EVALUATION OF THE STRAIGHT LINE GRADATION CHART AND THE PARTICLE INDEX TEST

MICHIGAN
DEPARTMENT OF TRANSPORTATION

TESTING AND RESEARCH DIVISION
RESEARCH LABORATORY SECTION

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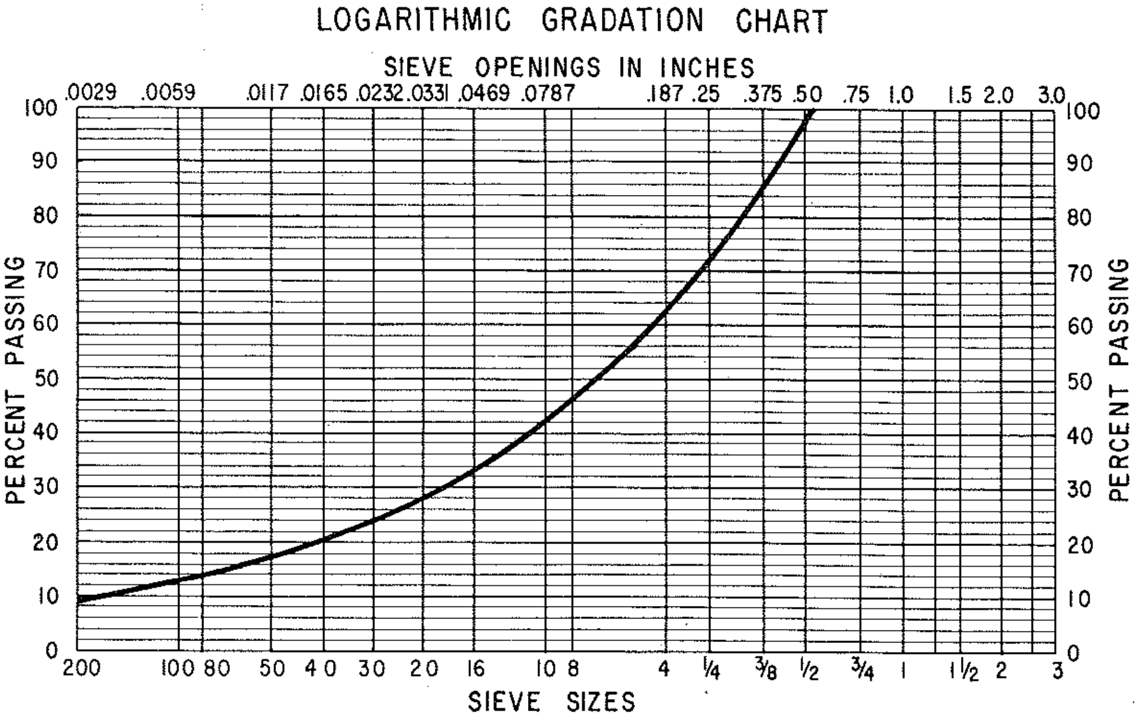


Figure 1. A dense, stable grading plotted on the logarithmic gradation chart.

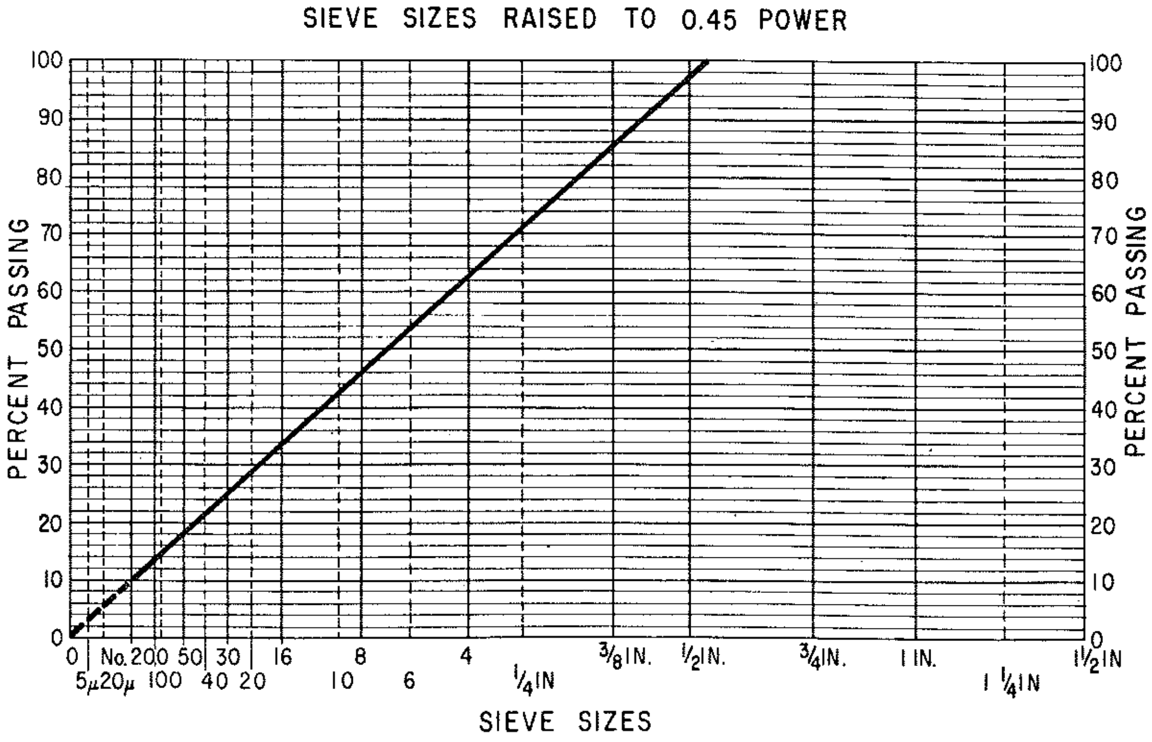


Figure 2. Grading shown in Figure 1 replotted on the 0.45 power gradation chart.

Based on this work, the straight line gradation chart, of the form shown in Figure 3, was adopted for these studies.

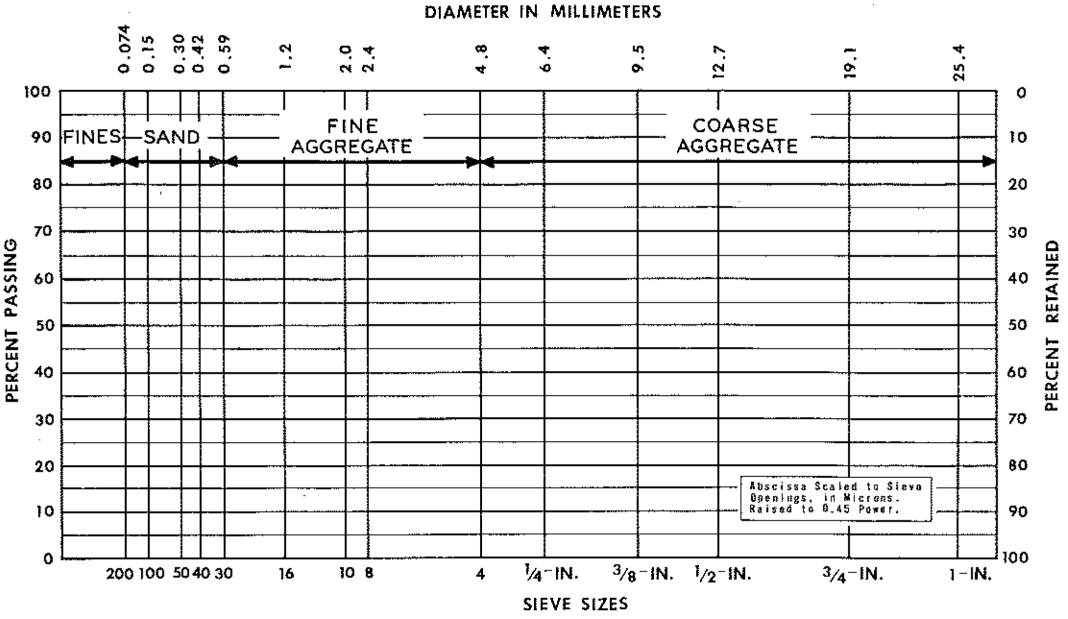


Figure 3. Straight line gradation chart as used in this study.

The general applicability of this chart to Michigan aggregate use was tested by studying controlled mixtures of aggregates having a wide range of gradation and geometric properties (angularity, shape, and surface texture of particles). Figure 4 includes the straight line gradation curve for four minus 4 materials (F1, F2, F3, and F4) and four coarse aggregates (C1, C2, C3, and C4) used for the test mixtures. The optimum fine aggregate content for obtaining maximum density of a mixture containing no plus No. 4 material was determined in the laboratory as shown in Figure 5. In this test, mixtures of fine aggregates ranging in minus 30 fraction from 15 to 75 percent (mixtures F1, F2, F3, and F4) were compacted with T-99 compaction effort and the maximum density determined for crushed and uncrushed conditions. The highest density was obtained with mixtures containing approximately 33 percent minus No. 30 material. This compares closely with the maximum value obtained by the straight line chart which gave a value slightly more than 33 percent (Fig. 4 gradation F3).

