PARTICLE INDEX EVALUATION OF AGGREGATES FOR ASPHALT PAVING MIXTURES

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INTRODUCTION

1. A criterion for the stability of an aggregate is provided by its angle of internal friction, represented by the symbol ϕ, which provides in a single term a measure of the combined contribution of particle shape, angularity and surface texture to the aggregate's stability. Aggregates consisting of rounded, smooth surfaced particles have low angles of internal friction and low stabilities, while aggregates comprised of particles that tend to be cubical or pyramidal in shape, with sharp, angular, rather than rounded edges, and with rough surface textures, have high angles of internal friction, and correspondingly high stabilities.
2. The particle index of an aggregate appears to provide an empirical measure of an aggregate's stability, similar to the angle of internal friction. For example, an aggregate composed of rounded particles with smooth surface textures, and therefore of low stability, will have a low particle index of 6 or 7 or less, while aggregates consisting of highly crushed angular particles with rough textured surfaces, and therefore of high stability, can have particle indices of from 15 to 20 or more. With this reasonably large range of values, the particle index provides a quite sensitive empirical stability measurement for aggregates.
3. By means of a triaxial test, the angle of internal friction can be measured for the aggregate as a whole. However, the particle index measurement must be performed on each closely sized fraction of an aggregate, such as 12.5 to 9.5 mm (1/2 to 3/8 in.), No. 16 to No. 30, No. 50 to No. 100, etc. Nevertheless, the overall average particle index for a graded aggregate can be calculated as a weighted average based on the particle index for the percentage of each narrowly sized portion of the aggregate. If a dense graded aggregate as a whole is subjected to the particle index test, a quite unrepresentative very low particle index of only 5 or 6 will be obtained whereas when the particle index for each of its closely spaced sieve sizes is determined, its overall weighted particle index can be from 12 to 15 or higher.
4. Consequently, as used throughout this paper, particle index (PI) is considered to provide an empirical measure of aggregate stability, with stability increasing with an increase in particle index.
5. The particle index procedure was developed by Eugene Y. Huang (*1*), and a standard method for this test is described in ASTM D 3398 (*2*).

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The oral presentation was made by Dr. McLeod.

the equipment required for this test is quite simple, consisting basically of a cylindrical steel mold 152 mm (6 in.) in diameter by 178 mm (7 in.) high (internal dimensions), and a steel tamping rod 15.88 mm (5/8 in.) in diameter, about 610 mm (24 in.) long, and weighing 930 grams (2.05 lb), with the tamping end rounded to a hemispherical tip. The procedure requires taking a clean, washed, oven dried, closely sized aggregate fraction, e.g. No. 8 (2.38-mm) to No. 16 (1.19-mm) sieves, filling the mold level full in three layers after compacting each layer with ten well distributed blows of the tamping rod, each blow dropping freely from a height of 51 mm (2 in.) above the surface of the layer being compacted, and repeating this procedure using the same materials but applying 50 blows on each of the three layers. The mass of the contents of the mold in each case in determined and the corresponding percent voids is calculated on the basis of the aggregate fraction's ASTM bulk specific gravity. The particle index is then derived by means of a simple equation:

$$I_a = 1.25V_{10} - 0.25V_{50} - 32.0$$

where

I_a = the particle index value

V_{10} = percent voids in the aggregate sample compacted with 10 blows per layer

V_{50} = percent voids in the same aggregate sample compacted with 50 blows per layer

or it can be obtained from a nomograph representing this formula, Figure 1.

6. For asphalt paving mixture design, testing and research, the biggest impediment to utilizing an aggregate's particle index, is the very large mold 152-mm (6-in.) in diameter by 178-mm (7-in.) high, which requires about 5000 grams (11 lb) of each *single size fraction* of an aggregate to fill. The smaller size fractions in the usual sample of aggregate sent to a laboratory for mix design do not even begin to approach this quantity of material.
7. To overcome this handicap, we have explored the use of two smaller molds 76-mm (3-in.) in diameter by 89-mm (3.5-in.) high, which has one-eighth the volume of the large mold, and 50.8 mm (2 in.) in diameter by 59 mm (2.33 in.) high, having only one twenty-seventh of the volume of the large mold, Figure 2. Very recently, we have also been investigating the adequacy of a steel mold 38 mm (1.5 in.) in diameter by 44 mm (1.75 in.) high, which has only one sixty-fourth of the volume of the large mold. In each case, the size and mass of the tamping rod have been proportionately reduced so as to apply for a 51-mm (2-in.) drop the same compactive effort per cubic centimeter (cubic in.) of material that is applied to the large mold.
8. It is the principal purpose of this paper to provide comparative data, which in our opinion at least, indicate that these smaller molds provide

particle index measurements that are as reliable as those obtained from the use of the large 152-mm (6-in.) diameter mold. A limited amount of relevant information will also be included to demonstrate how knowledge of the aggregate's particle index can contribute to a better understanding of asphalt paving mixture design, construction and service performance.

DESCRIPTION OF PARTICLE INDEX EQUIPMENT

1. The equipment specified by ASTM D 3398 for the standard measurement of the particle index of an aggregate consists of:
   a) a cylindrical steel mold 152.40 ± 0.13 mm (6.000 ± 0.005 in.) in

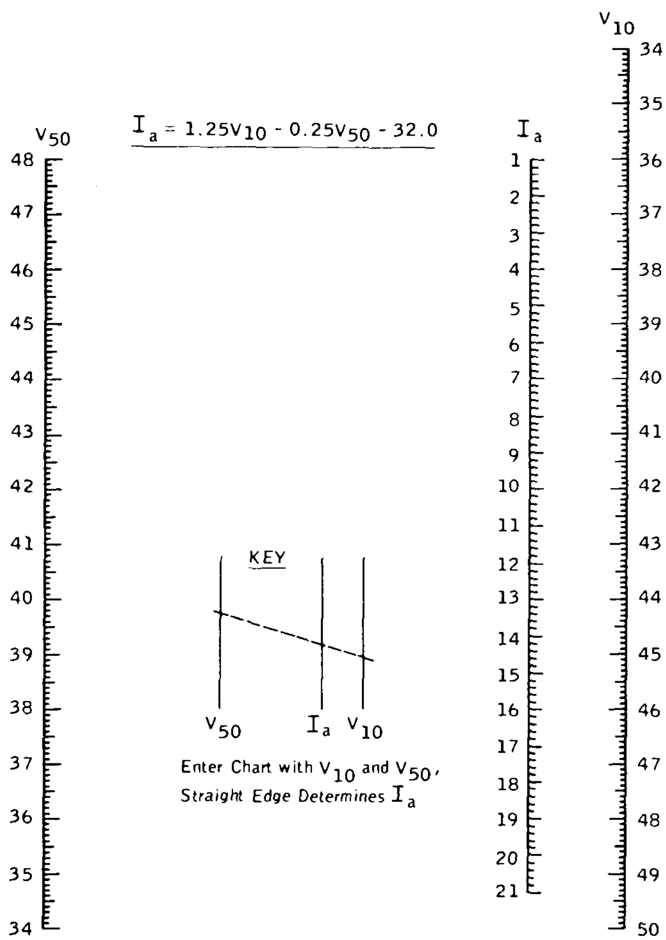

Fig. 1. Chart for Determining Particle Index (I_a).

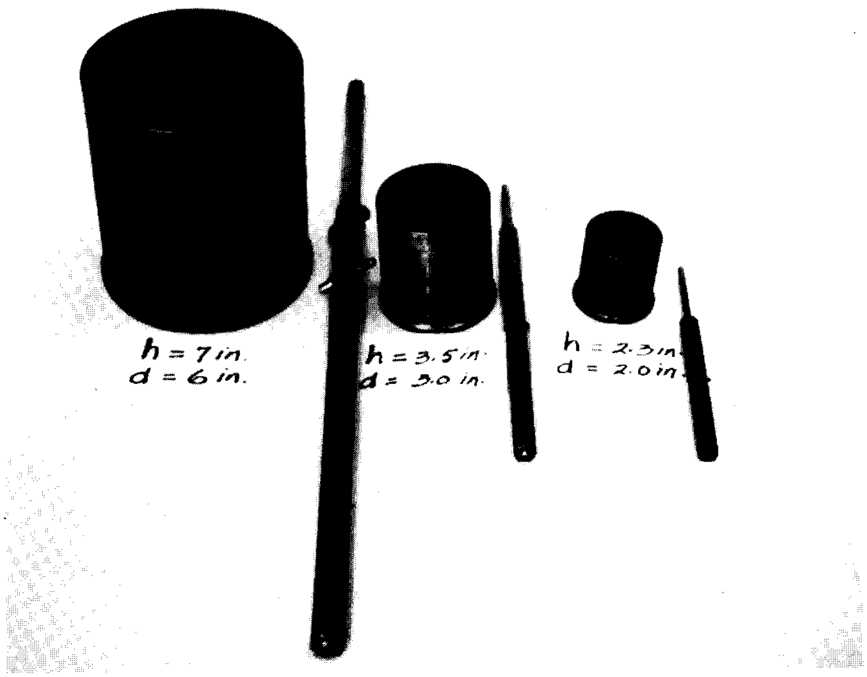

Fig. 2. Particle Index Molds and Tamping Rods.

diameter by 177.80 ± 0.13 mm (7.000 ± 0.005 in.) high, internal dimensions.

  b) a steel tamping rod 15.88 ± 0.25 mm (0.625 ± 0.010 in.) in diameter, approximately 610 mm (24 in.) long, having a mass of 930 ± 10 grams (2.05 ± 0.02 lb), with the tamping end rounded to a hemispherical tip having a diameter of 15.88 ± 0.25 mm (0.625 ± 0.010 in.).

2. For the largest of the three small molds we have employed, the equipment consists of:
   a) a cylindrical steel mold with internal dimensions of 76.2 mm (3.0 in.) in diameter by 88.9 mm (3.5 in.) high
   b) a steel tamping rod 7.94 mm (5/16 in.) in diameter, about 305 mm (12 in.) long, with a mass between 115 and 117.5 grams (0.25 and 0.26 lb), and with the tamping end rounded to a hemispherical tip.
3. The equipment for the next largest of our three small molds is comprised of:
   a) a cylindrical steel mold having internal dimensions of 51 mm (2.0 in.) in diameter, by 59 mm (2.33 in.) high
   b) a steel tamping rod 5.29 mm (5/24 in.) in diameter, about 203 mm (8 in.) long, having a mass between 34.07 and 34.81 grams (0.81 lb), and with the tamping end rounded to a hemispherical tip.
4. For the smallest of the three small molds, the equipment includes:

a) a cylindrical steel mold 38.10 mm (1.5 in.) in diameter, by 44.45 mm (1.75 in.) high
b) a steel tamping rod 3.97 mm (5/32 in.) in diameter, about 152.4 mm (6 in.) long, with a mass between 14.38 and 14.69 grams (0.03 lb), and having its tamping end rounded to a hemispherical tip.

5. When using all test molds, the height of drop of the tamping rod for each blow is 50 mm (2 in.) above the surface of the layer being compacted, and the material is compacted in three layers for both 10-blow and 50-blow compaction. According to ASTM D 3398, each drop of the tamping rod is to be applied "by holding the rod vertically with its rounded end approximately 2 in. (50 mm) above the surface and releasing it so that it drops freely." However, for our use of this equipment, the tamping rod in each case was enclosed in a loose fitting steel sleeve that controlled the height of drop to exactly 2 in. (50 mm).
6. For all four molds, the ratio of the cross sectional area of the tamping rod to the cross sectional area of the mold was 0.01085, and in addition, for each of the four molds the compactive effort was 43.71 gram centimeters/cm^3 (281.9 gram inches/inch^3) for 10-blow compaction per layer, and 218.5 gram centimeters/cm^3 (1409.6 gram inches/inch^3) for 50-blow compaction per layer, based on a mass of 930 grams for the tamping rod for the large 152-mm (6-in.) diameter mold.

