.0	100.0				100.0
3/8"	24.7	100.0			89.6	26.1	100.0			89.6
#3	9.2	26.7	100.0		69.9	10.5	30.0	100.0		70.2
#4	6.4	9.4	31.7	100.0	57.[illegible]	7.2	11.6	32.9	100.0	57.4
#6	4.4	6.8	14.2	95.2	51.1	5.8	7.4	17.1	96.7	51.8
#8	2.2	4.4	9.2	82.2	43.3	2.8	5.7	11.3	84.7	44.2
#16	1.1	3.2	5.5	45.0	23.3	1.7	4.2	6.7	47.9	34.4
#30	0.4	2.3	3.0	30.6	15.6	0.7	3.2	3.5	32.4	16.3
#50					9.2					9.8
#100					6.3					7.1
#200					4.2					4.8
Total Weight, gms	140.0	240.0	120.0	499.0	999.0	140.0	240.0	120.0	500.0	1000.0

TABLE 11

RESULTS OF SIEVE ANALYSIS OF COLORED AGGREGATES
GRADING B, 4% ASPHALT

Total Percent Passing

Compactive Effort	100 psi, 30 Rev.					100 psi, 100 Rev.				
Size Fraction	1/2"-3/8"	3/8"-#3	#3-#4	#4-#6	Total	1/2"-3/8"	3/8"-#3	#3-#4	#4-#6	Total
Color	Violet	Red	Green	Natural		Violet	Red	Green	Natural	
Sieves										
1/2"	100.0				100.0	100.0				100.0
3/8"	16.8	100.0			88.0	18.5	100.0			88.4
#3	3.9	23.7	100.0		65.8	4.7	24.6	100.0		68.6
#4	2.1	4.1	15.8	100.0	53.1	3.3	6.7	20.0	100.0	54.5
#6	1.7	2.4	5.4	93.5	48.1	2.2	4.6	9.2	93.7	49.4
#8	1.3	1.6	3.3	77.7	39.7	1.5	2.9	5.0	78.7	40.9
#16	0.7	1.0	1.6	40.3	20.4	0.9	1.5	2.1	41.1	21.2
#30	0.2	0.4	0.8	26.8	13.4	0.4	0.8	1.2	27.3	14.0
#50					9.0					9.4
#100					5.7					5.9
#200					3.6					3.8
Total Weight, gms	140.0	240.0	120.0	500.0	1000.0	140.0	240.0	120.0	500.0	1000.0

Compactive Effort	200 psi, 30 Rev.					200 psi, 100 Rev.				
Size Fraction	1/2"-3/8"	3/8"-#3	#3-#4	#4-#6	Total	1/2"-3/8"	3/8"-#3	#3-#4	#4-#6	Total
Color	Violet	Red	Green	Natural		Violet	Red	Green	Natural	
Sieves										
1/2"	100.0				100.0	100.0				100.0
3/8"	19.7	100.0			89.0	21.4	100.0			89.9
#3	5.7	26.3	100.0		69.1	8.2	27.5	100.0		69.4
#4	4.0	8.6	27.1	100.0	56.4	6.0	10.7	35.5	100.0	56.8
#6	3.0	6.8	12.9	94.2	50.6	4.3	8.8	18.8	94.7	50.6
#8	2.4	3.7	7.5	80.2	42.3	3.2	6.0	13.8	81.7	43.2
#16	1.9	2.6	3.8	42.0	22.1	2.5	3.2	7.3	44.1	23.1
#30	1.0	1.9	2.6	28.5	15.0	1.5	2.3	5.5	29.3	15.4
#50					9.1					9.5
#100					6.4					6.6
#200					4.4					4.7
Total Weight, gms	140.0	240.0	120.0	496.5	996.5	140.0	240.0	120.0	490.0	990.0