Further tests were made in which the percentage of fine and coarse aggregates were varied and optimum mix densities determined. Four different gradations of fine aggregates (F1, F2, F3, and F4) were each mixed

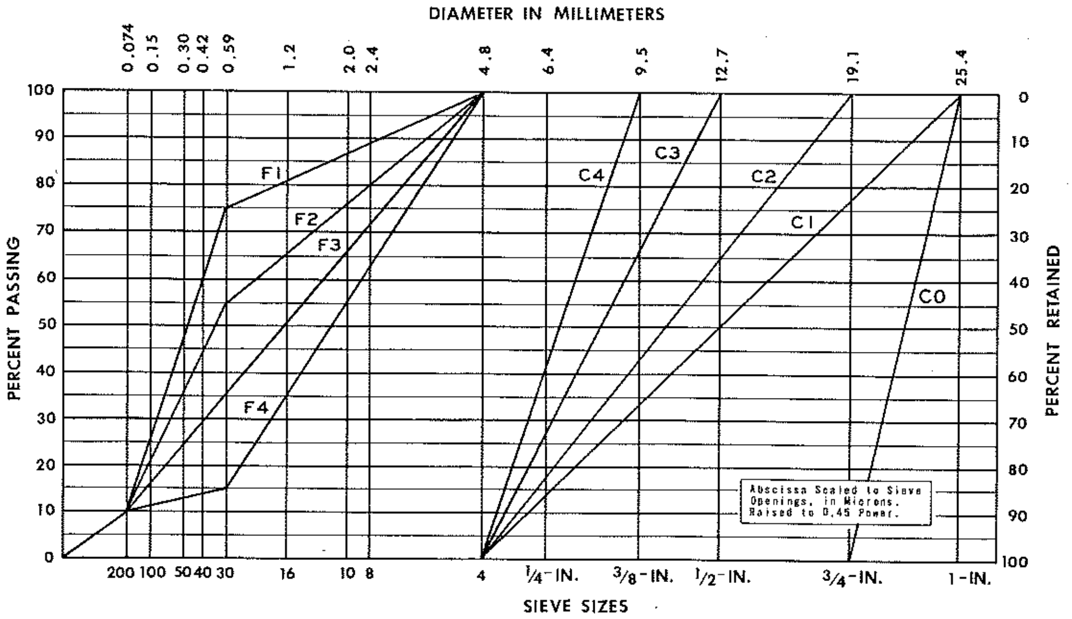


Figure 4. Gradation of coarse and fine aggregates prepared for the study.

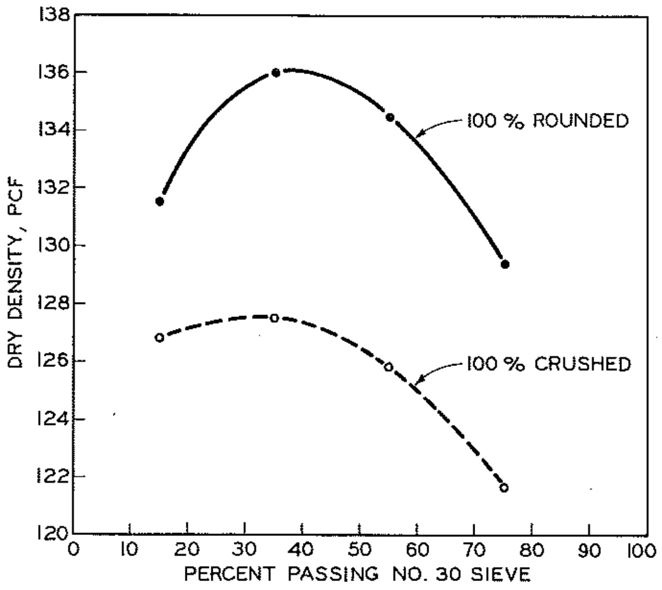


Figure 5. Effect of minus No. 30 material on the density of crushed and uncrushed fine aggregate (-No. 4).

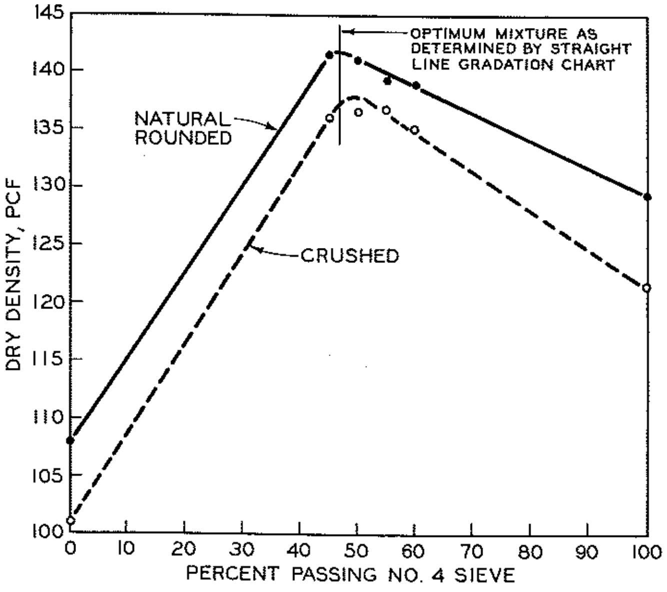


Figure 6. Effect of coarse and fine aggregates on density of crushed and rounded aggregate (gradation F1 and C1).

with 0, 45, 50, 55, 60, and 100 percent coarse material C1. The T-99 maximum density of each gradation was determined for both 100 percent crushed and 100 percent rounded materials. Figure 6 is typical of these tests, in which the average values from all of the tests, indicated a maximum density of approximately 53 percent coarse aggregate, the same value as predicted from the straight line gradation chart.

These maximum density gradation test results indicate that the straight line chart is applicable to Michigan's crushed and uncrushed aggregate mixtures.

Figure 7 shows a general form of the straight line gradation chart in which three different gradation conditions are shown, one of which yields maximum density. When the slope of a gradation line between designated sieve sizes parallels the slope of the gradation line for obtaining maximum density (in this case for 1-in. top size material) the aggregate content for the sieve size range is ideal for maximum density. Greater or lesser slope from the parallel condition indicates an excess or a deficiency in the particular range shown.

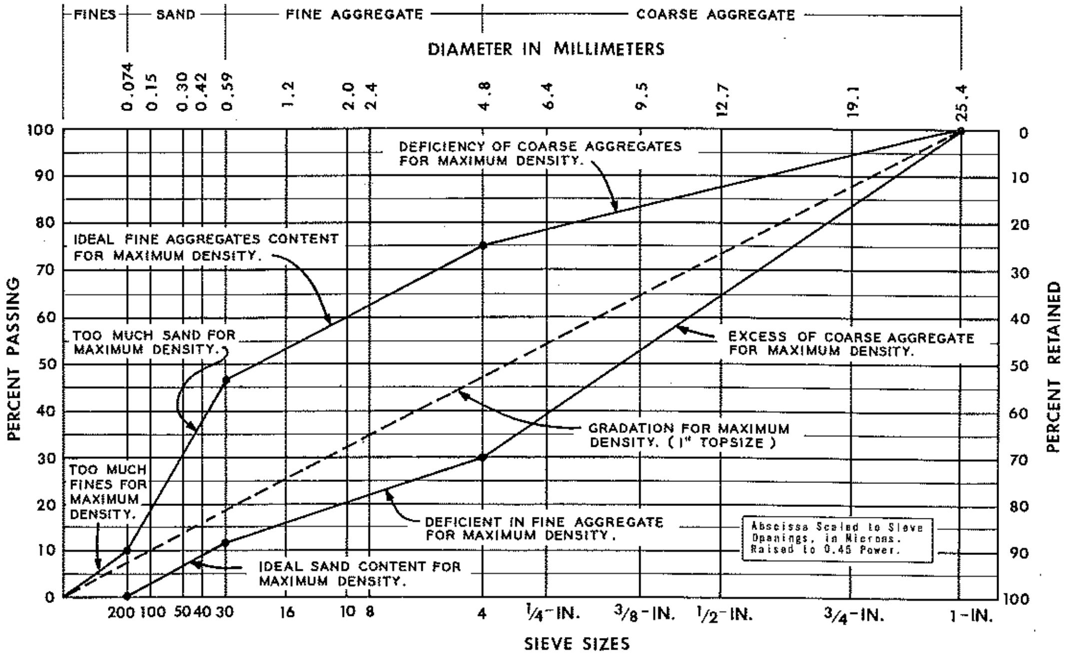


Figure 7. Various gradation conditions as indicated by the slope of the gradation when plotted on the straight line gradation chart.

The straight line gradation chart relationships shown in Figure 7 can be used to evaluate Department gradation specifications for coarse and dense graded aggregates. Specification requirements for Michigan's coarse, dense graded and fine aggregates and granular materials, plotted on the straight line gradation chart, are included in Appendix B (Figs. B-1 through B-17). With these curves, gradation conformity to specifications can be checked conveniently and alterations made to meet desired specific job requirements.

Additional tests were conducted to study the effects gradation and geometric properties have on the density of various aggregate mixtures. Results, summarized in Appendix C, indicate certain conditions where less expensive materials (containing excess sand) could be used with little loss in quality, particularly when using crushed aggregate.

PARTICLE INDEX TEST

The Particle Index Test described in ASTM D3398-75 is a measure of the geometric properties of coarse and fine aggregates, based on the concept that when a given size aggregate is rodded under standard conditions in a cylindrical mold, the resulting voids indicate the combined features of shape, angularity, and surface texture of the aggregate. In the standard test, the Particle Index is calculated from the formula

$$Ia = 1.25\ V_{10} - 0.25\ V_{50} - 32$$

where: Ia = Particle Index,

V_{10} = percent voids when aggregate is compacted at 10 drops per layer,

V_{50} = percent voids when aggregate is compacted at 50 drops per layer.

The Particle Index increases as the aggregate particles become more irregular in shape, more angular and more roughly surfaced.

To evaluate the applicability of the Particle Index Test to Michigan aggregate conditions, samples of coarse aggregate were obtained and separated into (-1/4 in. to +No. 4), (-3/8 in. to +1/4 in.), (-1/2 in. to +3/8 in.), (-3/4 in. to +1/2 in.), and (-1 in. to +3/4 in.) fraction sizes. The Particle Index value for each fraction was determined by the standard ASTM test. The particles were then combined into their densest possible gradation (gradation C1 from Fig. 4), and the Particle Index determined for the mixture. This series of tests was repeated using crushed material obtained from 1-1/2 in. or larger stones from the same pit, separating the crushed aggregate and preparing the sample to the required fraction sizes.

Results of these tests on natural and crushed aggregates are shown in Figure 8. The primary finding from these results is that the Particle Index Test can be used to differentiate between natural rounded and crushed aggregates, both when individual fractions are used, as in the standard test, or when a mixture of the aggregate fractions is used. The data also show that the Particle Index of coarse aggregate is more dependent upon geometric properties than on gradation and that Particle Index values are significantly higher for crushed aggregates than for natural rounded materials.