PRACTICAL SIGNIFICANCE OF THE PARTICLE INDEX TEST

1. It should be emphasized that the particle index test is made on each closely sized fraction of an aggregate. It is *not* performed on an asphalt paving mixture.
2. During an investigation of any given property of a paving mixture in the past, whenever a change in aggregate gradation has been involved, there has been no simple way to determine how much of any observed difference in the property being studied has been due merely to the change in gradation, and how much has been due to some unknown property of the new aggregate that has been introduced as a substitute for a portion of the old, in order to establish the new gradation. The new aggregate portion substituted could be more stable or less stable, and could be different in other respects than the aggregate fraction it has replaced.
3. Properties of a paving mixture that can be influenced by these changes in gradation include Marshall stability, flow index, percent voids in the mineral aggregate (VMA), percent air voids and the ease or difficulty of compaction.
4. By maintaining the particle index of each closely spaced sieve size fraction of an aggregate at a constant value when any change in aggregate gradation is being made, the influence on the value of any paving mixture property being investigated would be due solely to the change in aggregate gradation that has occurred.
5. Figure 3 demonstrates that a narrowly sized sieve fraction of any desired intermediate particle index value can be obtained by blending

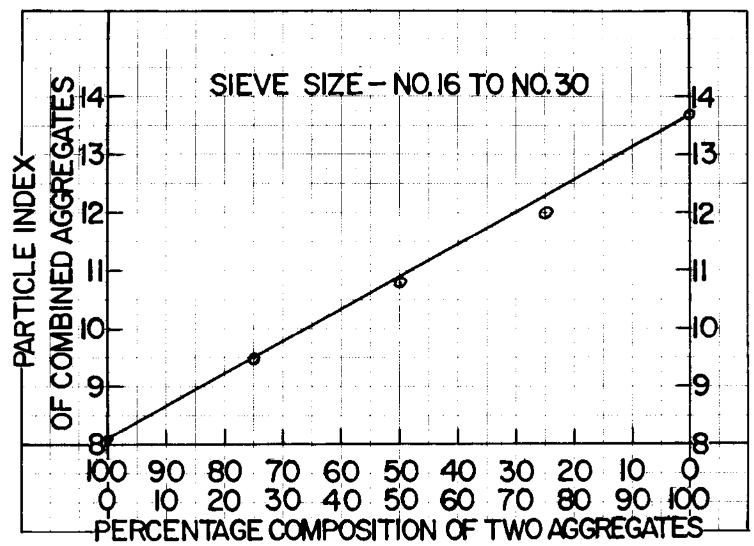

Fig. 3. Demonstrating That Particle Index Varies Directly with the Percentage Composition of Two Aggregates of the Same Sieve Size.

two aggregates of the same closely spaced sieve size, one with a particle index above, and the other with a particle index below the particle index value required. By joining the two particle index values that have been plotted on an arithmetic chart like Figure 3 with a straight line, the blend of the two aggregates that is needed for the particle index desired can be quickly determined. For example, as illustrated by Figure 3, if for a closely sized fraction of an aggregate within the size range of the No. 16 and No. 30 sieves, a particle index value of 12 is required, it can be obtained by blending 70 percent of the No. 16 to No. 30 size fraction of the aggregate having a particle index of 13.7 with 30 percent of the No. 16 to No. 30 size fraction of the aggregate with a particle index of 8.1. Figure 3 applies only to the sieve size range and particle indices illustrated. Similar charts can be prepared for other narrow sieve size ranges and for other combinations of particle index values. Preferably in this case, when blending two aggregates of any given sieve size, one above and the other below the particle index required, the two aggregates should have particle indices that are not too far apart.

6. In addition to aggregate gradation, asphalt content, Marshall stability, flow index, and degree of compaction, the particle index, as a measure of the stability of the aggregate employed for the paving mixture, may have been the missing link in the past when trying to determine the cause of dense-graded tender paving mixtures.

TEST PROCEDURES

1. Each of the Marshall briquettes referred to in this paper was prepared by weighing out separately, the quantity of each aggregate sieve size required, 19.0 to 12.5 mm (3/4 to 1/2 in.), 12.5 to 9.5 mm (1/2 to 3/8 in.) 9.5 mm to 4.75 mm (3/8 in. to No. 4 sieve), 4.75 mm to 2.38 mm (No. 4 to No. 8), 2.38 mm to 1.19 mm (No. 8 to No. 16), 1.19 mm to 0.59 (No. 16 to No. 30), 0.59 mm to 0.30 mm (No. 30 to No. 50), 0.30 mm to 00.14 mm (No. 50 to No. 100), 0.147 mm to 0.0075 mm (No. 100 to No. 200), and passing No. 200. In every case, the mineral dust fraction passing 0.075 mm (No. 200) sieve came from the screenings from a gravel crushing operation. Periodic hydrometer analysis by ASTM D 422 indicated its gradation to be quite uniform, Figure 4.

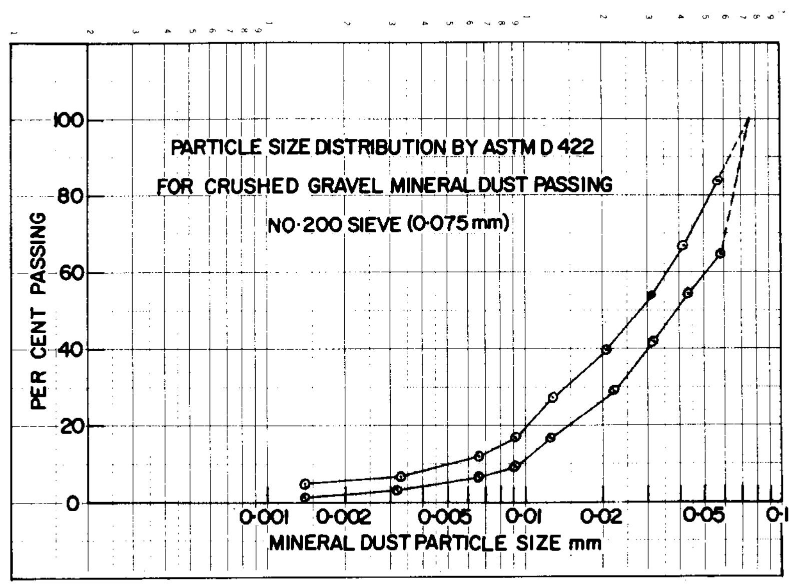

Fig. 4. Grading Band Established by Samples of Crushed Gravel Mineral Dust Passing No. 200 Sieve (0.075 mm).

2. After its particle index had been measured, each narrowly sized aggregate sieve fraction with the same particle index was stored in separate containers and carefully identified. Except when specifically indicated to be otherwise, every aggregate sieve size fraction used for the dense graded paving mixtures in this paper, had exactly the same particle index value. All earlier measurements of the particle index for each narrow sieve size fraction were made by using the large 152-mm (6-in.) mold described in ASTM D 3398, but more recently by employing the smaller diameter molds described in this paper, for the finer sieve size fractions.

3. It should be noted that representative values for the particle index of the passing 0.075-mm (No. 200) fraction cannot be determined because it is a graded material. Consequently, for this paper, the portion passing the 0.075 mm (No. 200) sieve has been assigned the weighted overall average particle index for the remainder of the aggregate in a paving mixture. Since the fraction passing a 0.075 mm (No. 200) sieve in a well designed asphalt concrete paving mixture is relatively small, this results in negligible error when establishing the weighted overall average particle index for the total aggregate in a paving mixture.
4. Except when specifically indicated to be otherwise, for all paving mixtures referred to in this paper, the filler/bitumen ratio was 0.9 by mass, where filler in this case is understood to be aggregate material passing a 0.075-mm (No. 200) sieve.
5. The asphalt cement employed was 150/200 penetration of relatively low temperature susceptibility (PVN about - 0.3).
6. The Marshall briquettes were normally compacted at 135 C (275 F) using 6, 20, 60 and 100 blows of a Marshall double compactor. One hundred percent of laboratory compacted density was considered to be provided by 60-blow compaction.
7. Marshall stability and flow index values were read from a chart provided by a stress strain recorder attached to a Rainhart testing machine.
8. Percent VMA values were determined by the following formula:

$$\% \text{ VMA} = 100 \left[1 - \left(\frac{100 - \% \text{ AC}}{100} \right) \cdot \left(\frac{\text{oven dry bulk specific gravity of thoroughly compacted paving mixture}}{\text{ASTM oven dry bulk specific gravity of the aggregate}} \right) \right]$$

where

% AC is the total asphalt content of the paving mixture based on mass of total mix

and

oven dry bulk specific gravity of the thoroughly compacted paving mixture is determined by ASTM D 2726 or D 1188

and

ASTM oven dry bulk specific gravity of the aggregate is determined by ASTM C 127 and C 128

and

all specific gravity values are corrected to 25 C (77 F).

9. Percent air voids values were determined by the formula:

$$\% \text{ air voids} = 100 \cdot \left[1 - \left(\frac{\text{oven dry bulk specific gravity of the thoroughly compacted mix}}{\text{theoretical maximum specific gravity of the oven dry mix}} \right) \right]$$

where

the oven dry bulk specific gravity of the thoroughly compacted paving mixture is obtained by ASTM D 2726 or D 1188

and

the theoretical maximum specific gravity of the oven dry paving mixture is obtained by ASTM D 2041

and

all specific gravity values are corrected to 25 C (77 F).

10. Marshall stabilities versus numbers of blows by a Marshall double compactor plot as a straight line on double logarithmic paper. The correlation coefficient for the least squares line through the data for more than 80 different combinations of paving mixture design and compactive effort was 0.98, as determined by Dr. J. C. Young of the Statistics Department of the Mathematics Faculty at the University of Waterloo, when all the statistically significant variables are taken into account.
11. Percent laboratory compacted specific gravities, with 60-blow compaction by the Marshall double compactor representing 100 percent of laboratory compacted specific gravity, versus numbers of blows by the Marshall double compactor, plot as a straight line on a semi-logarithmic chart. Percent laboratory compacted specific gravities are represented by the arithmetic ordinate, while numbers of blows are plotted as the logarithmic abscissa. The least squares line through the plotted data for the same number of combinations of paving mixture design and compactive effort was found by Dr. Young to have a correlation coefficient of 0.99, again, when taking into account all the statistically significant variables.

SOME TYPICAL EXAMPLES OF THE INFLUENCE OF AGGREGATE PARTICLE INDEX ON ASPHALT PAVING MIXTURE PROPERTIES

We have been slowly accumulating data in the laboratory on the influence of the particle index of aggregates on the properties of asphalt paving mixtures since 1972. The following examples illustrate some of the results that have been obtained.

1. Figure 5 illustrates the great influence that the particle index of the aggregate can have on the Marshall stability of a paving mixture. For

each curve, the particle index value shown was the particle index for each separate aggregate sieve size. For example, for the paving mixture shown to have an aggregate particle index of 11.5, every size fraction from 13 to 9.5 mm (1/2 to 3/8 in.), through to from 0.147 to 0.075 mm (No. 100 to No. 200) had a particle index of 11.5. At 100 percent of laboratory compacted density the Marshall stability versus particle index values were:

Particle Index	Marshall Stability
15	1386 kg (3050 lb)
11.5	761 kg (1675 lb)
8	398 kg (875 lb)

It should be particularly noted that all three paving mixtures in Figure 5 have a VMA of 15 percent, an air voids value of 4 percent and a filler/bitumen ratio of 0.9.

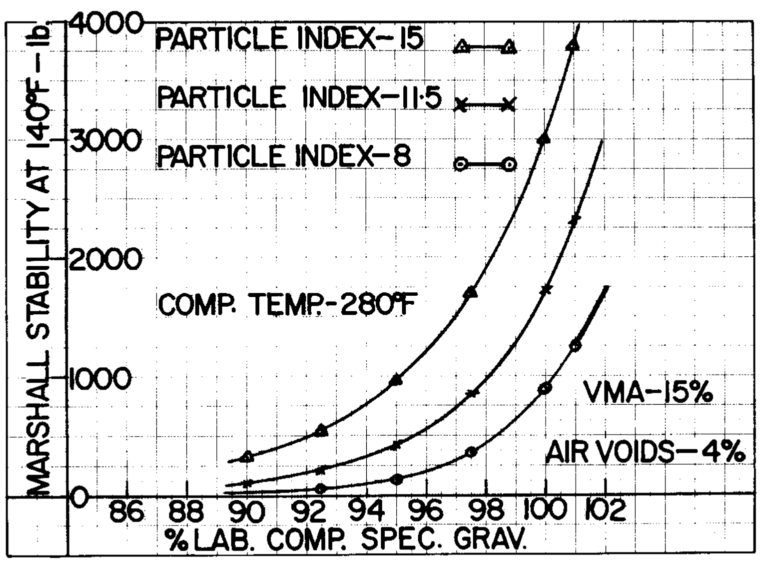

Fig. 5. Marshall Stability Increases with an Increase in the Particle Index of the Overall Aggregate.

The data points lie on the curves in Figure 5 in a regular fashion because they were taken from the least squares lines through the raw data. This also applies to the other figures in this section.

2. Rather surprisingly, the grading curves in Figure 6 for the corresponding paving mixtures in Figure 5 are all relatively close together, with a maximum difference at any sieve size of only 6 percent. However, as might be expected, the grading curve associated with a particle index (PI) of 8

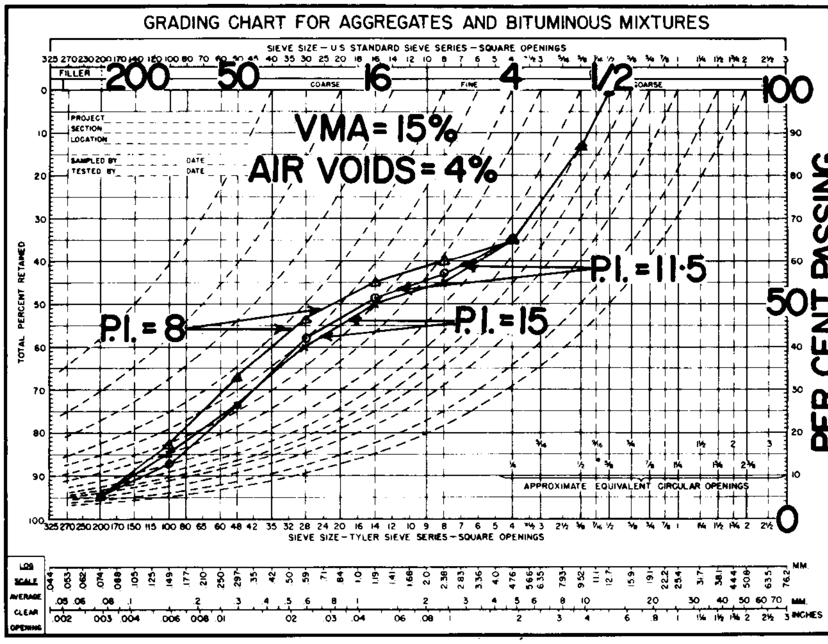

Fig. 6. Paving Mixture Aggregate Grading Curves Associated with PI Values of 8, 11.5, and 15.

is farthest from the corresponding Fuller curve of maximum density, while the grading curve for a PI of 15 tends to be nearest. The broken line curves in the background of Figure 6 belong to the family of Fuller curves associated with a wide range of maximum particle sizes.