TABLE 12

RESULTS OF SIEVE ANALYSIS OF COLORED AGGREGATES
GRADING F, 0% ASPHALT

Total Percent Passing

Compactive Effort	100 psi, 30 Rev.					100 psi, 100 Rev.				
Size Fraction	1/2"-3/8"	3/8"-#3	#3-#4	#4-#6	Total	1/2"-3/8"	3/8"-#3	#3-#4	#4-#6	Total
Sieves / Color	Violet	Red	Green	Natural		Violet	Red	Green	Natural	
1/2"	100.0				100.0	100.0				100.0
3/8"	15.7	100.0			86.7	18.9	100.0			87.7
#3	4.0	17.0	100.0		73.8	5.9	18.2	100.0		74.0
#4	2.6	4.7	16.8	100.0	63.9	3.9	5.7	21.1	100.0	64.2
#6	1.9	3.1	6.3	87.7	56.2	2.9	4.1	9.5	89.6	56.4
#8	1.2	2.2	3.7	74.1	47.4	1.8	2.8	6.3	76.5	47.8
#16	0.4	1.1	1.9	53.1	32.8	0.8	1.6	3.8	53.8	33.2
#30	0.1	0.7	1.1	37.5	23.0	0.5	0.9	2.3	38.5	23.6
#50					17.1					17.3
#100					13.3					14.3
#200					9.1					10.3
Total Weight, gms	134.0	159.0	95.0	612.0	1000.0	134.0	159.0	95.0	612.0	1000.0

Compactive Effort	200 psi, 30 Rev.					200 psi, 100 Rev.				
Size Fraction	1/2"-3/8"	3/8"-#3	#3-#4	#4-#6	Total	1/2"-3/8"	3/8"-#3	#3-#4	#4-#6	Total
Sieves / Color	Violet	Red	Green	Natural		Violet	Red	Green	Natural	
1/2"	100.0				100.0	100.0				100.0
3/8"	21.7	100.0			89.5	32.1	100.0			90.9
#3	8.3	22.1	100.0		76.1	11.9	26.6	100.0		79.9
#4	4.9	9.8	25.3	100.0	65.8	8.5	12.3	38.9	100.0	68.4
#6	3.8	6.3	11.1	91.0	58.1	6.3	8.4	20.5	92.3	61.0
#8	2.4	4.8	7.8	79.0	49.7	4.1	5.5	12.1	81.7	52.9
#16	1.1	2.5	4.8	56.0	34.7	2.3	3.3	6.9	58.8	36.9
#30	0.8	1.7	3.0	40.5	25.0	1.4	2.5	4.3	43.5	26.9
#50					18.5					19.8
#100					15.6					16.3
#200					11.6					12.9
Total Weight, gms	134.0	159.0	95.0	610.0	998.0	134.0	159.0	95.0	616.0	1000.0

TABLE 13

RESULTS OF SIEVE ANALYSIS OF COLORED AGGREGATES
GRADING F, 4% ASPHALT

Total Percent Passing

Compactive Effort	100 psi, 30 Rev.					100 psi, 100 Rev.				
Size Fraction	1/2"-3/8"	3/8"-#3	#3-#4	#4-#6	Total	1/2"-3/8"	3/8"-#3	#3-#4	#4-#6	Total
Color / Sieves	Violet	Red	Green	Natural		Violet	Red	Green	Natural	
1/2"	100.0				100.0	100.0				100.0
3/8"	11.2	100.0			88.0	15.4	100.0			89.6
#3	5.2	14.5	100.0		73.5	6.0	16.0	100.0		74.4
#4	3.7	7.3	25.3	100.0	64.1	4.1	8.2	28.9	100.0	64.4
#6	2.0	5.7	12.7	83.5	53.4	2.6	6.1	14.1	85.5	54.3
#8	1.9	4.0	9.0	73.2	46.5	2.1	4.4	11.9	75.4	47.7
#16	0.7	1.6	5.0	52.6	32.4	0.9	2.0	6.0	53.5	33.3
#30	0.2	0.6	1.2	38.0	23.1	0.4	1.0	2.0	38.9	24.0
#50					17.0					17.6
#100					12.4					12.8
#200					8.7					8.9
Total Weight, gms	134.0	159.0	95.0	607.0	995.0	134.0	159.0	95.0	612.0	1000.0