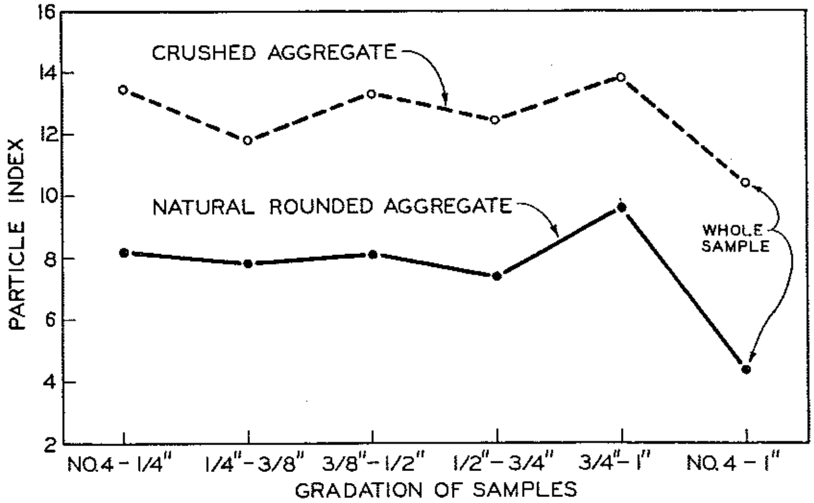


Figure 8. Comparison of Particle Index values for rounded and crushed coarse aggregates as determined for individual fractions and the whole sample of a C1 gradation mixture.

A time consuming factor in determining Particle Index values is the necessity of testing different individual fractions of a given mixture. The positions of the total mixture C1 in Figure 8 suggested that testing the total mixture might produce the same relative values as did testing the individual fractions. To check this possibility, four natural and crushed coarse aggregate gradations (C1, C2, C3, and C4, Fig. 4) were selected and the Particle Index determined for each total mixture rather than for each particle size sample. The test results were checked using five different technicians. Each test was repeated three times by each operator. Results are shown in Figure 9.

These tests show that Particle Index values decrease as particle size of the total sample increases and the Particle Index values are much higher for the crushed material. These tests also show, as did the previous tests, that Particle Index values clearly differentiate between natural rounded and angular aggregates and indicate the relative influence of gradation on test values. These results suggest that for those coarse granular materials for which gradations are now controlled by grading specifications, it should be possible to control characteristics by the Particle Index Test and that this test could be made more simple than the ASTM method by using the complete plus No. 4 mixture rather than the individual fractions. This would considerably reduce testing time without seriously affecting accuracy. The simplified version of the test appears to be reasonably reproducible, as shown in Figure 9, especially when considering that none of the five technicians used had performed the test before.

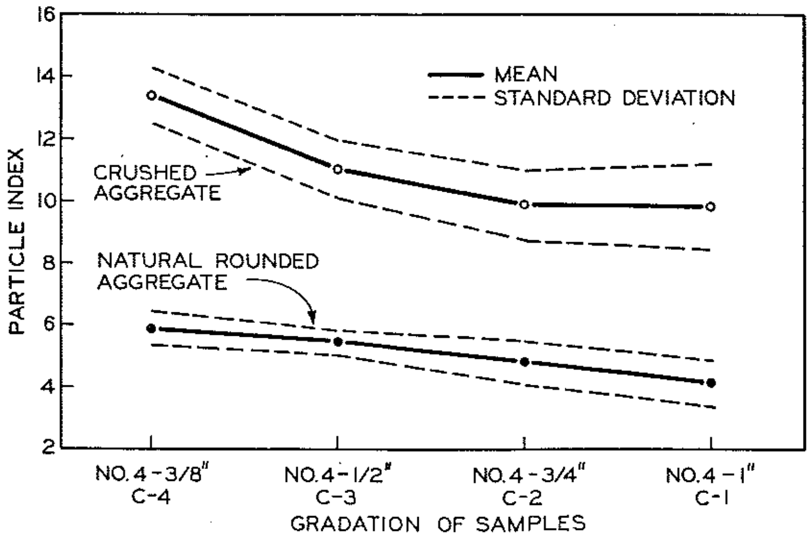


Figure 9. Particle Index for different aggregate gradations showing variabilities when using five different operators.

A further simplification was studied in which the two compactive efforts used in the ASTM test (10 and 50 blows) were studied separately to see if both compactive efforts were necessary and, if not, which effort would give the best Particle Index value correlation with void volume, or density. Results of these tests, in which natural rounded and crushed materials were used, are both shown in Figure 10. Although both curves show very good correlation between density (void volume) and Particle Index over a wide range of values, the 10 blow correlation is better than that for the 50 blows. When using the ASTM test, the 10 blow portion of the test is weighted much heavier (about five times) than is the 50 blow portion on the final test results. It is concluded, therefore, that the Particle Index can be more quickly determined and may be subject to less variation if based directly on the density obtained by 10 compactive blows rather than by adding the extra 50 blow compaction and using the ASTM equation.

The suggested revised test procedure for determining Particle Index for coarse and fine aggregates is described in Appendix D. Using this method, the testing time should be comparable to that required to determine the percent crushed material by Michigan's standard test method. In this study, only the coarse aggregate portion of the test has been used.

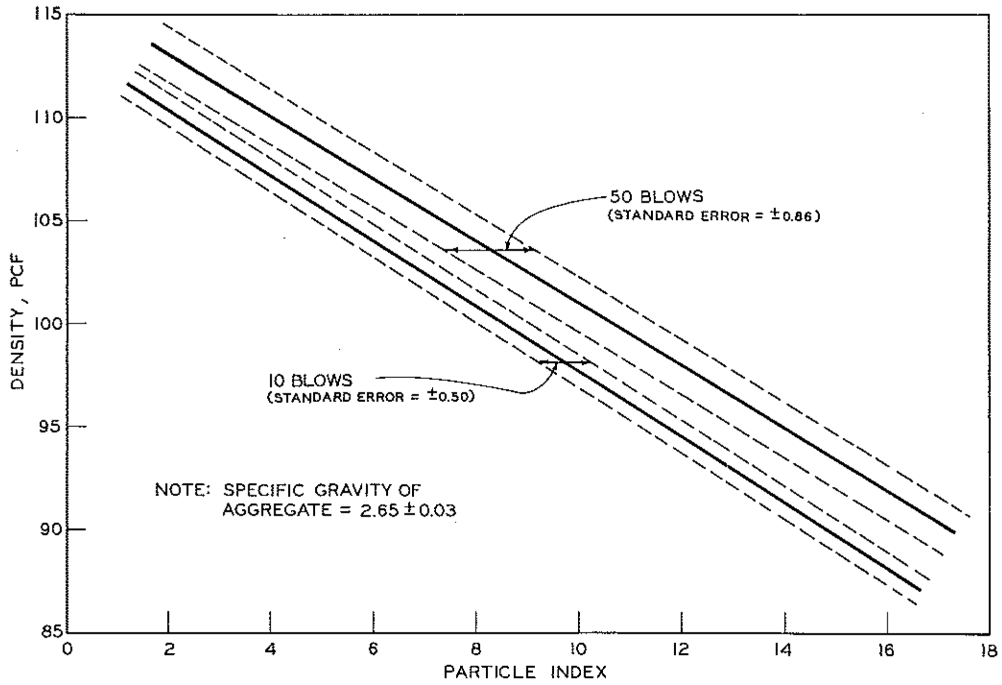


Figure 10. Effect of 10 and 50 blow compaction effort on Particle Index-density relationship of coarse aggregate.

The advantage of substituting the Particle Index Test for crushed requirements is that void volume and geometric properties could be controlled with greater resulting uniformity of the product. Thus, use of the Particle Index is more equitable for the producer as well as providing advantages to the Department. In addition, the usefulness of rejected coarse aggregates for other purposes would be readily determinable. A further advantage is that Particle Index values can be related to specific properties of a material such as stability, whereas crushed content cannot. It is felt that, with additional study, specific index requirements can be established to provide aggregate materials having desired performance characteristics.

TABLE 1
EFFECT OF GRADATION AND GEOMETRIC PROPERTIES
ON THE FRICTION ANGLE, Ø, OF DIFFERENT GRANULAR MATERIALS

Sample	Description	Density, pcf	Geometric Properties	-200 Material, percent	Friction Angle, Ø (degrees)
23A	Natural Aggregate	137.5	0 Percent Crushed	7	46.5
23A	Modified with Cadillac Sand	129.5	0 Percent Crushed	7	44.0
23A	Modified Gradation	141.8	0 Percent Crushed	15	36.5
22A	Natural Aggregate	136.6	Particle Index - 4.9	7	48.5
Cadillac Sand	-No. 8 to +200 Natural	105.1	0 Percent Crushed	0	38.0
U.P. Stamp Sand	Dry	108.3	100 Percent Crushed		57.0
U.P. Stamp Sand	At Optimum Moisture	106.8	100 Percent Crushed		60.5
Gradation C4	Prepared Aggregate (Fig. 4)	---	0 Percent Crushed	0	40.0
Gradation C4	Prepared Aggregate (Fig. 4)	---	50 Percent Crushed	0	43.5
Gradation C4	Prepared Aggregate (Fig. 4)	---	100 Percent Crushed	0	44.5
Gradation C0	Prepared Aggregate (Fig. 4)	---	0 Percent Crushed	0	45.8
Gradation C0	Prepared Aggregate (Fig. 4)	---	50 Percent Crushed	0	45.0
Gradation C0	Prepared Aggregate (Fig. 4)	---	100 Percent Crushed	0	48.5
Gradation C1	Prepared Aggregate (Fig. 4)	108.0	0 Percent Crushed	0	42.0
Gradation C1	Prepared Aggregate (Fig. 4)	108.0	50 Percent Crushed	0	44.8
Gradation C1	Prepared Aggregate (Fig. 4)	108.0	100 Percent Crushed	0	45.0
Gradation C1 (50%) and F3 (50%)	Mixed Aggregate Sizes	144.6	0 Percent Crushed	5	50.5
Gradation C1 (50%) and F3 (50%)	Mixed Aggregate Sizes	140.6	100 Percent Crushed	5	52.5
Gradation C1 (40%) and F1 (60%)	Mixed Aggregate Sizes	137.0	0 Percent Crushed	6	49.0
Gradation C1 (40%) and F1 (60%)	Mixed Aggregate Sizes	137.7	100 Percent Crushed	6	59.0

RELATIONSHIP OF PARTICLE INDEX AND GRADATION TO STRENGTH AND STIFFNESS OF AGGREGATE MIXTURE

A limited study of granular materials of known gradations and Particle Index values was conducted to determine the relationship these properties have with the strength of an aggregate as measured by the friction angle Ø. The quasi-elastic modulus test (2) was used to evaluate the effect that gradation and geometric properties have on stiffness.