3. For paving mixtures all with 4 percent air voids and a filler/bitumen ratio of 0.9, and all prepared from aggregates with a particle index of 11.5, Figure 7 demonstrates the relationship between gradation and VMA values. The Fuller grading curve, being the gradation for maximum aggregate density, has the lowest VMA value of 11.5 percent. VMA values of 13.5, 15.0 and 16.5 percent are achieved by employing grading curves that have been deliberately made to deviate farther and farther from the corresponding Fuller curve. Figure 7 also shows that because there is more void space available for asphalt, the asphalt contents of the paving mixtures increase from 3.9 to 4.8 to 5.4 to 6.2 percent as the VMA values increase from 11.5 to 13.5 to 15 to 16.5 percent, respectively. Provided that the paving mixtures are satisfactory in other respects, the higher asphalt contents associated with these higher VMA values could be expected to provide asphalt pavements with substantially longer maintenance free service lives.
4. Figure 8 demonstrates that for the data in Figure 7 for a constant PI of 11.5 and constant air voids value of 4.0 percent, as the VMA of a paving

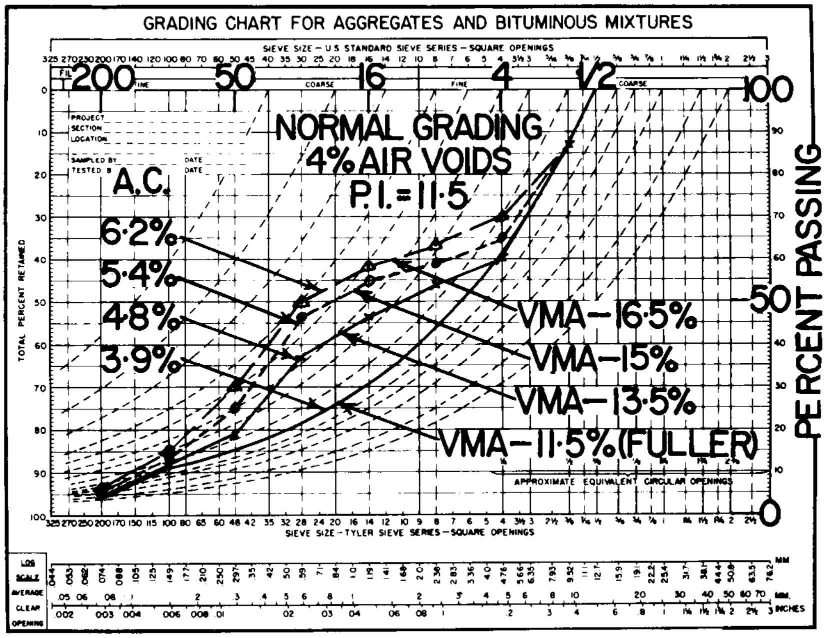

Fig. 7. For Constant Air Voids, Higher VMA Values Are Obtained by Deviating Farther From the Corresponding Fuller Curve.

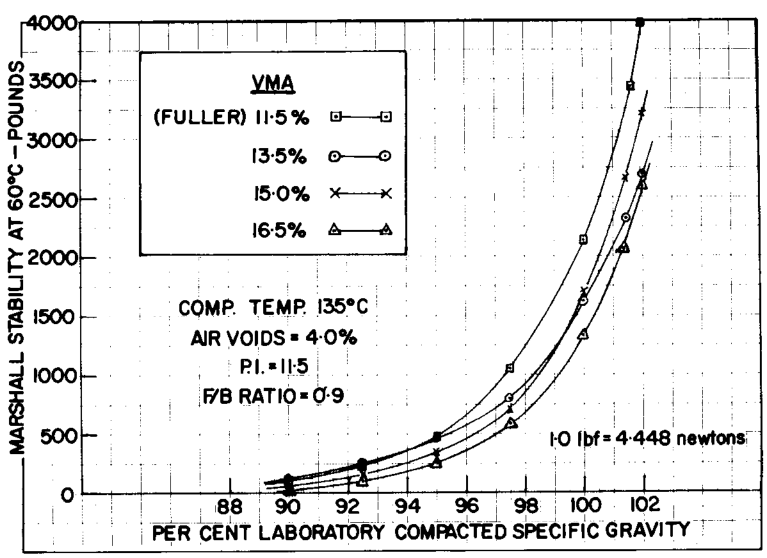

Fig. 8. At Constant PI and Air Voids Values, Marshall Stability Decreases as VMA Increases.

mixture is increased, its Marshall stability decreases. For the data on which Figure 8 is based, the Marshall stability for 100 percent of laboratory compacted specific gravity decreases from 968 to 773 to 739 to 602 kg (2130 to 1700 to 1625 to 1325 lb) as the VMA increases from 11.5 to 13.5 to 15.0 and to 16.5 percent. As shown by Figure 8, and as could be expected occasionally due to variability of Marshall test results, the curve for 15.0 percent VMA overlaps the curves for 13.5 and 11.4 percent VMA for lower percentages of laboratory compacted specific gravity. However, Figure 9 shows that this does not always happen and that the curves can be more or less parallel to each other throughout the full range of laboratory compacted specific gravity.

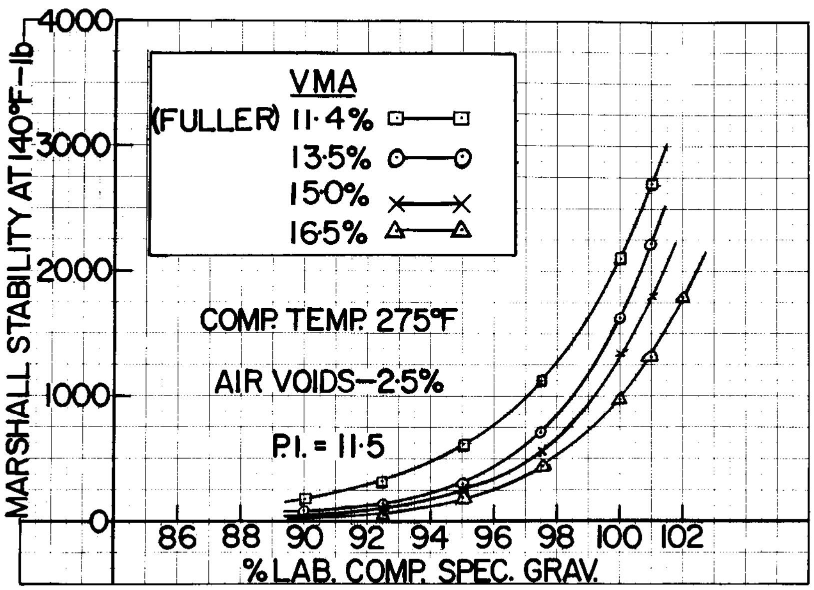

Fig. 9. At Constant Air Voids and PI Values, as VMA Increases Marshall Stability Decreases.

5. Figure 10 illustrates the influence that the particle index of the aggregate can have on the ease or difficulty of compaction of paving mixtures all of which have a VMA of 15 percent and an air voids of 4 percent. Figure 10 shows that the paving mixture made with aggregate of PI = 8 is compacted to a reasonably high density with little compactive effort and then becomes more difficult to compact to higher density. On the other hand, the paving mixture containing aggregate with a high particle index of 15.0 offers greater resistance to compaction at all compaction stages.
6. For the compaction of all road materials, Figure 11 shows that a semilogarithmic relationship exists between specific gravity being achieved by compaction as arithmetic ordinate versus logarithm of compactive effort

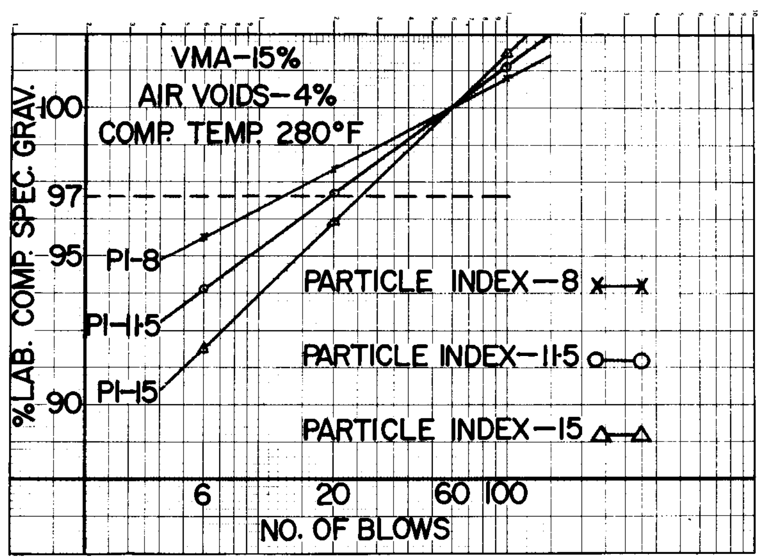

Fig. 10. Resistance of a Paving Mixture to Compaction Increases with an Increase in the Particle Index of the Aggregate.

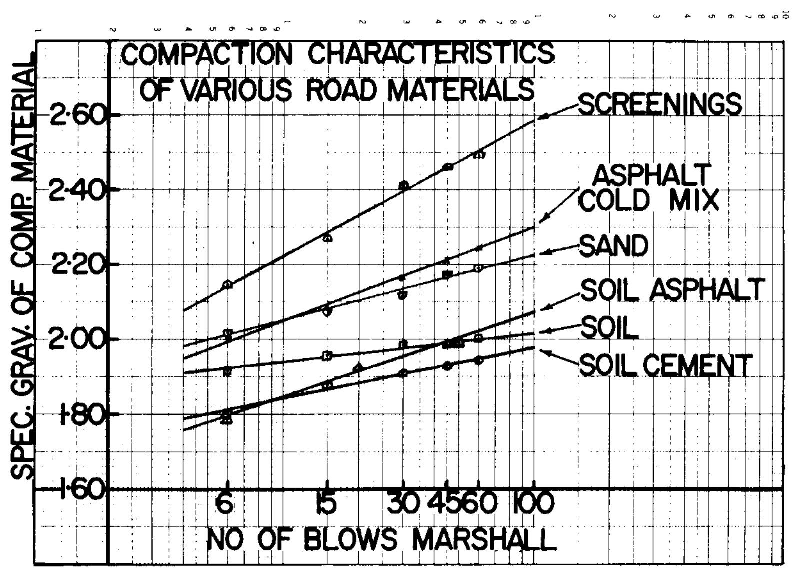

Fig. 11. Illustrating Compaction Characteristics of Various Road Building Materials.

(number of blows, number of roller passes, etc.) as abscissa. Figure 11 demonstrates that to accomplish each successive 0.1 unit specific gravity increase can require two or more times the compactive effort that provided the immediately previous 0.1 unit increase in specific gravity.

7. A wide spacing of aggregate gradations is illustrated in Figure 12, with percent passing 4.76-mm (No. 4) sieve ranging from 55 to 75 percent, but each with a particle index of 11.5 for all sieve sizes, for paving mixtures that have a VMA of 15 percent, an air voids value of 4 percent and a filler/bitumen ratio of 0.9.

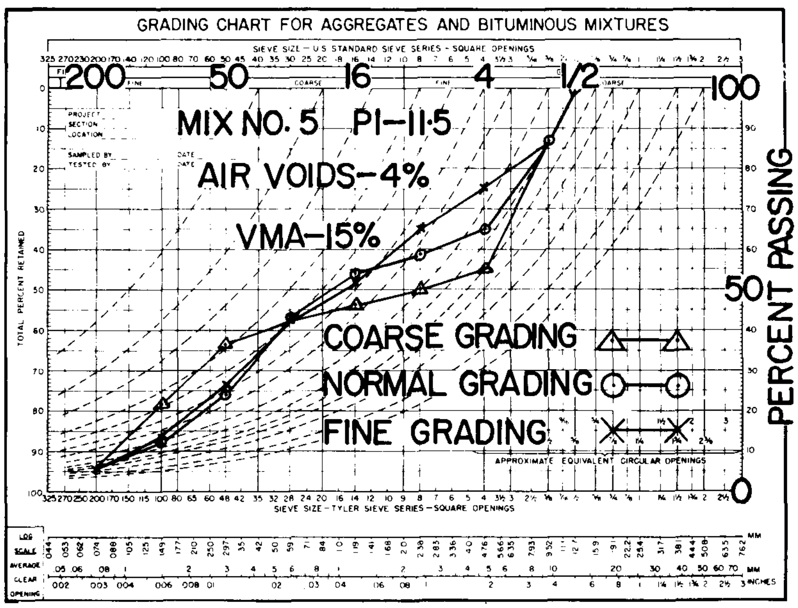

Fig. 12. Illustrating the Influence of a Change in Percent of Coarse Aggregate on the Grading Curve When PI Air Voids, VMA and Filler/Bitumen Ratio Are Held Constant.

8. It might have been expected that the wide spacing of aggregate gradations shown in Figure 12 would have resulted in a wide difference in corresponding Marshall stabilities. However, Figure 13 demonstrates that the Marshall stabilities of the paving mixtures containing these aggregates are all very nearly identical. It appears therefore, that provided paving mixtures are designed to have the same specified VMA, air voids and filler/bitumen ratio values, and are made with aggregates having the same particle index rating for all sieve sizes, the grading curves for the aggregates employed can vary over a wide range with very little effect on the corresponding Marshall stability value.