Compactive Effort	200 psi, 30 Rev.					200 psi, 100 Rev.				
Size Fraction	1/2"-3/8"	3/8"-#3	#3-#4	#4-#6	Total	1/2"-3/8"	3/8"-#3	#3-#4	#4-#6	Total
Color / Sieves	Violet	Red	Green	Natural		Violet	Red	Green	Natural	
1/2"	100.0				100.0	100.0				100.0
3/8"	18.3	100.0			89.9	26.5	100.0			90.1
#3	6.6	16.9	100.0		74.6	7.7	17.6	100.0		74.9
#4	4.8	8.8	36.3	100.0	65.4	5.4	9.6	47.9	100.0	65.9
#6	2.9	6.8	15.8	87.8	56.3	3.5	7.4	16.4	88.9	56.5
#8	2.4	5.0	12.6	77.9	49.6	3.0	5.8	13.1	78.2	50.5
#16	1.2	2.3	7.0	55.5	34.5	1.6	3.2	8.1	56.4	35.2
#30	0.7	1.2	2.9	40.5	24.8	1.1	1.8	3.6	42.0	25.4
#50					18.4					19.0
#100					13.4					14.1
#200					9.1					10.3
Total Weight, gms	134.0	154.0	95.0	612.0	995.0	134.0	159.0	95.0	605.0	993.0

TABLE 14

PERCENT INCREASE IN SURFACE AREA
Dolomite

Original Grading		Grading O				Grading B				Grading F			
		% Asphalt				% Asphalt				% Asphalt			
PSI	Rev.	0	2	4	6	0	2	4	6	0	2	4	6
	30	258.0				24.0				11.2			
	100	321.0				35.5				16.3			
50	250	420.0				44.0				20.0			
	500	500.0				72.2				23.9			
	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	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	
	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
200	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	1250.0	890.0	915.0		120.0		84.5		39.0		33.0	
	500	1440.0		1070.0		146.0		92.0		44.0		37.0	
	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
250	100	1058.7	859.0	892.0	919.0		80.0	82.0	78.2		29.0	28.6	38.1
	250	1480.0	1000.0	1050.0				95.0				36.2	
	500	1700.0		1230.0				102.0				41.5	

TABLE 15

PERCENT INCREASE IN SURFACE AREA
Limestone

Original Grading		Grading O				Grading B				Grading F			
		% Asphalt				% Asphalt				% Asphalt			
PSI	Rev.	0	2	4	6	0	2	4	6	0	2	4	6
	30	85.0		68.4		19.6				5.2			
	60	120.5		105.3									
50	100	175.5		134.0		30.5				7.4			
	250	220.0		158.0									
	500	275.0		185.0		45.1				14.1			
	1000	378.0		249.0									
	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	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	
	1000	580.0		484.0									
	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
200	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	
	1000	929.0		776.0									
	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
250	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	
	1000			955.3									

TABLE 16

PERCENT INCREASE IN SURFACE AREA
Quartzite

Original Grading		Grading O			Grading B				Grading F			
		% Asphalt			% Asphalt				% Asphalt			
PSI	Rev.	0	2	4	0	2	4	6	0	2	4	6
	30				11.2				2.0			
50	100				18.1				4.8			
	250				25.0				7.9			
	500				28.8				13.5			
	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	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	
	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
200	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	
	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
250	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	

TABLE 17

PERCENT INCREASE IN SURFACE AREA
Rounded Quartzite

Original Grading		G Grading O		Grading B		Grading F	
		% Asphalt		% Asphalt		% Asphalt	
PSI	Rev.	0	4	0	4	0	4
	30	67.8	82.9	7.2	10.8	1.0	0.7
100	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
	30	114.0	142.4	12.2	20.0	2.6	2.5
200	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
	30	128.0	175.0	13.3	23.3	2.9	4.5
250	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