Relationships between Particle Index and strength characteristics of a soil aggregate mixture, first presented by Huang (3), are shown in Figure 11. Huang's results indicate that the deviator stress increases with increase in both confining pressure and Particle Index. Relationships between Particle Index and angle Ø, obtained by replotting the data included in Figure 11, showed only a small difference in angle Ø for Particle Index values ranging from 5 to 17. This indicates that factors such as gradation and geometric properties of the finer fraction may have had considerable effect on Huang's results, more so than did Particle Index of the coarse aggregate.

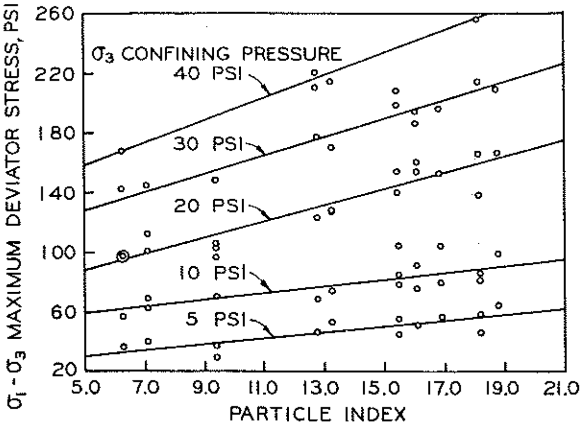


Figure 11. Relationship between strength characteristics of soil-aggregate mixtures and Particle Index of coarse aggregates.

The influence that gradation and geometric properties have on the angle Ø was studied further using data assembled from previous aggregate studies made in our Laboratory. Unfortunately, the Particle Index for most of the materials is unknown. Materials tested included 100 percent crushed, 100 percent natural uncrushed and a blend of crushed and natural materials. Results, summarized in Table 1, indicate that:

1) Friction angles developed in sand are greater than could be developed in coarse aggregate.

2) Crushed sand develops much higher friction angles than does rounded sand.

3) Crushing coarse aggregates has only a small effect on friction angle for total aggregate mixtures.

4) Inclusion of larger aggregate sizes has little effect on friction angle.

The significant results of the above study are that the shear strength of dense graded aggregates is influenced very little by the crushing of coarse aggregate and, geometric properties of sands have great effect on stability when the sand is present in excess of quantities needed for maximum density—a condition found in most dense graded aggregates.

Figure 12 shows the gradations used in a study to determine the effects of gradation and Particle Index values of +3/8-in. coarse aggregate on the stiffness of different dense graded aggregates. Results, shown in Table 2, indicate that the more dense gradations tend to be stiffer but that there is no clear cut relationship between the geometric properties of the coarse aggregate and stiffness of a material.

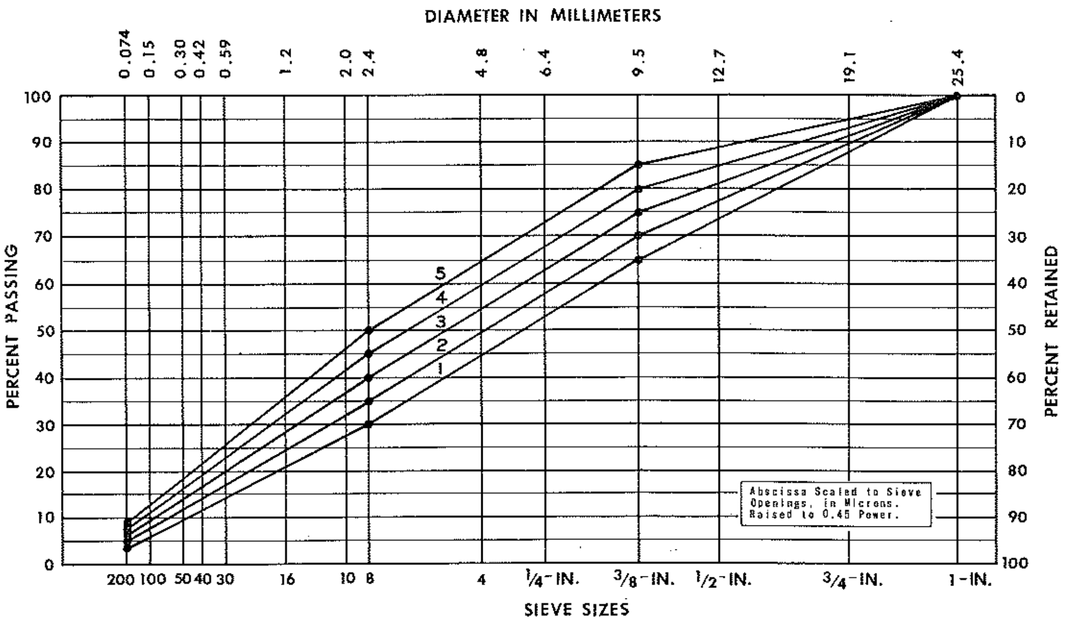


Figure 12. Gradation of samples used to measure quasi-elastic modulus.

TABLE 2
RELATIONSHIP BETWEEN STIFFNESS AND GEOMETRIC PROPERTIES OF VARIOUS GRADATIONS OF 22A AGGREGATE

Gradation	Geometric Properties of +3/8 in. Particles		Quasi-Elastic Modulus, E (psi)
	MDOT Percent Crushed	Particle Index	
1	100	10.1	23,500
	50	8.3	23,700
	0	5.3	25,200
2	100	11.5	24,200
	50	9.0	20,800
	0	5.1	17,400
3	100	11.1	17,700
	50	8.3	23,700
	0	3.4	21,000
4	100	10.7	19,800
	50	8.3	25,000
	0	3.5	16,700
5	100	10.5	18,600
	50	9.3	18,800
	0	3.6	16,900

CONCLUSIONS

From this study the following conclusions have been reached concerning the usefulness of the straight line gradation chart and the Particle Index Test for the control of Michigan's aggregates and granular material specifications.

1) Use of the FHWA straight line gradation chart should improve the Department's ability to evaluate the grading requirements for fine, coarse and dense graded aggregates and granular materials.

2) Use of the modified Particle Index Test, as described in Appendix D to this report, provides a more uniform control of void volume and geometric properties of coarse and dense graded aggregates than do presently specified crushed requirements. Results can be obtained in about the same time as is required for percent crushed determination.

3) Methods developed in this study indicate that the geometric characteristics and quantity of sand contained in an aggregate mixture can exert considerable influence on the performance of the mixture. Further study in this area is suggested.

4) Evaluation of MDOT gradation and crushed content specifications using straight line gradation and Particle Index methods indicates that improvements and cost savings may be possible in aggregate use through increased knowledge of engineering properties of the materials.

REFERENCES

1. "Aggregate Gradation for Highways," U. S. Department of Commerce, Bureau of Public Roads, May 1962.

2. AlNouri, I., "Evaluation of a Quasi-Elastic Modulus of Granular Base Material," Michigan Department of State Highways, Research Report R-749, September 1970.

3. Huang, E. Y., "A Test for Evaluating the Geometric Characteristics of Coarse Aggregate Particles," American Society for Testing Materials, Proceedings, Vol. 62, 1962.

APPENDIX A

DEFINITIONS OF TERMS USED

1. Stability = strength = shear strength = $s = c + p \tan \phi$

   where: c = cohesion or $q_u/2$,
   q_u = unconfined compressive strength,
   p = normal pressure on plane of failure,
   ϕ = friction angle.

2. Percent crushed. The weight of the particles picked because they have at least one newly fractured face divided by the weight of that portion of the sample from which they were selected.

3. Aggregate base course. That layer directly beneath the portland cement or bituminous concrete pavement surface layer.

4. Aggregate surface course. Any aggregate layer intended to directly support traffic.

5. Coarse aggregate. Any aggregate retained on the No. 4 sieve.

6. Fine aggregate. Any aggregate passing the No. 4 sieve and retained on the No. 30 sieve.

7. Sand. Any particle passing the No. 30 sieve and retained on the No. 200 sieve.

8. Fines. All particles passing the No. 200 sieve.

9. Total aggregate material. Any aggregate material containing coarse and fine aggregates, sand, and fines.

10. Stiffness. Quasi-elastic modulus of an aggregate material defined as follows:

$$E' = \frac{\sigma}{\Sigma}$$

   where: E = quasi-elastic modulus,
   σ = stress,
   Σ = recoverable strain.

11. Geometric properties. Properties of angularity, shape, and surface texture are collectively referred to as the geometric properties of an aggregate.

12. Void ratio.

$$e = \frac{V_v}{V_s}$$

where: e = void ratio,
V_v = volume of the voids,
V_s = volume of the solids.

13. Index properties. The result of classification tests. Generally, Index properties are divided into two general types: soil grain and soil aggregate properties. Soil grain properties are the properties of the individual grains of which the soil is composed and include: geometric properties, gradation, mineralogical composition, etc. Soil aggregate properties depend on the structure and arrangement of the particles in the soil mass. Soil grain properties are commonly used for identification while soil aggregate properties have a greater influence on the engineering behavior.