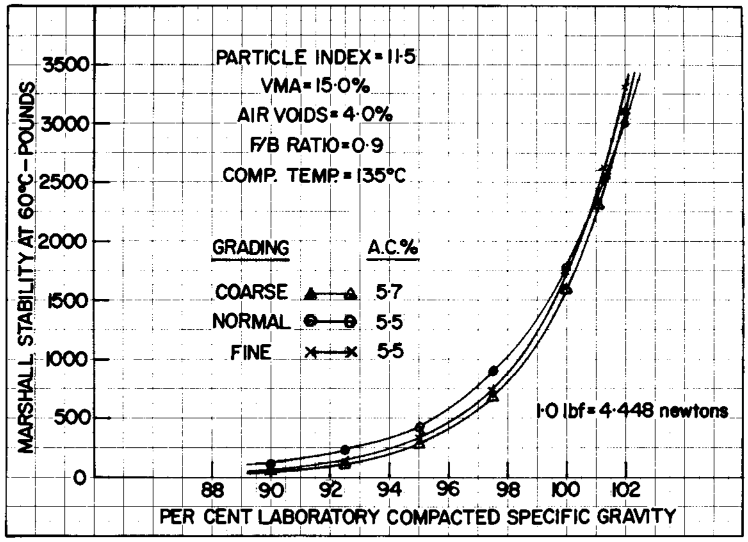

Fig. 13. Marshall Stability Values as Influenced by Coarse Grading, Normal Grading and Fine Grading of the Aggregate.

9. For the previous examples, every size fraction of the aggregate employed had the particle index specified for the aggregate as a whole. In actual pavement construction it is quite common to employ an aggregate blend consisting of a crushed highly angular coarse aggregate having a high particle index, with a fine aggregate having a much lower particle index, and vice versa. Figure 14 illustrates the effect on Marshall stability of a paving mixture by combining a coarse aggregate having a particle index of 15 with a fine aggregate having a particle index of 8, by combining a coarse aggregate having a particle index of 11.5 with a fine aggregate having a particle index of 11.5, and by combining a coarse aggregate having a particle index of 8 with a fine aggregate having a particle index of 15. For each of these three cases, the coarse and fine aggregates were blended in proportions that resulted in an overall particle index of 11.5. Each of the three paving mixtures was designed to have an air voids value of 4 percent, a VMA value of 15.0 percent and a filler/bitumen ratio of 0.9.

Insofar as Marshall stability is concerned, Figure 14 shows that the highest Marshall stability results from the blend of coarse aggregate having a particle index of 8.0 with a fine aggregate for which the particle index is 15.0. The lowest Marshall stability was developed by the paving mixture resulting from an aggregate blend of coarse aggregate having a particle index of 15.0 with a fine aggregate having a particle index of 8.0. The Marshall stability for the paving mixture for which both the coarse and fine aggregates had a particle index of 11.5 was intermediate between the other two.

A comparison of the Marshall stabilities at 100 percent of laboratory compacted density for the paving mixtures made with the three aggregate blends of Figure 14 is shown in the following table:

Aggregate Blend	Marshall Stability
Coarse PI = 8.0 Fine PI = 15.0	1023 kg (2250 lb)
Coarse PI = 11.5 Fine PI = 11.5	761 kg (1675 lb)
Coarse PI = 15.0 Fine PI = 8.0	705 kg (1550 lb)

It is quite clear from Figure 14 that the particle index of the fine aggregate has a much greater influence on the Marshall stability of an asphalt paving mixture than the particle index of the coarse aggregate. Further reference to this finding will be made later in the paper.

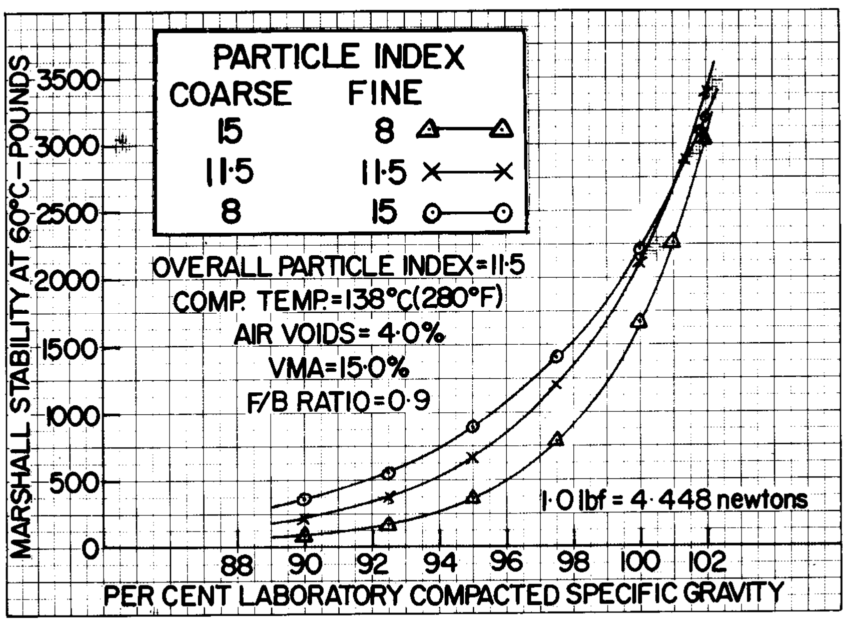

Fig. 14. For Given VMA, Air Voids, Filler/Bitumen Ratio and Overall Particle Index Values, Marshall Stability Increases with an Increase in the Particle Index of the Fine Aggregate.

10. Figure 15 indicates that there is only a very small difference in the grading curves for the three paving mixtures referred to in Figure 14. However, to achieve a VMA of 15 percent, the grading curve for the paving mixture containing coarse aggregate with a PI of 15.0 and fine aggregate with a PI of 8.0 deviates slightly farther from the corresponding Fuller curve, probably because of its smaller resistance to compaction due to the presence of fine aggregate with the lowest particle index value.

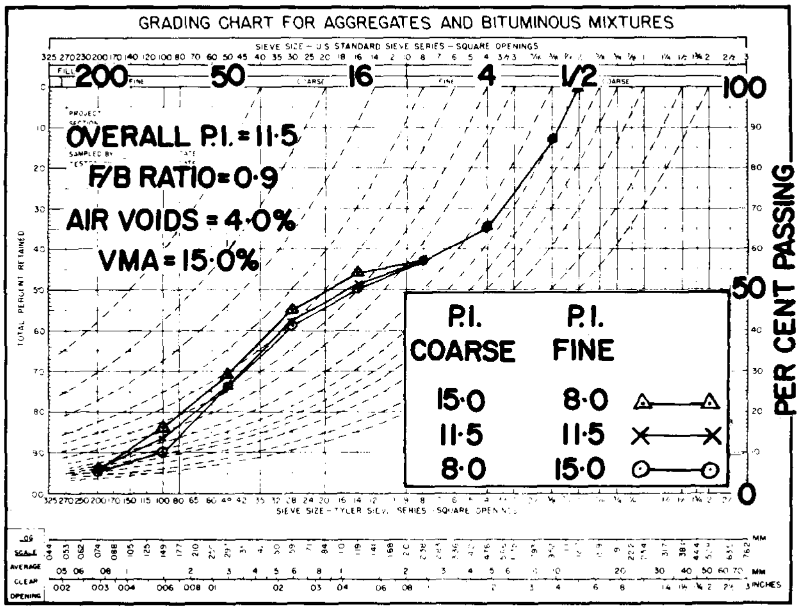

Fig. 15. Grading Curves Associated with the Particle Index Blends of Coarse and Fine Aggregates.

11. Figure 16 illustrates Fuller grading curves for paving mixtures for which the percent passing the No. 200 sieve was varied from 2.0 to 3.65 to 8.0 percent, while maintaining a PI of 11.5 for every aggregate sieve fraction.
12. Figure 17 demonstrates that as usually appears to be expected, the Marshall stabilities for the three paving mixtures of Figure 16 all with PI ratings of 11.5, increase from 750 to 1034 to 1182 kg (1650 to 2275 to 2600 lb) as the fraction passing the 0.075-mm (No. 200) sieve increases from 2.0 to 3.65 to 8.0 percent, for 100 percent laboratory compacted specific gravity. It will be recalled that the compactive effort for 100 percent laboratory specific gravity is provided by 60 blows of a Marshall double compactor. However, it should be noted that when the passing 0.075-mm (No. 200) sieve fraction is considered to be part of the aggregate and is therefore a void filling material, in order to maintain an air voids value of 4.0 percent for Fuller grading as the percent passing 0.075-mm (No. 200) sieve is increased from 2.0 to 3.65 to 8.0 percent, both the VMA and the asphalt content of the paving mixture must decrease, thereby contributing to the observed increase in Marshall stability shown in Figure 17.

The passing 0.075-mm (No. 200) sieve fraction of 3.65 in Figures 16 and 17 was selected to provide a filler/bitumen ratio of 0.9 for this particular paving mixture. The filler/bitumen ratio was different from 0.9 for each of the paving mixtures for which the fractions passing a 0.075-mm (No. 200) sieve were 2.0 and 8.0 percent.

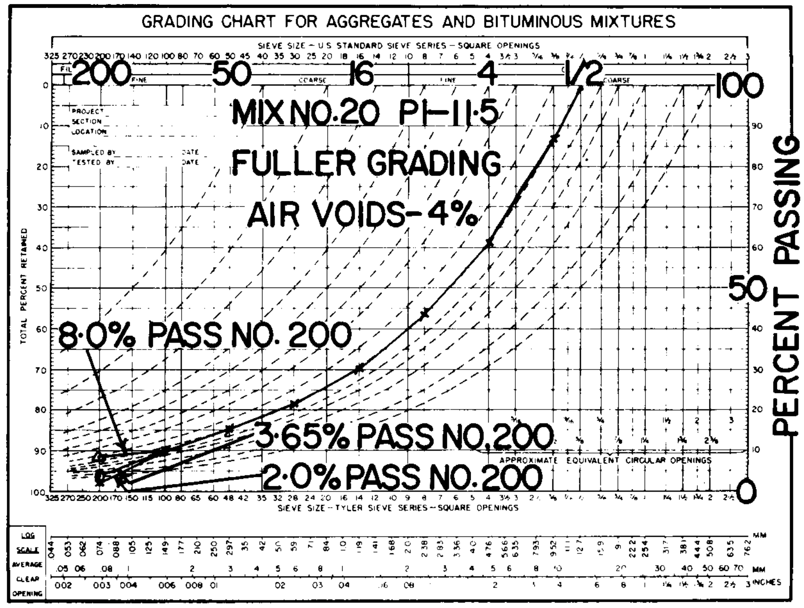

Fig. 16. Fuller Grading Curves with Various Percentages Passing No. 200 Sieve.

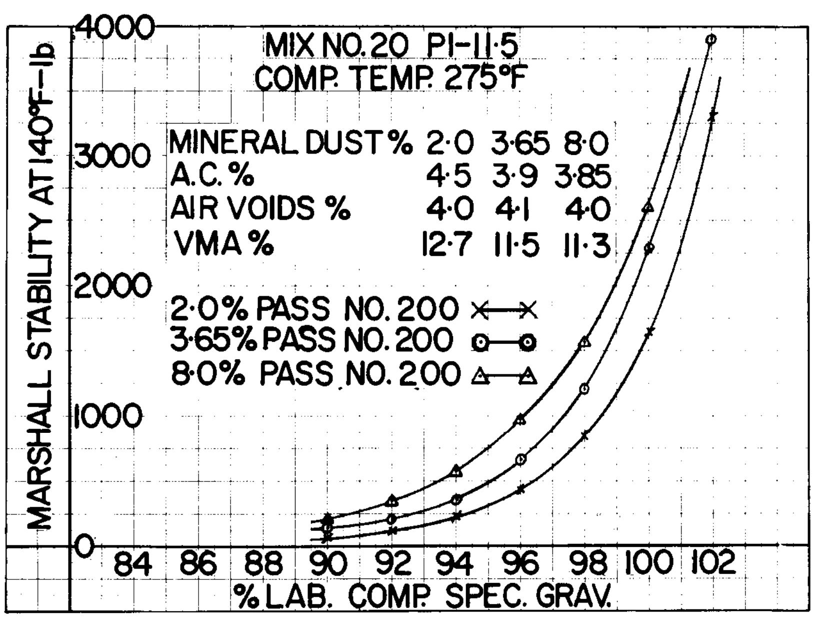

Fig. 17. Illustrating Increase in Marshall Stability for an Increase in Percent Passing No. 200 (Fuller Grading and Constant Air Voids).

13. Unlike Figure 16, for which the aggregate grading curves were restricted to Fuller grading, the three aggregate grading curves shown in Figure 18 had the mobility to provide paving mixtures containing these aggregates with values of 15 percent for VMA and 4.0 percent for air voids. Like those of Figure 16, each particle size fraction for each of the three grading curves in Figure 18 had a particle index of 11.5. The variable being investigated in paving mixtures made with the three aggregate gradations of Figure 18, was the influence of 2.0, 5.14 and 8.0 percent passing a 0.075-mm (No. 200) sieve on Marshall stability. The gradation with 5.14 percent passing 0.075-mm (No. 200) sieve in Figure 18 provided a paving mixture with a filler/bitumen ratio of 0.9. The other

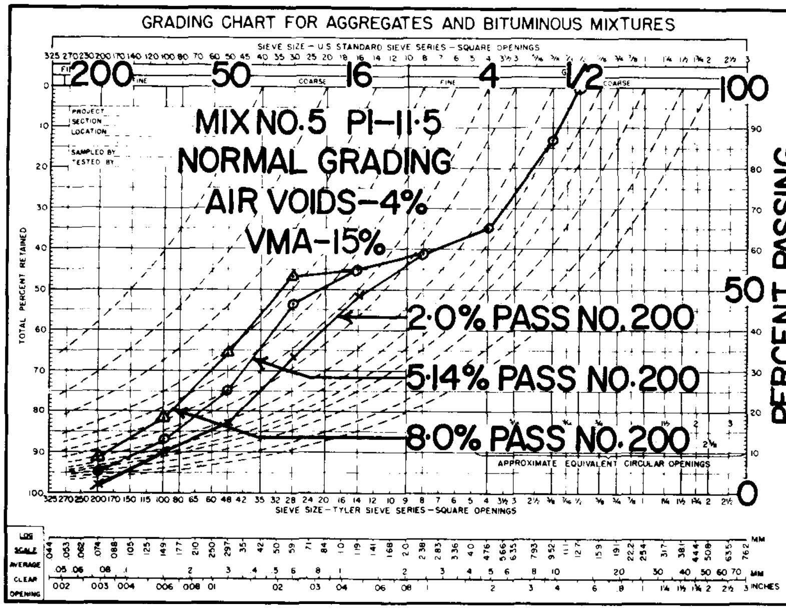

Fig. 18. For Constant PI, Air Voids and VMA, Grading Curves Illustrate Reason For No Increase in Marshall Stability For an Increase in Percent Passing No. 200.

percentages passing a 0.075-mm (No. 200) sieve, 2.0 and 8.0 percent in Figure 18, resulted in other values for the filler/bitumen ratio.

Since the fraction passing 0.075-mm (No. 200) sieve is void filling material, Figure 18 demonstrates that to maintain a VMA value of 15 percent, the grading curve for the paving mixture made with 8.0 percent passing 0.075-mm (No. 200) had to be deviated farthest from its corresponding Fuller curve, the grading curve for the paving mixture made with 5.14 percent passing a 0.075-mm (No. 200) sieve did not have to be made to deviate as far from the corresponding Fuller curve, while the paving mixture made with aggregate containing 2.0 percent passing 0.075-mm (No. 200) sieve was the nearest to the corresponding Fuller curve. It should be obvious that 8.0 percent passing 0.075-mm (No. 200) sieve will fill more void space than 5.14 or 2.0 percent. Consequently, to compensate for the greater void filling capacity of 8.0 percent passing 0.075-mm (No. 200) sieve, as has been clearly demonstrated by Figure 7, the grading curve for the paving mixture containing this aggregate had to be made to deviate farthest from the corresponding Fuller curve, *if a VMA value of 15.0 percent was going to be maintained.* Similar reasoning explains why the grading curves from Figure 18 for paving mixtures containing 5.14 and 2.0 percent passing a 0.075-mm (No. 200) sieve are increasingly closer to the corresponding Fuller curve.

14. Figure 19 indicates, probably rather surprisingly, that the three paving mixtures with the aggregate grading curves of Figure 18, each have practically the same Marshall stability values in spite of their widely differing contents of percent passing the 0.075-mm (No. 200) sieve, 2.0, 5.14, and 8.0 percent. Figure 8 showed that for the same PI, air voids and filler/bitumen ratio values, the Marshall stability decreases with increased deviation from the corresponding Fuller curve. Therefore, at least for the passing 0.075-mm (No. 200) mineral dust, Figure 4, employed for the three paving mixtures with the aggregate gradings of Figure 18, the Marshall stabilities are approximately the same, because the successively

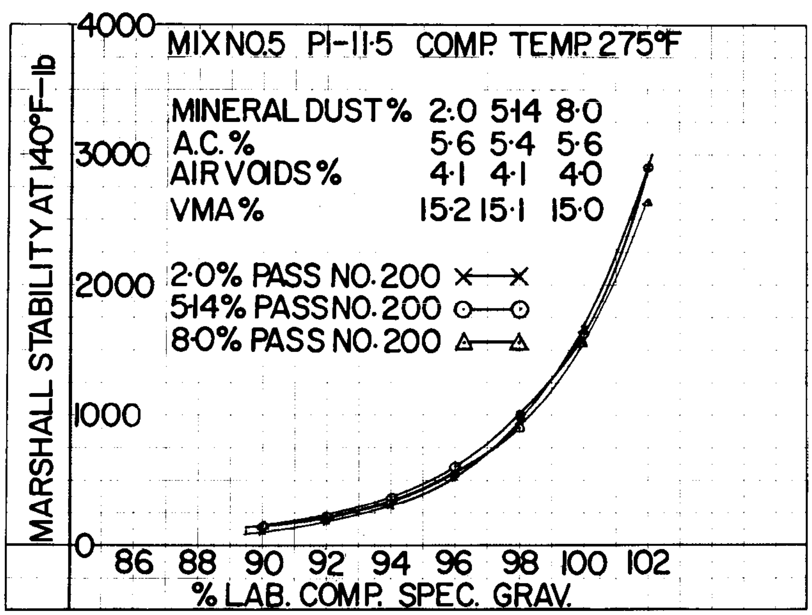

Fig. 19. Illustrating No Increase in Marshall Stability For an Increase in Percent Passing No. 200, When PI, Air Voids and VMA Are Held Constant.

increasing deviations of the grading curves from the corresponding Fuller curve of the paving mixtures containing 2.0, 5.14 and 8.0 percent passing a 0.075-mm (No. 200) sieve reduces the Marshall stability by the same amount that it is increased by the successively increasing percent passing the 0.075-mm (No. 200) sieve.

15. Further examples of the influence of particle index on the properties of asphalt paving mixtures are given in reference (*3*).

COMPARISON OF PARTICLE INDEX VALUES PROVIDED THREE STEEL MOLDS OF DIFFERENT DIAMETERS FOR EACH SIEVE SIZE IN TWO AGGREGATES

1. For the typical examples of the practical usefulness of the particle index described in the previous section, all particle index values were determined with the large 152.4-mm (6-in.) diameter mold. Because of the limited quantities of the finer sizes in most aggregates submitted for paving mixture design, we have recently compared the particle index values provided for single size aggregate fractions when using the 152-mm (6-in.), 76-mm (3-in.) and 51-mm (2-in.) diameter molds previously described.
2. Table 1 lists particle index values obtained when using all three molds for each closely spaced sieve size from 19.0 mm to 12.5 mm (3/4 in. to

Table 1. Influence of Mold Size on Particle Index Determination for Each of a Complete Range of Aggregate Particle Sizes for an Aggregate of Low Particle Index and Another Aggregate of High Particle Index

Sieve Size	Mold Diameter 6 inches	3 inches	2 inches
	Low Particle Index		
3/4 - 1/2 inch	10.6	13.2	15.8
1/2 - 3/8 inch	6.6	7.7	10.6
3/8 - No. 4	8.2	8.3	8.8
No. 4 - No. 8	10.5	10.2	11.3
No. 8 - No. 16	11.0	11.0	11.8
No. 16 - No. 30	8.7	8.6	9.1
No. 30 - No. 50	9.2	9.2	9.4
No. 50 - No. 100	10.1	9.9	10.2
No. 100 - No. 200	12.3	12.0	12.7
	High Particle Index		
3/4 - 1/2 inch	16.0	17.0	19.9
1/2 - 3/8 inch	14.3	14.3	15.1
3/8 - No. 4	14.8	14.8	17.4
No. 4 - No. 8	19.5	19.2	18.7
No. 8 - No. 16	18.1	17.8	18.3
No. 16 - No. 30	18.0	18.1	18.0
No. 30 - No. 50	17.8	17.4	18.1
No. 50 - No. 100	19.7	19.5	20.1
No. 100 - No. 200	20.5	20.4	19.5

1/2 in.) to from 0.147 to 0.074-mm (No. 100 to No. 200) sieves, for two aggregates, one with a moderately low average particle index of about 9, and the other with a relatively high average particle index of about 17. Before being tested for its particle index value, each narrowly sized aggregate fraction was carefully sieved, washed and oven dried, and its ASTM bulk specific gravity was measured. The data for Table 1 were obtained by an experienced operator, and each value recorded is the average value for three trials.

3. Using the particle index values determined with the 152-mm (6-in.) diameter mold as the standard, the data of Table 1 indicate conservatively that the 51-mm (2-in.) diameter mold is quite accurate for particle size fractions from the 0.59 to 0.295-mm (No. 30 to No. 50) sieve size and smaller, while the 76-mm (3-in.) diameter mold is acceptably accurate for single size fractions between 4.76 to 2.38-mm (No. 4 to No. 8) sieves, and smaller. On this basis the 152-mm (6-in.) diameter mold would be employed to measure particle index values for single size fractions larger than 4.76-mm (no. 4) sieve. Within the limits imposed by these restraints, there is reasonably good agreement between particle index values provided by all three molds for single size aggregate fractions smaller than 0.59-mm (No. 30) sieve, and very close agreement between the particle index values furnished by the 152-mm (6-in.) and 76-mm (3-in.) diameter molds for all closely spaced aggregate size fractions finer than the 4.76-mm (No. 4) sieve.

COMPARISON BETWEEN PARTICLE INDEX VALUES PROVIDED BY THREE MOLDS OF DIFFERENT DIAMETERS FOR EACH OF THREE SINGLE SIZE AGGREGATE FRACTIONS FROM TWO DIFFERENT AGGREGATE SOURCES

1. The results represented by Table 1 were so promising that ten particle index tests were performed with each of the three mold sizes on each of three single size fractions 9.5-mm to 4.75-mm (3/8-in. to No. 4), 2.38-mm to 1.19-mm (No. 8 to No. 16), and 0.295-mm to 0.147-mm (No. 50 to No. 100) sieves from each of two aggregate sources, one with a relatively low particle index, while the other had a moderately high particle index.
2. For these ten trials performed with each of the three molds, it was necessary to prepare from about 55 to 65 kg (120 to 150 lb) of each size fraction from each aggregate. Each material was carefully sieved, washed, oven dried and its ASTM bulk specific gravity determined before being tested for particle index.
3. The ten trials for each of the three molds (a total of 30 trials) for each of the three sieve sizes for each aggregate, were randomized to avoid any suggestion of bias.
4. The particle index data for the ten individual trials along with values for mean, $\bar{x}$, and for the standard deviation, s, for the 9.5-mm to 4.75-mm (3/8-in. to No. 4) sieve size for each of the two aggregates are listed in Table 2, for the 2.38-mm to 1.19-mm (No. 8 to No. 16) sieve size in

Table 2. Influence of Mold Size on the Particle Index Determination of the 3/8-Inch to No. 4 Size Fraction of a Low Particle Index and of a High Particle Index Aggregate

Trial No.		Mold Diameter 6 inches	3 inches	2 inches
		Low Particle Index		
1		5.41	5.87	6.94
2		5.02	5.52	7.40
3		5.30	5.35	7.98
4		5.37	5.55	6.87
5		5.77	6.30	6.45
6		5.06	6.27	6.44
7		5.26	5.39	5.84
8		5.07	6.16	6.29
9		5.20	5.87	6.40
10		5.00	6.49	6.10
	$\bar{x}$ =	5.25	5.88	6.67
	s =	0.24	0.41	0.64
	$\bar{x} \pm 2s$ =	5.25 ± 0.48	5.88 ± 0.82	6.67 ± 1.28
		High Particle Index		
1		12.80	13.71	14.15
2		12.77	13.52	14.15
3		13.51	13.00	14.93
4		13.61	13.88	15.44
5		13.30	13.52	13.33
6		13.24	14.13	14.69
7		13.59	14.18	14.50
8		13.20	14.52	14.80
9		12.99	13.65	13.07
10		13.29	13.63	14.49
	$\bar{x}$ =	13.23	13.77	14.35
	s =	0.30	0.42	0.72
	$\bar{x} \pm 2s$ =	13.23 ± 0.60	13.77 ± 0.84	14.35 ± 1.44

Table 3 and for the 0.295-mm to 0.147-mm (No. 50 to No. 100) sieve size fraction in Table 4.

5. The mean particle index values for the three molds reported in Table 2 for the 9.5-mm to 4.75-mm (3/8-in. to No. 4) sieve size indicate clearly that the 51-mm (2-in.) diameter mold should not be used to determine the particle index for this size fraction because it gives particle index values that are much too high. Nor on a conservative basis should the 76-mm (3-in.) diameter mold be employed to determine the particle index of this sieve size for the same reason.
6. For particle index values for the 2.38-mm to 1.19-mm (No. 8 to No. 16) size fraction reported in Table 3, the mean particle index data for the two aggregates would appear to rule out the 51-mm (2-in.) mold because they are too low, particularly with regard to the high particle index aggregate, whereas the 76-mm (3-in.) mold would be acceptable.
7. The mean particle index values recorded in Table 4 for the 0.295-mm to 0.147-mm (No. 50 to No. 100) size fraction for each of the two aggregates demonstrate that all three molds are satisfactory for determining

the particle index of the 0.295-mm to 0.147-mm (No. 50 to No. 100) sieve size.