APPENDIX B

SPECIFICATION GRADATIONS FOR MICHIGAN AGGREGATES SHOWN ON THE STRAIGHT LINE GRADATION CURVE

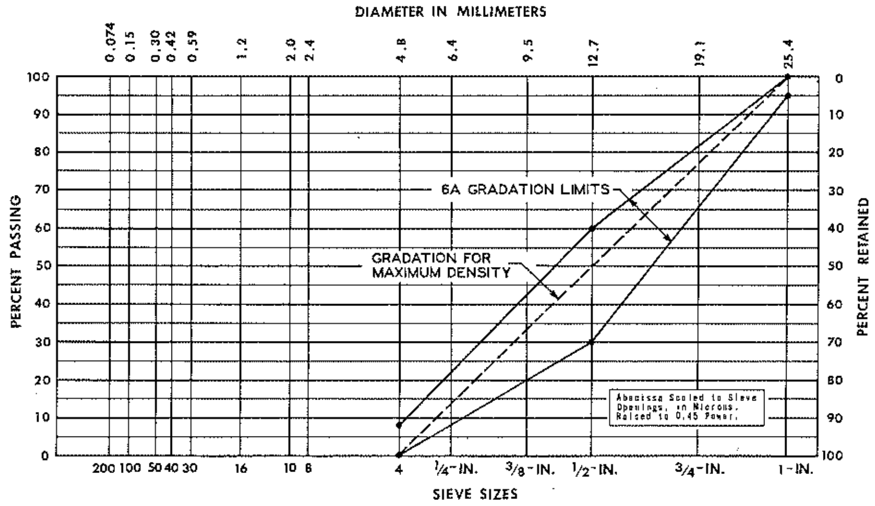


Figure B-1. Gradation specification limits—6A aggregate.

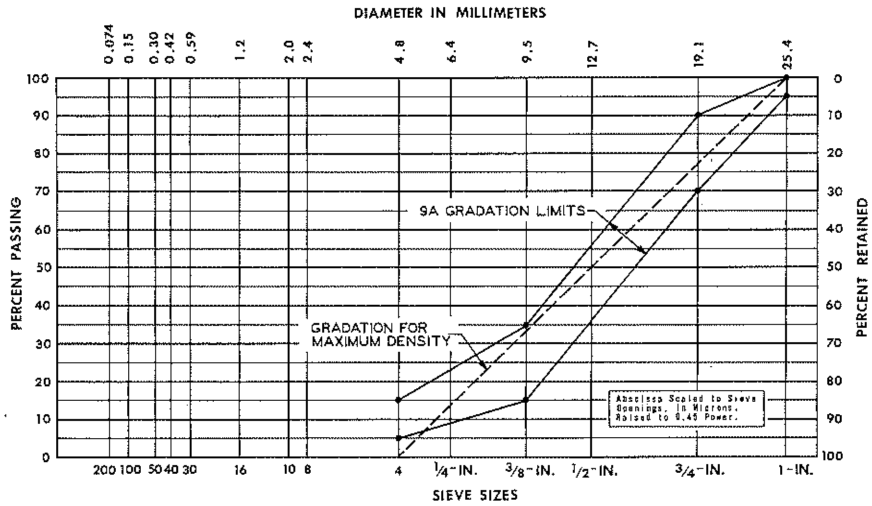


Figure B-2. Gradation specification limits—9A aggregate.

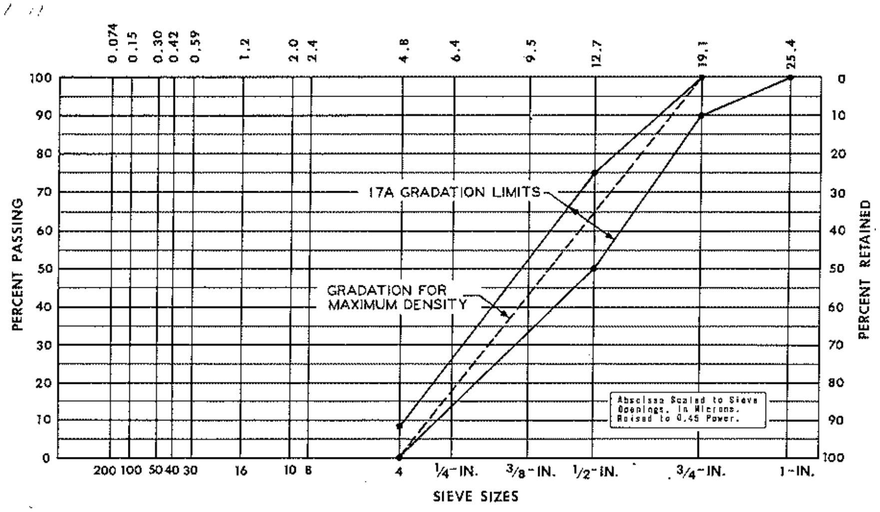


Figure B-3. Gradation specification limits—17A aggregate.

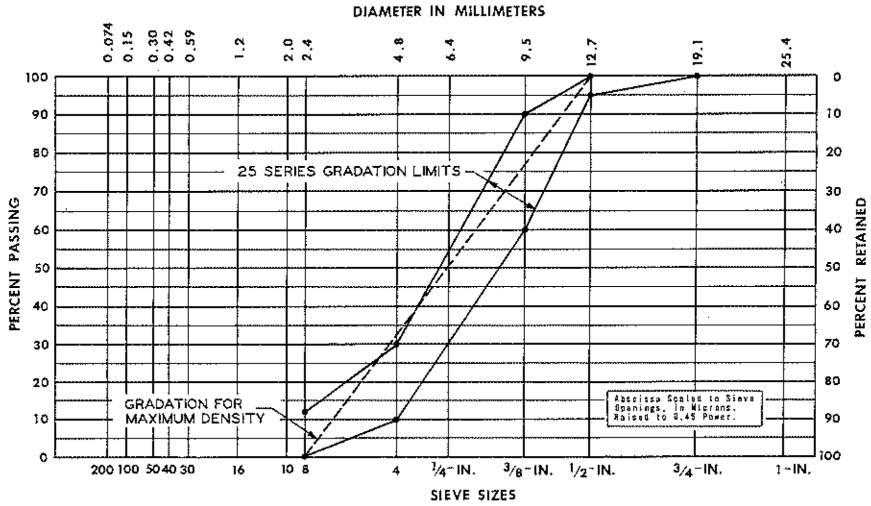


Figure B-4. Gradation specification limits—25 series aggregates.

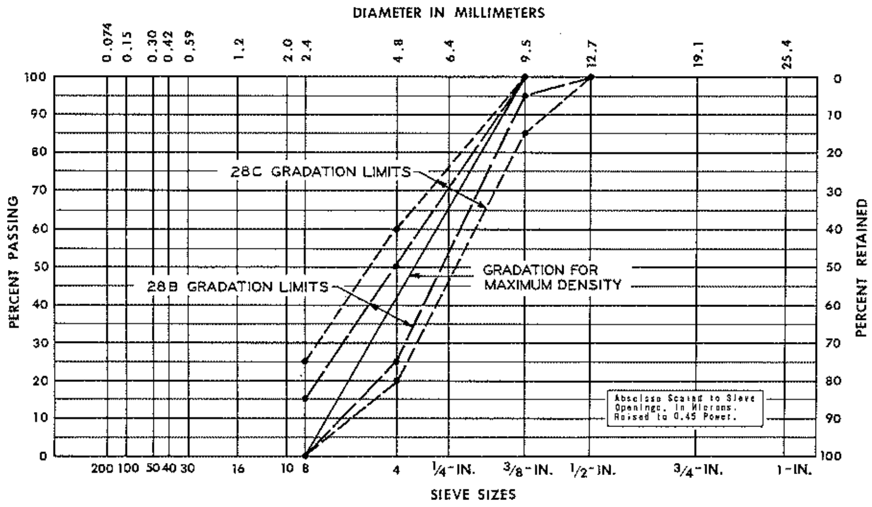


Figure B-5. Gradation specification limits—28 series aggregates.

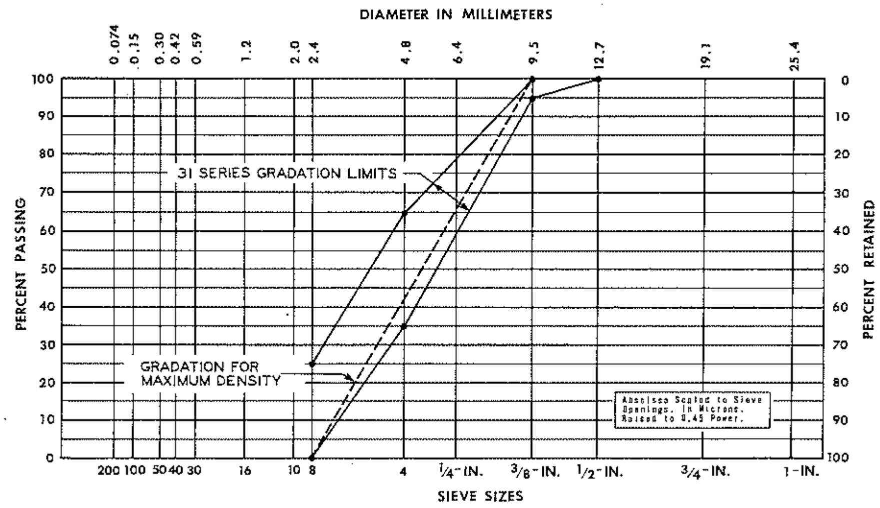


Figure B-6. Gradation specification limits—31 series aggregates.

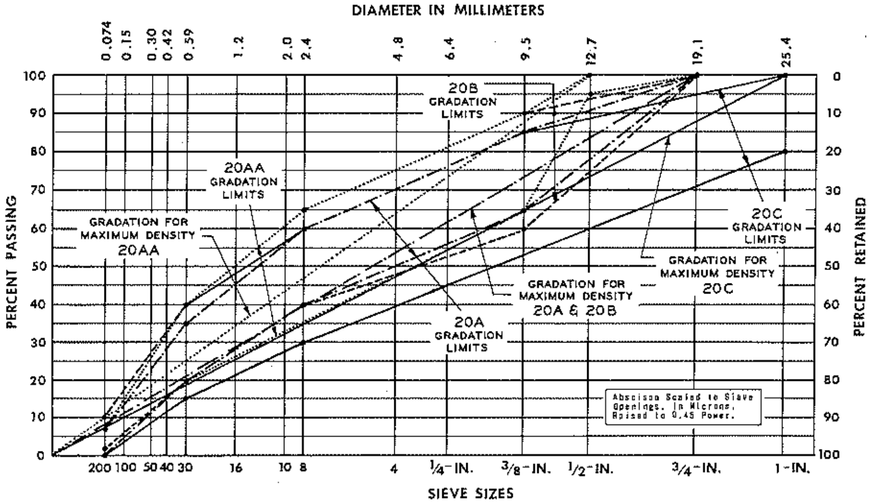


Figure B-7. Gradation specification limits—20 series aggregates.