POSSIBLE USE OF A 38-MM (1.5-IN.) DIAMETER STEEL MOLD FOR PARTICLE INDEX DETERMINATIONS ON THE SMALLEST AGGREGATE SIZE FRACTIONS

1. Since a 51-mm (2-in.) diameter mold appears to provide representative particle index values for the smaller aggregate particle sizes, we have very recently investigated the possible use of a 38.1-mm (1.5-in.) diameter steel mold for the same purpose. This mold has just one-sixty fourth of the volume of the large 152-mm (6-in.) diameter mold, and normally requires less than 100 g of material per test.
2. Table 5(a) records particle index measurements determined for three steel molds 76-mm (3-in.), 51-mm (2-in.), and 38.1-mm (1.5-in.) in diameter, for the 0.295-mm to 0.147-mm (No. 50 to No. 100) sieve size fraction from two aggregates, one with a low particle index and the

Table 3. Influence of Mold Size on the Particle Index Determination of the No. 8 to No. 16 Size Fraction of a Low Particle Index and High Particle Index Aggregate

		Mold Diameter		
		6 inches	3 inches	2 inches
Trial No.			Low Particle Index	
1		10.14	10.47	8.83
2		9.99	10.10	9.89
3		10.14	10.00	9.03
4		10.19	9.90	9.40
5		9.94	9.78	9.07
6		10.12	9.65	9.93
7		10.05	9.53	9.34
8		10.19	10.03	10.02
9		10.14	10.37	9.76
10		10.16	10.09	9.89
	$\bar{x}$ =	10.11	9.99	9.74
	s =	0.08	0.29	0.45
	$\bar{x} \pm 2s$ =	10.11 ± 0.16	9.99 ± 0.58	9.74 ± 0.90
			High Particle Index	
1		17.09	16.88	16.12
2		16.98	16.78	15.67
3		16.96	16.86	15.87
4		17.04	16.85	16.57
5		16.77	16.87	16.31
6		16.98	16.94	16.62
7		17.15	16.59	16.47
8		17.06	17.10	16.64
9		17.44	16.79	16.91
10		17.52	16.74	16.86
	$\bar{x}$ =	17.10	16.84	16.40
	s =	0.23	0.13	0.41
	$\bar{x} \pm 2s$ =	17.10 ± 0.46	16.84 ± 0.26	16.40 ± 0.82

Table 4. Influence of Mold Size on the Particle Index Determination of the No. 50 to No. 100 Size Fraction of a Low Particle Index and High Particle Index Aggregate

Trial No.		Mold Diameter 6 inches	3 inches	2 inches
		Low Particle Index		
1		7.83	7.65	7.45
2		7.63	7.68	7.48
3		7.66	7.65	7.86
4		7.70	7.94	7.93
5		7.59	7.89	7.78
6		7.52	8.03	7.39
7		7.90	8.01	7.77
8		8.07	8.00	8.76
9		8.56	8.33	8.47
10		8.43	8.14	8.64
	$\bar{x}$ =	7.89	7.93	7.95
	s =	0.34	0.22	0.50
	$\bar{x} \pm 2s$ =	7.89 ± 0.68	7.93 ± 0.44	7.95 ± 1.00
		High Particle Index		
1		16.62	17.02	16.67
2		16.68	16.96	16.74
3		16.45	16.97	16.97
4		16.51	16.99	17.30
5		16.46	17.06	16.61
6		16.43	16.95	16.87
7		16.51	17.03	16.86
8		16.60	17.21	16.85
9		16.79	17.16	16.86
10		17.02	16.94	16.84
	$\bar{x}$ =	16.61	17.03	16.86
	s =	0.18	0.09	0.19
	$\bar{x} \pm 2s$ =	16.61 ± 0.36	17.03 ± 0.18	16.86 ± 0.38

other with a high particle index rating. The 0.295-mm to 0.147-mm (No. 50 to No. 100) fraction with a low particle index was different from that referred to in Table 4, but the 0.295-mm to 0.147-mm (No. 50 to No. 100) fraction with a high particle index was the same as that for Table 4.

3. For Table 5(a), the order in which the 30 trials (10 trials for each of the three molds) were performed on each of the low and high particle index 0.295-mm to 0.147-mm (No. 50 to No. 100) sieve size fractions, was randomized.
4. Based on the data in Figure 5(a), the particle index values for the 38-mm (1.5-in.) diameter mold appear to agree very well with those provided by the 76-mm (3-in.) and 51-mm (2-in.) molds for each of the 0.295-mm to 0.147-mm (No. 50 to No. 100) sieve fractions with both low and high particle indices. However, as demonstrated by the larger standard deviations, somewhat greater spread in the data occurs with the 38.1-mm (1.5-in.) mold than for the other two molds.
5. Because the average particle index value of 17.03 for the 0.295-mm to

0.147-mm (No. 50 to No. 100) sieve size of high particle index obtained with the 78-mm (3-in.) mold in Table 4, was somewhat higher than the particle index value of 16.56 provided by the same mold on the same material in Table 5(a), a third randomized series of particle index tests was made on the same 0.295-mm to 0.147-mm (No. 50 to No. 100) high particle index sieve fraction with the three 76-mm (3-in.), 51-mm (2-in.) and 38-mm (1.5-in.) molds. The particle index values for this series of tests are listed in Table 5(b). The particle index value for the 76-mm (3-in.) mold in Table 5(b), 16.79 is approximately midway between the particle index ratings for the same material and the same mold recorded in Table 4, 17.03, and in Table 5(a), 16.56. It may be noted that particle index values for the 51-mm (2-in.) mold, 16.86 in Table 4, 16.44 in Table 5(a) and 16.61 in Table 5(b), parallel those in the same three

Table 5(a). A Comparison of 76.2-mm (3-Inch), 50.8-mm (2-Inch) and 38.1-mm (1.5-Inch) Diameter Steel Molds for Particle Index Determination on the No. 50 to No. 100 Sieve Size Fraction of a Low Particle Index and High Particle Index Aggregate

		Mold Diameter		
		76.2 mm (3-inch)	50.8 mm (2-inch)	38.1 mm (1.5-inch)
Trial No.		Low Particle Index		
1		8.63	8.54	8.95
2		8.86	8.44	8.96
3		8.83	8.48	9.12
4		8.81	8.34	8.96
5		8.66	8.49	8.86
6		8.78	8.27	8.76
7		8.55	8.62	8.93
8		8.88	8.38	8.92
9		8.92	8.69	8.52
10		8.89	8.46	8.95
	$\bar{x}$ =	8.78	8.47	8.89
	s =	0.125	0.126	0.159
	$\bar{x} \pm 2s$ =	8.78 ± 0.25	8.47 ± 0.25	8.89 ± 0.32
		High Particle Index		
1		16.59	16.43	16.30
2		16.37	16.36	16.59
3		16.50	16.44	16.32
4		16.58	16.40	16.18
5		16.62	16.58	16.40
6		16.61	16.34	16.42
7		16.48	16.58	15.86
8		16.66	16.56	16.20
9		16.58	16.40	16.41
10		16.61	16.34	16.39
	$\bar{x}$ =	16.56	16.44	16.31
	s =	0.086	0.096	0.196
	$\bar{x} \pm 2s$ =	16.56 ± 0.17	16.44 ± 0.19	16.31 ± 0.39

Table 5(b). Replicate Particle Index Data for 76.2-mm (3-Inch), 50.8-mm (2-Inch) and 38.1-mm (1.5-Inch) Diameter Steel Molds for the No. 50 to No. 100 Sieve Size Fraction from the High Particle Index Aggregate

		Mold Diameter		
		76.2 mm (3-inch)	50.8 mm (2-inch)	38.1 mm (1.5-inch)
Trial No.		High Particle Index		
1.		16.75	16.64	16.85
2.		16.77	16.73	16.66
3.		16.81	16.54	16.75
4.		16.76	16.58	16.54
5.		16.76	16.66	16.70
6.		16.78	16.64	16.61
7.		16.79	16.60	16.72
8.		16.89	16.57	16.44
9.		16.83	16.60	16.80
10.		16.80	16.57	16.79
	$\bar{x}$ =	16.79	16.61	16.69
	s =	0.042	0.056	0.127
	$\bar{x} \pm 2s$ =	16.79 ± 0.084	16.61 ± 0.11	16.69 ± 0.25

tables for the 76-mm (3-in.) mold for the 0.295-mm to 0.147-mm (No. 50 to No. 100) high particle index sieve fraction.

The same experienced operator performed all the particle index tests on this high particle index material that are reported in all three tables. Consequently, the difference in particle index values for the 76.2-mm (3-in.) and 51-mm (2-in.) molds in Tables 4, 5(a) and 5(b), may merely reflect differences in operator technique at three quite separate times since the same equipment and same material were employed on the three different dates when the tests were made.

6. The data in Table 5(b) indicate that satisfactory particle index values can probably be obtained with the 38-mm (1.5-in.) diameter mold for the 0.295-mm to 0.147-mm (No. 50 to No. 100) sieve size fraction. However, as with Table 5(a), the larger standard deviation implies that a somewhat wider spread in data can be expected if the 38-mm (1.5-in.) mold is used rather than the 51-mm (2-in.) or 76.2-mm (3-in.) molds.
7. ASTM D 3398 does not contain a precision statement with respect to the particle index test. The data listed in Tables 2, 3, 4, 5(a), and 5(b) would seem to imply that a repeatability value of about 0.5 particle index unit and a reproducibility of about 1.0 unit in particle index might be reasonably expected, particularly if the values for two particle index trials are averaged in each case, as ASTM D 3398 presently

stipulates. In this connection, to avoid any suggestion of an attempt at perfection, we used a novice operator with no previous experience with the particle index test procedure, to obtain the all particle index values reported in Tables 2 and 3 and for the 0.295-mm to 0.147-mm (No. 50 to No. 100) low particle index sieve size fraction in Table 4. An experienced operator performed the particle index tests for the particle index ratings recorded in Tables 4, 5(a) and 5(b) for the 0.295-mm to 0.147-mm (No. 50 to No. 100) sieve fraction of high particle index. The very substantial differences in the standard deviations for the particle index values obtained by the two operators is readily apparent.

8. To those interested in statistics, for both the low and high particle index sieve size fractions in Tables 2, 3 and 4, when the mean particle index values provided by the 152-mm (6-in.) diameter mold are used as the standard for comparison with the mean particle index values obtained with the 76-mm (3-in.) and 51-mm (2-in.) diameter molds, for most comparisons the differences between these mean particle index values are statistically significant. This is also true for the mean particle index values provided by the 51-mm (2-in.) and 38-mm (1.5-in.) molds in Tables 5(a) and 5(b), where the mean particle indices furnished by the 77-mm (3-in.) mold are employed as the standard for comparison. On a purely statistical basis therefore, in general the particle indices provided by the three molds in each of Tables 2, 3, 4, 5(a) and 5(b) are not the same, in spite of visually appearing to be very nearly so.

However, in this case, such a statistical comparison could be just an academic mathematical exercise, without much or any practical significance. In actual practice, the particle index values furnished by the 152-mm (6-in.) and 76-mm (3-in.) molds that are employed as standards, represent a variable target in themselves. Also variations in particle index values can arise because of differences between successive tests when estimating the 51-mm (2-in.) height of drop of the tamping rod above the level of the surface being tamped. In addition, in spite of careful attempts to obtain uniformity of distribution of the 10 blows and 50 blows of the tamping rod on the surface of each of the three levels, this is certain to vary in trial after trial. Furthermore, the pattern of distribution of blows applied by even an experienced operator can change from one day to the next, and even during the compaction of a given sample. Consequently, while on a statistical basis, differences between particle index values provided by molds of different diameters on a given aggregate sieve size fraction can exist, from a pratical point of view, the small variations between the mean particle index values in Tables 2, 3, 4, 5(a) and 5(b) do not seem to be important. The data appear to indicate that if each mold size employed is confined to the respective aggregate sieve size fractions below the upper limits illustrated by the horizontal bars in Table 1, quite representative particle index values can be obtained.

INFLUENCE OF PARTICLE INDEX VALUES ON THE PROPERTIES OF ORIGINAL AND ASSOCIATED PAVING MIXTURES

1. In an ordinary paving mixture, each size fraction will normally have a different particle index. This fact led to the following investigation of the influence of particle index on the properties of three original and associated paving mixtures for which data are presented in Tables 6, 7 and 8.

Table 6. Low Marshall Stability Paving Mixtures

Comparison of an Actual Paving Mixture Design With Its Different Particle Index (PI) For Each Sieve Size Fraction, With Corresponding Paving Mixture Designs For Which Each Sieve Size Fraction Has the Overall Average Particle Index (PI) For the Original Paving Mixture, or For Which Each of the Plus No. 4 and Minus No. 4 Portions Have the Same Overall Average Particle Index (PI) as the Corresponding Portions of the Original Paving Mixture.

Aggregate Composition of Original Paving Mixture
38% pea gravel
6% crushed gravel screenings
56% natural sand

1	2	3	4	5	6	7	8	9	10
	Sieve Size	Sieve Analysis		Particle Index Calculation		Part. Ind. 8.55 For All Size Fractions Original Gradation	Part. Ind. 8.55 For All Size Fractions Original Design	PI Coarse 7.13 PI Fine 9.55 Original Gradation	PI Coarse 7.13 PI Fine 9.55 Original Design
		Cumulative % Passing	Differential % Pass & Ret	Each Sieve Fraction	Weighted Col.5xCol.4 ÷ 94.76				
	1/2 inch	100				100	100	100	100
	3/8 inch	84.8	15.2	7.5	1.20	84.8	85.2	84.8	84.8
	No.4 Sieve	60.9	23.9	6.9	1.74	60.9	61.8	60.9	60.9
	No.8 Sieve	57.3	3.6	8.0	0.31	57.3	59.2	57.3	57.3
	No. 16 Sieve	52.6	4.7	11.0	0.54	52.6	55.1	52.6	52.6
	No. 30 Sieve	40.3	12.3	9.5	1.23	40.3	42.2	40.3	40.3
	No. 50 Sieve	17.9	22.4	9.4	2.23	17.9	18.3	17.9	17.9
	No.100 Sieve	5.3	12.6	9.7	1.29	5.3	5.0	5.3	5.3
	No.200 Sieve	5.24	0.06	12.1	0.01	5.24	4.94	5.24	5.14
Overall Ave.Part.Ind.		8.55			8.55	8.55	8.55	8.55	8.55
% Asphalt Content (basis total mix)		5.5				5.5	5.2	5.5	5.4
Filler/Bitumen Ratio (by mass)		0.9				0.9	0.9	0.9	0.9
Ave.Aggregate ASTM Bulk Sp. Gr.		2.646				2.648	2.648	2.644	2.644
Bulk Specific Gravity		2.380				2.400	2.377	2.382	2.380
Theor. Max. Spec. Grav.		2.463				2.450	2.461	2.463	2.466
% Air Voids		3.4				2.0	3.4	3.3	3.5
% VMA		15.0				14.4	14.9	14.9	14.9
Marshall Stability (lb at 140°F)		1073				850	766	1096	1174
Flow Index (units of 0.01 inch)		8.8				10.2	8.4	9.1	9.0
% Asphalt Absorption (lb per 100 lb oven dry agg.)		0.61				0.35	0.35	0.64	0.62

a) Three paving mixtures, each with a VMA value of 15 ± 0.2 percent, and air voids value of 3.5 ± 0.2 percent, and of low, intermediate, and high Marshall stability were prepared, Column 3 in Tables 6, 7 and 8.

b) The Marshall stability, flow index, VMA and air voids values, the particle index values for the individual size fractions, and the weighted average particle index for the aggregate as a whole were determined, Columns 3, 4, 5 and 6 in each table.

c) Paving mixtures having the same gradations as the three original paving mixtures, but with the particle index for each sieve size equal to the weighted average particle index for the aggregate as a whole were prepared, and their Marshall stability, flow index, percent VMA and percent air voids values were measured, Column 7 in each table.

d) Since the percent VMA and percent air voids are usually changed from their original values by the procedure of (c), the same particle index for each sieve size utilized for (c) was retained, but the gradation and asphalt content were changed when necessary to restore the VMA to 15 percent and the air voids to 3.5 percent. The influence of these changes on Marshall stability and flow index were determined, Column 8 in the three tables.

e) Normally, the average weighted particle index for the coarse aggregate as a whole will be different from the overall average weighted particle index for the fine aggregate. Consequently, for Column 9 each of the coarse aggregate size fractions (retained on 4.76-mm (No. 4) was prepared to have the same overall weighted average particle index determined for these size fractions in the original paving mixture, for example, 7.13 from Columns 9 and 10 in Table 6. The same procedure was followed for the fine aggregate with the target particle index for

Table 7. Intermediate Marshall Stability Paving Mixtures

Comparison of an Actual Paving Mixture Design With Its Different Particle Index (PI) For Each Sieve Size Fraction, With Corresponding Paving Mixture Designs For Which Each Sieve Size Fraction Has the Overall Average Particle Index (PI) For the Original Paving Mixture, or For Which Each of the Plus No. 4 and Minus No. 4 Portions Have the Same Overall Average Particle Index (PI) as the Corresponding Portions of the Original Paving Mixture.

Aggregate Composition of Original Paving Mixture
- 20% crushed gravel
- 15% crushed limestone
- 15% gravel screenings
- 50% natural sand

1	2	3	4	5	6	7	8	9	10
Properties	Sieve Size	Sieve Analysis		Particle Index Calculation		Part. Ind. 11.4 For All Size Fractions Original Gradation	Part. Ind. 11.4 For All Size Fractions Original Design	PI Coarse 12.7 PI Fine 10.7 Original Gradation	PI Coarse 12.7 PI Fine 10.7 Original Design
		Cumulative % Passing	Differential % Pass & Ret	Each Sieve Fraction	Weighted Col.5xCol.4 ÷ 94.86				
	1/2 inch	100				100	100	100	100
	3/8 inch	87.7	12.3	12.4	1.61	87.7	87.7	87.7	87.7
	No.4 Sieve	65.7	22.0	12.9	2.99	65.7	65.7	65.7	65.7
	No.8 Sieve	59.2	6.5	11.1	0.76	59.2	58.8	59.2	59.2
	No. 16 Sieve	53.1	6.1	11.5	0.74	53.1	52.5	53.1	53.1
	No. 30 Sieve	40.6	12.5	10.1	1.33	40.6	40.6	40.6	40.6
	No. 50 Sieve	19.3	21.3	10.5	2.35	19.3	19.3	19.3	19.3
	No.100 Sieve	6.9	12.4	10.6	1.38	6.9	7.1	6.9	6.9
	No.200 Sieve	5.14	1.76	13.1	0.24	5.14	5.24	5.14	5.34
Overall Ave.Part.Ind.		11.4			11.4	11.4	11.4	11.4	11.4
% Asphalt Content (basis total mix)		5.4				5.4	5.5	5.4	5.6
Filler/Bitumen Ratio (by mass)		0.9				0.9	0.9	0.9	0.9
Ave.Aggregate ASTM Bulk Sp. Gr.		2.647				2.646	2.646	2.646	2.646
Bulk Specific Gravity		2.382				2.372	2.380	2.377	2.380
Theor Max. Spec. Grav		2.470				2.476	2.468	2.471	2.464
% Air Voids		3.6				4.2	3.6	3.8	3.4
% VMA		14.9				15.2	15.0	15.0	15.1
Marshall Stability (lb at 140°F)		1565				1832	1669	1589	1354
Flow Index (units of 0.01 inch)		9.4				9.5	9.5	9.6	10.6
% Asphalt Absorption (lb per 100 lb oven dry agg.)		0.65				0.76	0.70	0.68	0.69

Table 8. High Marshall Stability Paving Mixtures

Comparison of an Actual Paving Mixture Design With Its Different Particle Index (PI) For Each Sieve Size Fraction, With Corresponding Paving Mixture Designs For Which Each Sieve Size Fraction Has the Overall Average Particle Index (PI) For the Original Paving Mixture, or For Which Each of the Plus No. 4 and Minus No. 4 Portions Have the Same Overall Average Particle Index (PI) as the Corresponding Portions of the Original Paving Mixture.

Aggregate Composition of Original Paving Mixture
35% crushed limestone
17% limestone screenings
48% natural sand

1	2	3	4	5	6	7	8	9	10
	Sieve Size	Sieve Analysis Cumulative % Passing	Sieve Analysis Differential % Pass & Ret	Particle Index Calculation Each Sieve Fraction	Particle Index Calculation Weighted Col.5xCol.4 ÷ 94.66	Part. Ind. 12.7 For All Size Fractions Original Gradation	Part. Ind. 12.7 For All Size Fractions Original Design	PI Coarse15.1 PI Fine 11.4 Original Gradation	PI Coarse15.1 PI Fine 11.4 Original Design
	1/2 inch	100				100	100	100	100
	3/8 inch	91.1	8.9	15.9	1.50	91.1	91.1	91.1	91.1
	No.4 Sieve	66.6	24.5	14.8	3.83	66.6	66.6	66.6	66.6
	No.8 Sieve	58.8	7.8	11.5	0.95	58.8	58.8	58.8	59.3
	No. 16 Sieve	51.6	7.2	12.3	0.94	51.6	51.6	51.6	52.4
	No. 30 Sieve	38.7	12.9	11.2	1.52	38.7	38.7	38.7	39.5
	No. 50 Sieve	18.3	20.4	11.1	2.39	18.3	18.3	18.3	18.5
	No.100 Sieve	7.0	11.3	11.3	1.36	7.0	7.0	7.0	6.8
	No.200 Sieve	5.34	1.66	12.8	0.22	5.34	5.34	5.34	5.64
Overall Ave.Part.Ind.		12.7			12.7	12.7	12.7	12.7	12.7
% Asphalt Content (basis total mix)		5.6				5.6	5.6	5.6	5.9
Filler/Bitumen Ratio (by mass)		0.9				0.9	0.9	0.9	0.9
Ave.Aggregate ASTM Bulk Sp. Gr.		2.650				2.643	2.643	2.641	2.642
Bulk Specific Gravity		2.389				2.380	2.380	2.388	2.389
Theor Max. Spec. Grav		2.473				2.470	2.470	2.484	2.473
% Air Voids		3.4				3.6	3.6	3.8	3.4
% VMA		14.9				15.0	15.0	14.6	14.9
Marshall Stability (lb at 140°F)		2167				2234	2234	2069	2135
Flow Index (units of 0.01 inch)		11.3				11.2	11.2	10.0	10.9
% Asphalt Absorption (lb per 100 lb oven dry agg.)		0.79				0.84	0.84	1.1	1.1

each size fraction being the overall weighted average particle index for the fine aggregate [passing 4.76-mm (No. 4)] in the original paving mixture, for example, 9.55, from Columns 9 and 10 for Table 6. Employing these two different but constant particle indices for each size fraction of the coarse and fine aggregate portions, respectively, paving mixtures having the original grading were prepared and their VMA, air voids, Marshall stability and flow index values were determined, Column 9 in each of Tables 6, 7 and 8.

f) The procedure of (e) usually results in a change from the design values of 15 percent for VMA and 3.5 percent for air voids. Therefore, while maintaining the particle index values for the coarse and fine aggregate size fractions established for (e), the gradation and asphalt content were changed as necessary to bring the VMA and air voids back to their original design values. After these changes in gradation and asphalt content were made, the Marshall stability and flow index for the paving mixture was determined and is reported in Column 10 of each of the three tables.

g) The Marshall stability and flow index readings were read from a stress strain recorder attached to a Rainhart Marshall testing machine, and each of the Marshall stability, flow index, VMA and air voids values listed in Tables 6, 7 and 8 is the average value for four Marshall briquettes.

2. From this investigation, the following trends are indicated by the data in Table 6 for the low Marshall stability paving mixture.
   a) The original paving mixture satisfied the design criteria of 15 ± 0.2 percent for VMA, and 3.5 ± 0.2 percent for air voids and had a Marshall stability of 488 kg (1073 lb), Column 3.
   b) Columns 7 and 8 for which each sieve size fraction for the entire aggregate had a particle index of 8.55 shows a drop in Marshall stability to 386 and 348 kg (850 and 766 lb), respectively.
   c) Columns 9 and 10 demonstrate that the drop in Marshall stability, indicated by Columns 7 and 8, was due to reducing the particle index of each sieve size of the fine aggregate from its overall rated value of 9.55 in the original mix to 8.55, the weighted average particle index for the aggregate as a whole in the original paving mixture. Columns 9 and 10 show that when the particle index value for each size fraction in the fine aggregate was restored to 9.55, which was the overall weighted average particle index value for the fine aggregate in the original mix, the Marshall stability value increased to 498 to 534 kg (1096 and 1174 lb) respectively, which is very close to the value of 488 kg (1073 lb) found for the original paving mixture. This increase in Marshall stability occurred even though the particle index of the coarse aggregate had been reduced from 8.55, its value for Columns 7 and 8, to its original overall weighted average particle index value of 7.13. The influence of the particle index of the fine aggregate on Marshall stability indicated by the data of Table 6 therefore, is in agreement with those illustrated by Figure 14, which showed that the particle index of the fine aggregate has a much greater influence on Marshall stability than the particle index of the coarse aggregate.
3. a) The data in Table 7 for a paving mixture of intermediate Marshall stability, 716 kg (1575 lb), provide similar information to that of Table 6, with the exception that the overall average weighted particle index of the fine aggregate in the original mix, 10.7, is less than that for the coarse aggregate, 12.7, and is also less than the average weighted particle index for the aggregate as a whole, 11.4.
   b) Because of this, for the paving mixtures of Columns 7 and 8 for which the particle index of each size fraction in the total aggregate was the average weighted particle index for the aggregate as a whole, 11.4, whereas the overall average weighted particle index for the fine aggregate in the original mix was only 10.7, the Marshall stability has been increased to 833 and 759 kg (1832 and 1669 lb) respectively, due to the increase in particle index of the fine aggregate portion of the mix.
   c) For the paving mixtures in Columns 9 and 10, where the weighted average particle index for the fine aggregate as a whole is 10.7 the same as that for the fine aggregate in the original mix, the Marshall stabilities of the paving mixtures 721 and 615 kg (1587 and 1354 lb)

are more nearly equal to that for the original paving mixture 711 kg (1565 lb).

4. The data for the paving mixture of high Marshall stability, 985 kg (2167 lb), listed in Table 8, parallel the results illustrated in Table 7, because the average weighted particle index for the aggregate as a whole is 12.7, while the average weighted particle index for the fine aggregate by itself is 11.4. Consequently, the Marshall stabilities in Columns 7 and 8 at 1015 kg (2234 lb) are higher than the Marshall stability for the original mix, 985 kg (2167 lb). On the other hand, for the paving mixtures in Columns 9 and 10, where the particle index for each size fraction in the fine aggregate, 11.4 is the same as the overall average weighted particle index for the fine aggregate in the original paving mixture, the corresponding Marshall stability values of 940 and 970 kg (2069 and 2135 lb) are more nearly equal to the Marshall stability for the original paving mixture, 985 kg (2167 lb).
5. The data in Tables 6, 7 and 8 demonstrate that by substituting sieve size fractions all with a particle index equal to the average weighted particle index for the aggregate as a whole, in a paving mixture, while maintaining the gradation and asphalt content constant, can result in a noticeable change in VMA and air voids values. For example, for the paving mixture in Column 7, Table 6, the VMA changed from 15.0 to 14.4 percent and the air voids dropped from 3.5 to 2.0 percent. However, in all cases the changes in gradation and asphalt content required to restore these paving mixtures to the original design values for VMA and air voids are relatively small as demonstrated by Column 8 in Table 6, where the maximum change in gradation at any sieve size was 2.5 percent, and the change in asphalt content was 0.3 percent.
6. The most important conclusions to be drawn from the data in Tables 6, 7 and 8 are:
   a) The particle index of the fine aggregate in an asphalt paving mixture has a much greater influence on Marshall stability than the particle index of the coarse aggregate.
   b) For a given aggregate gradation and asphalt content required to satisfy stipulated VMA and air voids values, any changes in the average weighted particle index of the fine aggregate, with a corresponding change in the average weighted particle index for the coarse aggregate, even when there is no change in the overall average weighted particle index for the total aggregate, can require an adjustment in the gradation and asphalt content of the paving mixture if the VMA and air voids values are to be maintained unchanged.