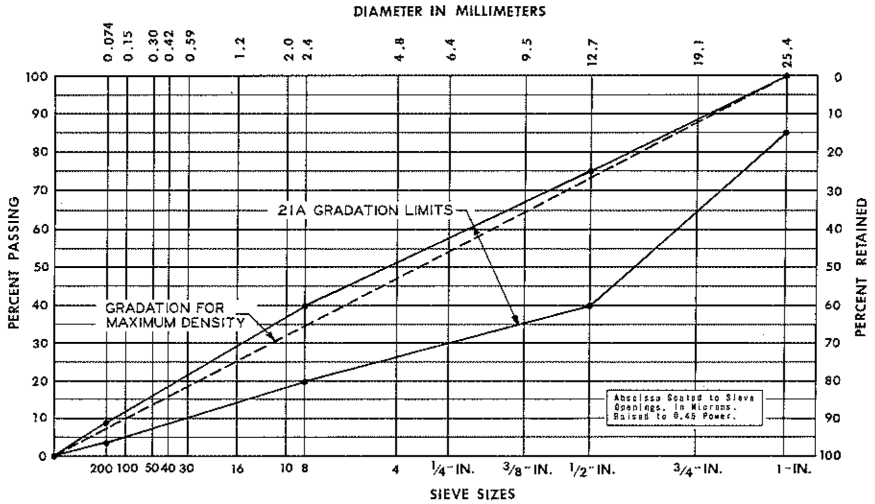


Figure B-8. Gradation specification limits—21A aggregate.

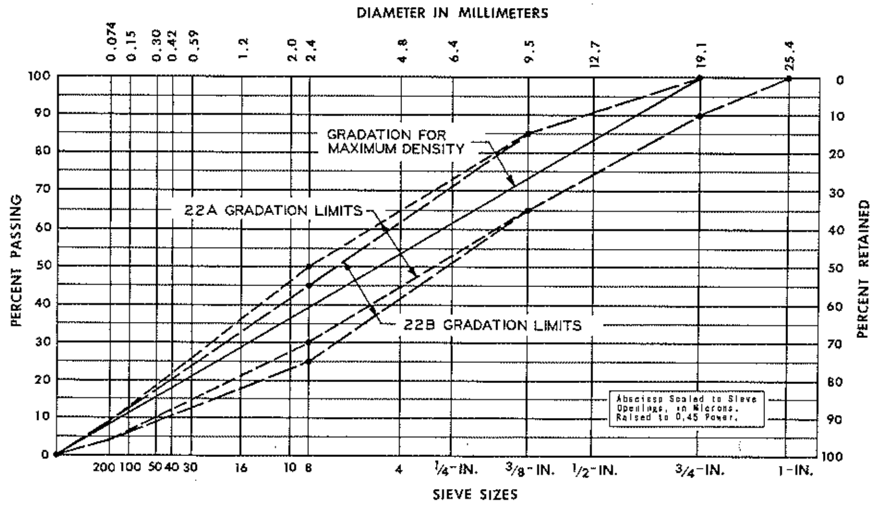


Figure B-9. Gradation specification limits—22 series aggregates.

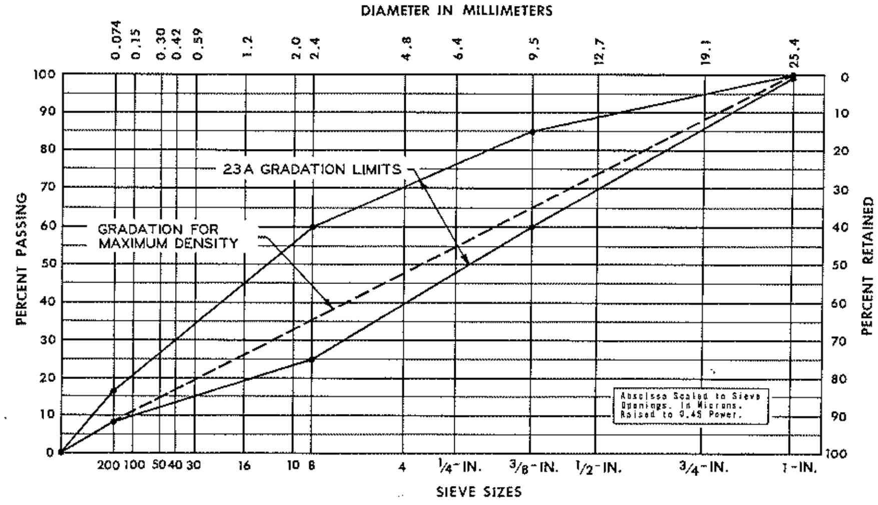


Figure B-10. Gradation specification limits—23A aggregate.

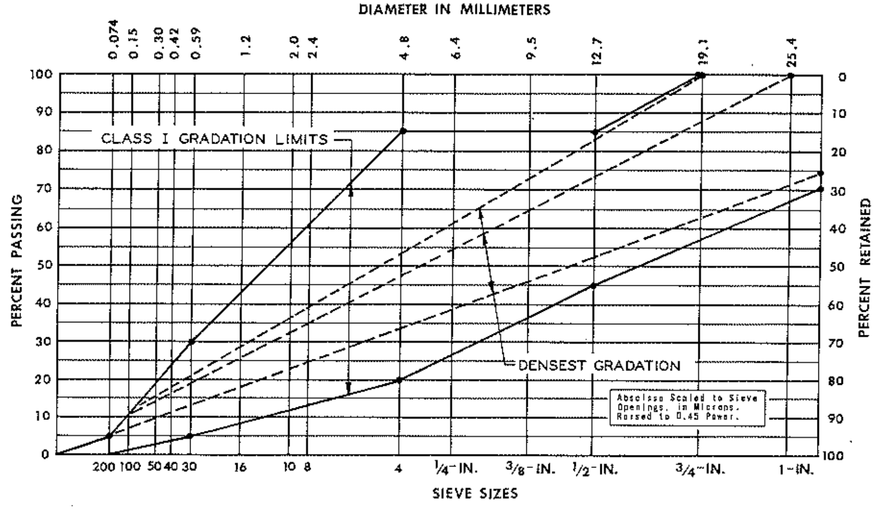


Figure B-11. Gradation specification limits—class I material.

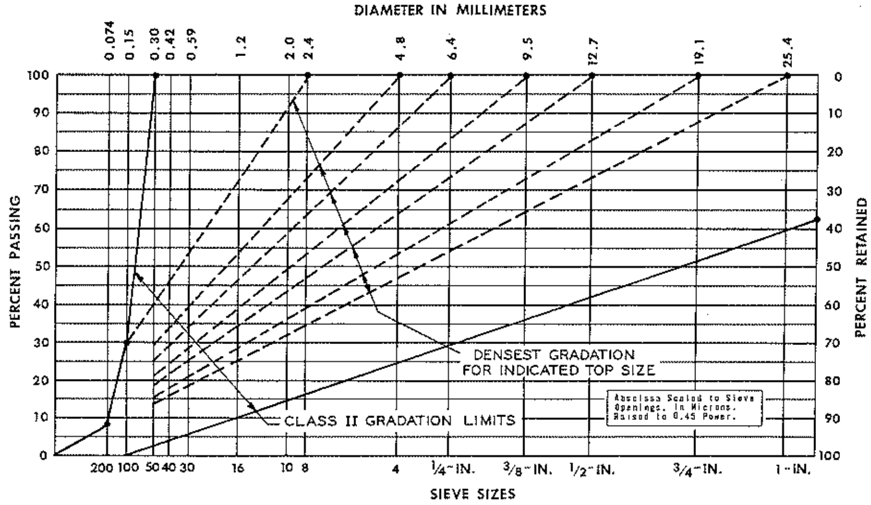


Figure B-12. Gradation specification limits—class II material.

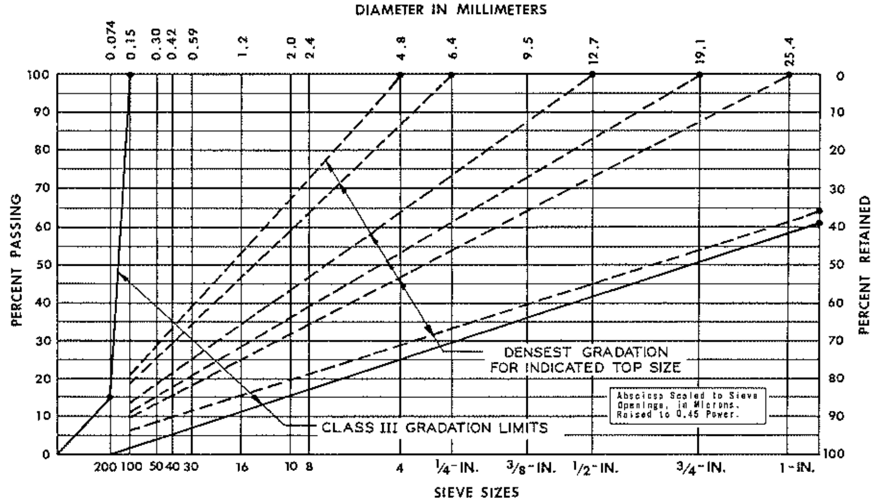


Figure B-13. Gradation specification limits—class III material.

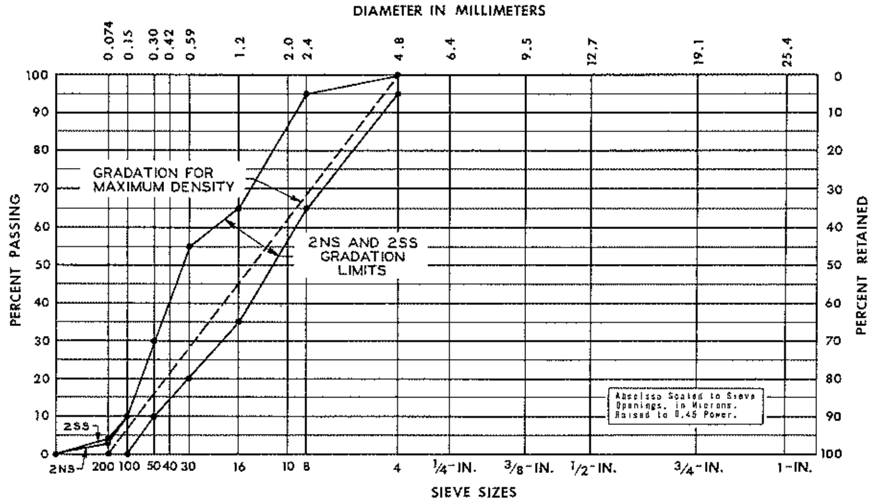


Figure B-14. Gradation specification limits—2NS and 2SS material.

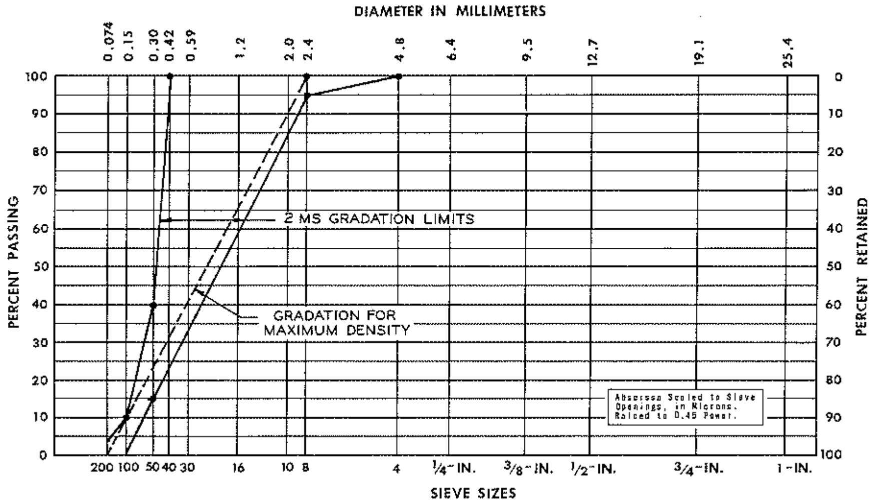


Figure B-15. Gradation specification limits—2MS material.

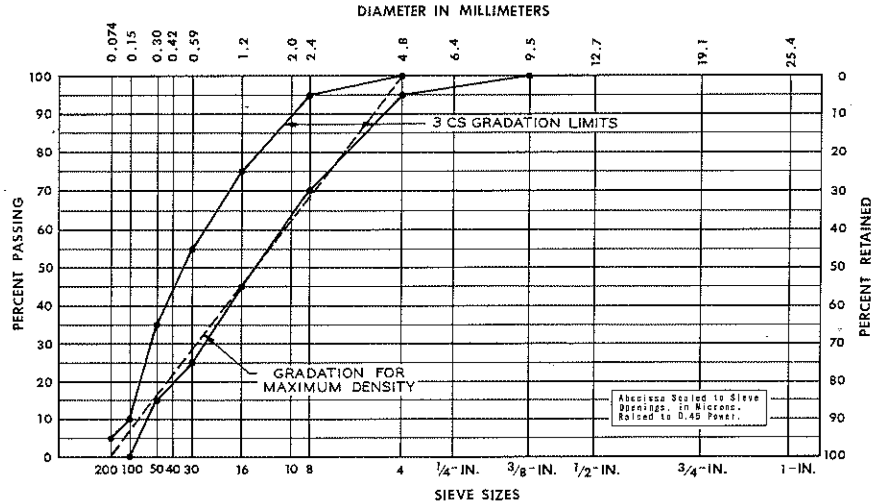


Figure B-16. Gradation specification limits—3CS material.

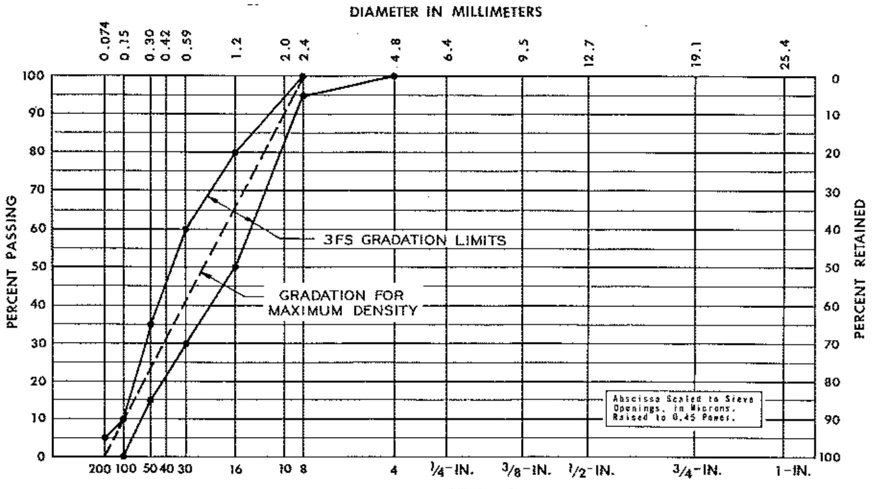


Figure B-17. Gradation specification limits—3FS material.

APPENDIX C

EFFECT OF GRADATION AND GEOMETRICAL PROPERTIES ON THE VOID CONTENTS OF VARIOUS AGGREGATE MIXTURES

Specifications for the Department's dense graded aggregates permit a wide range of sand contents varying from more to less than is needed for maximum density. These specifications apply to aggregates used for various purposes including bituminous concrete and porous base applications. It is, therefore, important to know how the specific use of the material will be affected by the sand content. For this purpose, a laboratory study was made to determine the relative influence of sand content and geometric properties on the void volume (as expressed by density) of different aggregate mixtures.

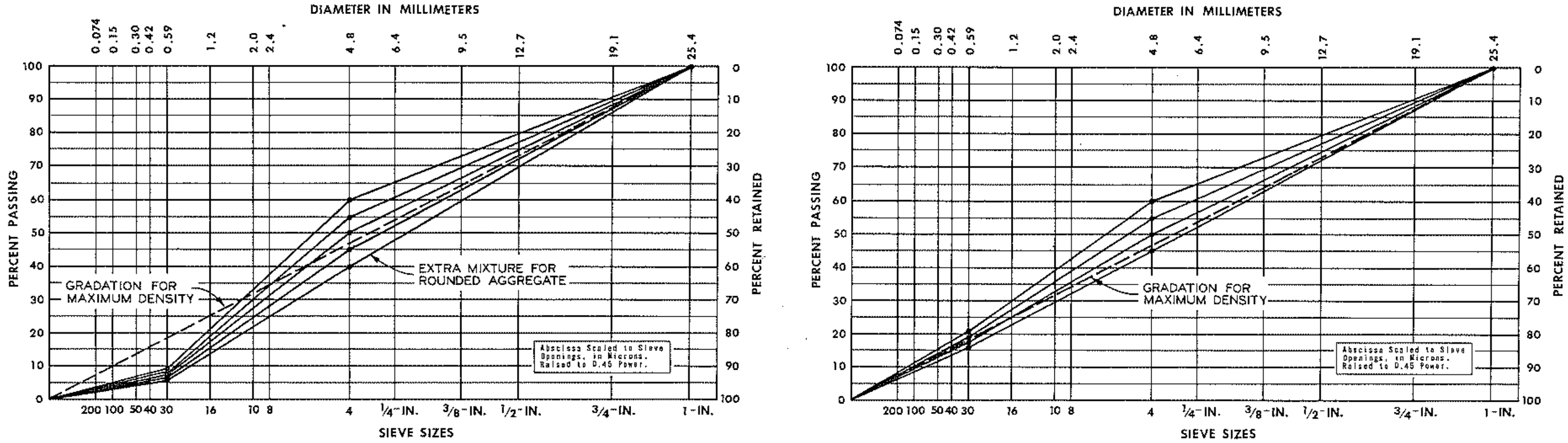
Four basic test mixtures were prepared in which different portions (40 to 60 percent) of a coarse graded aggregate (C1 from Fig. 4) were mixed with portions of minus 4 aggregates (F1, F2, F3, and F4, from Fig. 4). Both natural and rounded aggregate and crushed aggregate (from the same natural aggregate source) were used. Gradations of the four test mixtures are shown in Figure C-1. These represent gradations within the Department's dense graded aggregate specifications and include mixtures of low sand content (A), maximum density gradation (B), high sand content (C), and very high sand content (D).

The effect that sand content (as represented by the minus 30 fraction) has on density within the four basic mixtures is shown in Figure C-2. Each point on the curves represents an average of three density values obtained by standard T-99 compaction effort. The curves show clearly the maximum density attainable at optimum sand content for each of the four mixtures. The relationships between gradation and geometric properties (represented as crushed and rounded aggregate) is also apparent. In using these curves, however, it should be realized that they apply only to those aggregates containing coarse material in the range of 40 to 60 percent.