SOME COMMENTS ON THE MARSHALL STABILITY VALUES REPORTED IN THIS PAPER

The writer is aware that a round robin series of tests conducted by an ASTM task force some years ago, resulted in such a large value for the reproducibility of the Marshall stabilities measured, that the inclusion of a reproducibility precision statement for Marshall stability in ASTM D 1559 would have been meaningless. This experience probably results in some skepticism concerning the precision of the Marshall stability values reported in this paper. The authors' confidence in the correctness of the message conveyed by the Marshall stability values recorded in this paper is supported by the following considerations:

1. A straight line relationship obtained by the method of least squares exists when percent laboratory compacted specific gravity for a dense graded paving mixture on the arithmetic ordinate is plotted versus the logarithm of the corresponding number of Marshall compaction blows as the abscissa on a semi-logarithmic chart. The correlation coefficient for this relationship for compaction by 6, 20, 60 and 100 blows by a Marshall double compactor, for which 60 blow compaction was taken to represent 100 percent of laboratory compacted specific gravity, was 0.99, as determined by Dr. J. C. Young of the Statistics Department of the Faculty of Mathematics at the University of Waterloo, for 21 paving mixtures prepared and tested in our laboratory, having VMA values ranging from 11.4 to 16.5 percent and air voids values from 2.5 to 5.5 percent (*3*). Each of the 84 data points included in Dr. Young's evaluation was the average for at least three Marshall briquettes.
2. Because of the very high correlation coefficient of 0.99 obtained by Dr. Young, for Figures 5 to 19, and particularly as illustrated by Figure 10, the plotted data for percent laboratory compacted specific gravity versus number of blows employed for compaction, were taken from the least squares line through the raw data.
3. A straight line relationship, provided by the method of least squares exists when the logarithm of Marshall stability values as ordinate is plotted versus the logarithm of the corresponding number of blows of a Marshall double compactor as the abscissa on log-log graph paper. When evaluated on this basis, for Marshall stability values resulting from corresponding compaction by 6, 20, 60 and 100 blows by the Marshall double compactor, Dr. Young found a correlation coefficient of 0.98 for the 21 paving mixtures referred to in Item 1, immediately above (*3*). Each Marshall stability data point in Dr. Young's evaluation was the average value for at least three Marshall briquettes.
4. Again, because of the high correlation coefficient of 0.98 determined by Dr. Young, for figures from Figure 5 to Figure 19, all plotted data for Marshall stability values were taken from the least squares line through the raw data for Marshall stability values versus the corresponding number of blows 6, 20, 60 and 100 by a Marshall double compactor. In turn, for each paving mixture, the number of blows applied for compaction can be converted to the corresponding percent laboratory compacted specific gravity by the method described in item 1 immediately above. Consequently, in Figures 5 to 19, Marshall stability has been plotted versus percent of laboratory compacted specific gravity.
5. Consequently, Marshall stability data for 100 percent of laboratory compacted specific gravity for example, that are plotted in Figures 5 to 19,

were established not merely as the average Marshall stability for the four briquettes that were compacted by 60 blows, but by means of the least squares line were also influenced by the average Marshall stabilities for the corresponding groups of three briquettes in each that were compacted at 6, 20 and 100 blows. This also applies to the average Marshall stability values in these figures that were plotted for other percentages of laboratory compacted specific gravity.

6. All Marshall stability values reported in this paper were read from a chart operated by a stress versus strain recorder attached to our Rainhart testing machine. We believe that this reduces the personal error involved when obtaining Marshall stability values by reading a strain gauge in a proving ring.
7. For each Marshall briquette for each paving mixture represented by the data reported in Figures 5 to 19 and in Tables 6, 7 and 8, each sieve size fraction 12.5 to 9.5 mm (1/2 to 3/8 in.), 9.5-mm to 4.76-mm (3/8-in. to No. 4), 4.76-mm to 2.38-mm (No. 4 to No. 8), 2.38-mm to 1.19-mm (No. 8 to No. 16), 1.19-mm to 0.59-mm (No. 16 to No. 30), 0.59-mm to 0.295-mm (No. 30 to No. 50), 0.295-mm to 0.147-mm (No. 50 to No. 100), 0.147-mm to 0.075-mm (No. 100 to No. 200), and passing 0.075-mm (No. 200), was carefully weighed out individually, to avoid any difference in aggregate gradation for each paving mixture being investigated.
8. With the exceptions that have been specifically noted, the filler/bitumen ratio for each Marshall briquette was 0.9.
9. The particle index for each of the sieve size fractions was 11.5 except when specifically indicated to be otherwise.
10. The Marshall stability values reported in Tables 6, 7 and 8 were the average in each case of the Marshall stability measurement for each of four Marshall briquettes that were all similarly carefully prepared, but only for 60 blow compaction with a Marshall double compactor.
11. As evidence of the precision of the Marshall stability values reported in this paper, it would appear to be particularly significant that the Marshall stability data in Figure 14 and in Tables 6, 7 and 8 for paving mixtures with a wide range in Marshall stability are in unanimous agreement that for dense graded paving mixtures, the particle index of the fine aggregate has a greater influence on the Marshall stability of a paving mixture than the particle index of the coarse aggregate.

SUMMARY

1. Like the angle of internal friction, the particle index appears to provide a measure of the combined contribution of particle shape, angularity, and surface texture to the stability of an aggregate.
2. A standard method for determining the particle index of an aggregate is described in ASTM D 3398.
3. A number of typical examples are provided that illustrate the usefulness of the particle index test in contributing to a better understanding of the properties of paving mixtures.

4. Because the large mold specified by ASTM D 3398, 154-mm (6-in.) in diameter by 178-mm (7-in.) high, requiring about 5 kg (11 lb) of material to fill, is much too large to be used for measuring the particle index of the smaller size fractions in the samples of aggregate usually submitted for paving mixture design, or that are used for other paving mixture investigational purposes, it was the principal purpose of this paper to explore the ability of much smaller steel molds to provide particle index values as accurate as those provided by the large mold.
5. The test data recorded in the paper appear to indicate that a 51-mm (2-in.) diameter mold can provide accurate particle index values for closely spaced aggregate sieve size fractions smaller than a 0.59-mm (No. 30) sieve. A mold 38-mm (1.5-in.) in diameter could also apparently be used to determine particle index values for the same small aggregate sieve size components, but the test data in Figures 5(a) and 5(b) show that its use results in a somewhat greater standard deviation, indicating that a rather wider spread in particle index values could be expected than for the 51-mm (2-in.) diameter mold. The data show that accurate particle index values can be obtained with a 76-mm (3-in.) diameter steel mold for all narrowly sized sieve fractions smaller than a 4.76-mm (No. 4) sieve, while the 152-mm (6-in.) diameter mold should be employed for all closely spaced sieve size fractions coarser than a 4.76-mm (No. 4) sieve.
6. Data are also presented to indicate that the particle index of the fine aggregate has a much greater influence on the Marshall stability of a paving mixture than the particle index of the coarse aggregate, even when the overall particle index of the total aggregate remains unchanged.

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3. Norman W. McLeod and John A. McLean, "A Laboratory Investigation of the Compaction of Dense Graded Asphalt Concrete," *Proceedings, Canadian Technical Asphalt Association*, Vol. 19 (1974).

Discussion

MR. W. K. PARR: Dr. McLeod, this is a very interesting paper. I can speak from some practical experience on the effectiveness of crushed sands. The FAA requires 1800 lb minimum Marshall Stability. This is rarely obtainable with local natural sands of glacial origin but substituting manufactured sand for 10 to 25 percent of the natural sand in bituminous concrete base or surface course mixes will result in an increase in the stability value sufficient to meet the FAA requirements.

We have not gone into the particle index of such blends but do know from experience that crushed sands or a mixture of crushed and natural glacial sands increase the stability of mixes even when the coarse aggregate particles are 100 percent crushed.

The data that you showed in your oral presentation did not include flow values of the mixes. We feel flow values are also important as a high Marshall Stability value will not assure good pavement stability unless it also has a low flow value necessary to achieve bearing strength or rutting resistance.

DR. N. W. MCLEOD: Flow index values are given in the paper for the paving mixtures referred to in Tables 6, 7 and 8. They vary from 8.4 to 11.3, which in our experience is a very desireable range.

MR. PARR: We prefer flow values in the 8 to 11 range and feel that flow values higher than this may give mixes with poor rutting resistance.

DR. MCLEOD: We certainly agree with you. Normally we do not like to have the flow index exceed 12.

MR. J. IZATT: Norman, I foresee, in your work here and the work of others in the use of this particle index, the elimination of a whole lot of descriptive material in the average specification for asphalt concrete mineral aggregate. We always have terms that relate to flat and elongated particles and they are described, of course, as many of you know in terms of length versus thickness. In the case of crushed gravel we normally have requirements for one crushed face or two crushed faces. We also have requirements on soft and friable materials. Most of these requirements wind up in the Description of the materials. Isn't it possible that we can use the particle index to eliminate most, if not all, of these descriptive specifications?

DR. MCLEOD: I would agree that the particle index could be substituted for at least an occasional asphalt concrete aggregate requirement. However, it would seem doubtful that it could be used in place of the present limits for some of these. The particle index appears to be primarily an empirical stability test for aggregates, which is evaluated on the basis of the difference in aggregate voids between 10-blow and 50-blow compaction, rather than being an aggregate quality test. We have no data from actual tests to indicate whether the presence of soft and fragile particles would increase or decrease the particle index value for an aggregate. If for example, they always result in a decrease in particle index, it might then be difficult to decide, based on the particle index itself, whether some lower particle index value was due to the presence of soft and friable particles, or to the presence of some hard, rounded particles with smooth surface textures.

MR. IZATT: The flat and elongated particles?

DR. MCLEOD: Again, the particle index test appears to provide empirical stability values for aggregates. There are probably reasons other than the need for adequate stability for rejecting an excess of flat and elongated particles, such as their bridging action within a paving mixture, increased difficulty in compaction to specified density which can lead to higher air voids in a finished pavement, and their tendency to fracture with time under traffic, thereby exposing the uncoated surface.

MR. IZATT: As far as crushed particles in crushed gravel are concerned, do you think this test could eliminate that requirement?

DR. MCLEOD: Most specifications for coarse aggregates contain a requirement for a minimum percentage of particles with crushed faces, apparently in an attempt to achieve greater aggregate stability. This is a purely *qualitative* requirement which tells very little about the degree of increase in aggregate stability actually being achieved. This would appear to be an aggregate specification requirement that could be greatly improved by substituting a minimum particle index limit to provide a *quantitative* measure of the minimum aggregate stability desired.

Mr. Izatt's questions are quite thought provoking, and their implications should be examined in more detail.

MR. R. C. MEININGER: I think you have an excellent compilation of data here, and I agree with your approach. The National Sand and Gravel Association, Joint Research Laboratory, has been working on another type of particle shape test method for fine aggregate which is not quite as involved as measuring the shape on each of the individual sizes. We have been regrading the sand to one fixed gradation, or I suppose you could extend that concept to have several standard gradations that might be used. We are working with the loose voids content as a measure of the angularity of the fine aggregate. One test represents each fine aggregate. Of course the National Crushed Stone Association also has a test method where they test three different sizes, again using the loose voids concept. Committee C-9 of ASTM is going to be working on possibly standardizing this loose voids test for the measurement of fine aggregate shape and texture. I think the particle index test has a great appeal for the coarser sizes, but it involves a lot of tedious work to run particle index on each fine size. Have you given any thought to using some sort of graded sample for a fine aggregate?

DR. MCLEOD: A major advantage of the particle index test is that while it must be performed on each closely sized sieve fraction of the aggregate, the average particle index for the complete aggregate can then be calculated based on the percentage of each size fraction in the aggregate. I believe the particle index test procedure is unique in being able to provide an empirical stability value for an aggregate as a whole.

We have run the particle index test on samples of graded aggregates a number of times, but the particle index values obtained have always been very low, about 4 to 6, in comparison with the weighted overall particle index value which can be from 12 to 15 or higher when determined from the particle index measurement for each individual closely sized sieve fraction of the same aggregate.

I am not sure that the size fractions have to be as closely spaced as indicated by ASTM D 3398. It may be that at least two of these size fractions could be combined and still provide significant particle index values, but this would require some investigation.

MR. F. P. BONNAURE: In your paper you are only dealing with Marshall tests. Do you think the particle index might be of interest for other mix characteristics such as creep, fatigue, etc.? Have you done or are you planning to look at that?

DR. MCLEOD: We have not investigated the influence of aggregate particle index on paving mixture characteristics such as fatigue and creep, but we feel it would be very much worthwhile for others to do so. I would also like to suggest to the Professors who are here, that investigating the relationship, if any, between the particle index and angle of internal friction of an aggregate could be a very good thesis topic for one of their graduate students.