The more important relationships developed indicate:

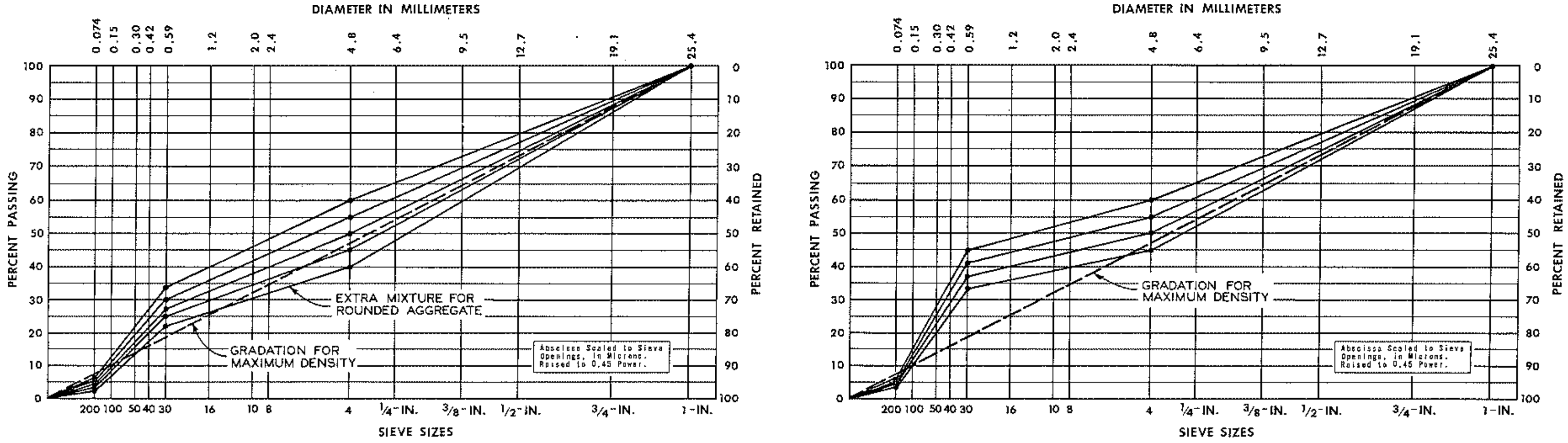
1) The maximum densities of rounded aggregate are more sensitive to sand content than are the densities of crushed aggregates. For this reason, gradation specifications for rounded aggregates should be more restrictive of sand content than are specifications for crushed materials, which permit a wider range of sand content with less affect on density change.

2) For aggregates well graded for maximum density (gradation B) the geometric properties (crushed or rounded) exert more influence on maximum density than does the sand content. This indicates that permeability



Low Sand Contents

Maximum Density Gradations



High Sand Contents

Very High Sand Contents

Figure C-1. Gradation of test mixtures used to evaluate the effect of different sand contents on density.

and quantity of bituminous binder required for materials close to having a straight line gradation will be highly dependent on the geometric properties of the aggregate.

3) Geometric properties of aggregates very high in sand content (gradation D) have little effect on attainable densities. Rounded or crushed aggregates yield almost equal results when used under these grading conditions.

In general, the relationships shown in Figure C-2 show that void content (density) which controls permeability, asphalt binder requirements, as well as stability of an aggregate, can vary considerably with both the geometric properties and the gradation of an aggregate mixture. Effective application of these relationships could result in improved aggregate specification and selection. Both the straight line gradation chart and the Particle Index Test would be useful for such an effort.

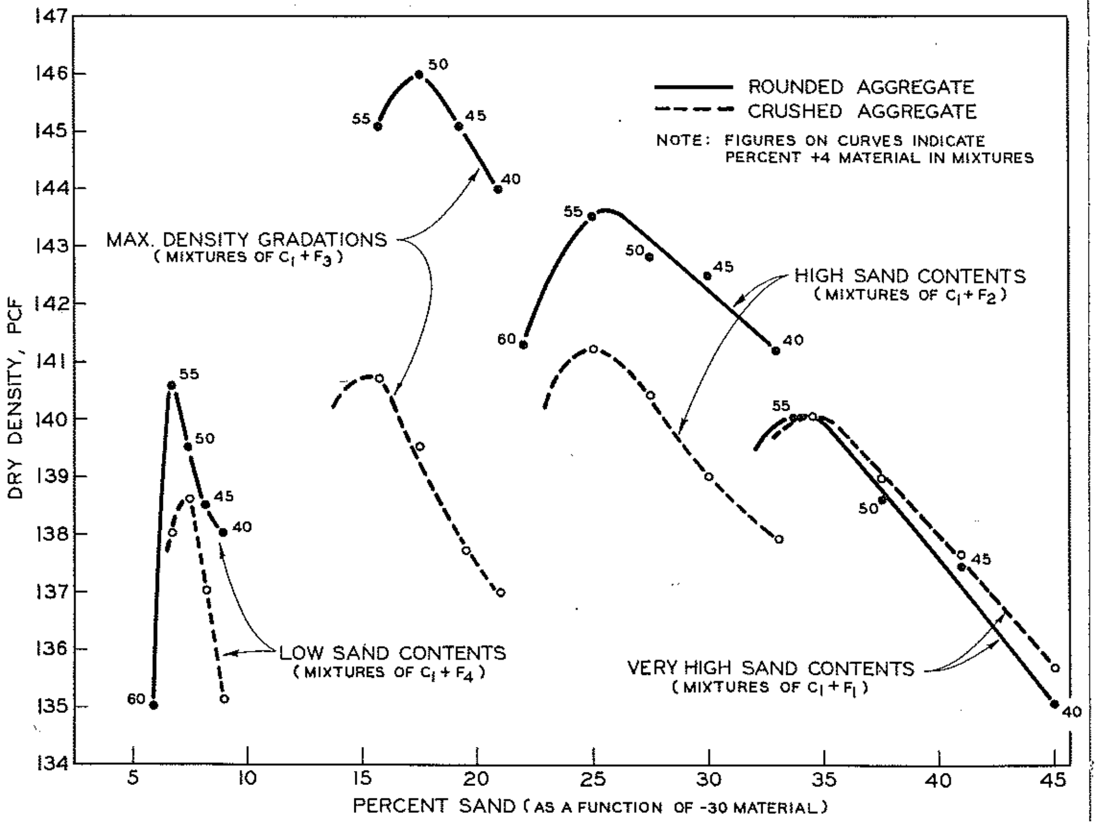


Figure C-2. Effect of sand content on the density of aggregate mixtures containing 40-60 percent coarse (+4) material.

APPENDIX D

PARTICLE INDEX TEST PROCEDURES

Scope

This method covers the determination of the Particle Index of aggregate as an overall measure of particle shape and texture characteristics.

Apparatus

1) Cylindrical mold. A cylindrical mold with an inside diameter of 6 in. and an inside height of 7 in.

2) Tamping rod. A round steel rod 0.622 in. in diameter and 24 in. long having one end rounded to a hemisphere of 0.625 in. diameter. The rod shall weigh 930 grams ± 10 grams.

Test Specimen

1) Obtain a sample weighing about 50 lb. Split the sample into the following two sizes: +No. 30 to No. 4 sieve size (fine aggregate), and +No. 4 to 1-1/2-in. sieve size (coarse aggregate). Discard the -30 sieve material. Fine and coarse aggregate samples must weigh at least 13 lb each.

2) Wash each aggregate sample clean removing all fines. Dry to a constant weight and cool to room temperature.

Percentage of Voids

Using oven-dried samples for fine and coarse aggregate size samples, determine percentage of voids at one level of compaction in accordance with the following procedure.

1) Place the cylindrical mold on a uniform, solid foundation. Gently place the coarse aggregate sample from the lowest height possible into the mold until it is approximately one-third full. Level the surface with the fingers, and compact the layer using 10 drops of the tamping rod evenly distributed over the surface. Apply each drop by holding the rod vertically with its rounded end approximately 2 in. above the surface of the aggregate and releasing it so that it falls freely. Place a second layer in the mold using the same procedure, filling the mold approximately two-thirds full. As before, level the surface and apply 10 drops of the rod. Fill the remaining space in the mold with a third layer and again level the surface and apply the same compactive effort, 10 drops of the rod. After the final layer has been compacted, add individual pieces of aggregate to make the surface

of the aggregate mass even with the rim of the mold, with no projection above the rim. Determine the net weight of the coarse aggregate in the mold to an accuracy of at least 4 grams.

2) Repeat the filling of the mold using the same coarse aggregate sample and compaction. Make a second determination of the net weight of the coarse aggregate in the mold as described in Step 1 above. Use the average weight of the two runs in calculating the percentage of voids at 10 drops.

3) Repeat Steps 1 and 2 above using the fine aggregate sample.

4) Calculate the percentage of voids in the coarse aggregate and fine aggregate samples by the following relationship:

$$V_{10} = \left[1 - (W_{10}/SV)\right] 100$$

where:
V_{10} = voids in aggregate compacted at 10 drops per layer, percent
W_{10} = average weight of the aggregate in the mold compacted at 10 drops per layer
S = bulk dry specific gravity of the coarse or fine aggregate size fraction, and
V = volume of the cylindrical mold, ml.

Particle Index

Determine the Particle Index for coarse and fine aggregate samples by Figure D-1.

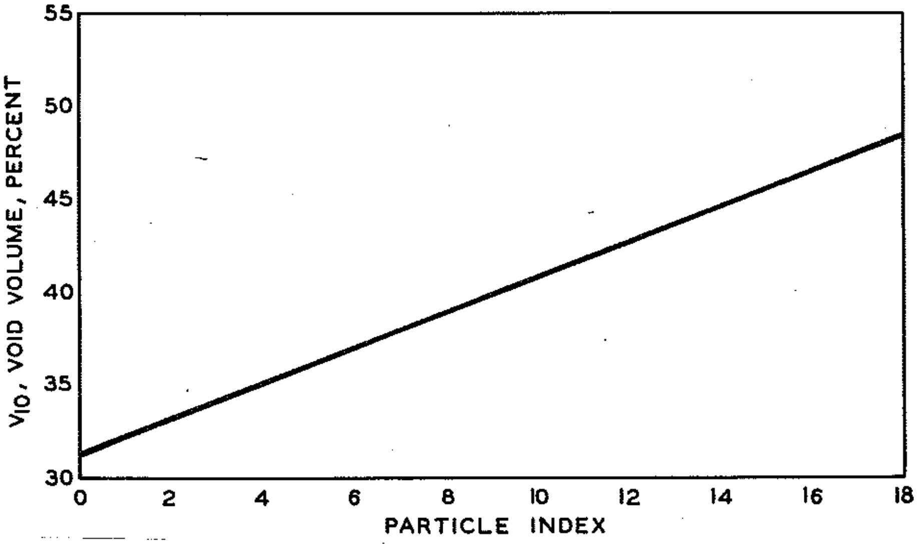


Figure D-1. Void volume vs. Particle Index at a compactive effort of 10 blows per layer.