Effect of Geometric Characteristics of Coarse Aggregates on Compaction Characteristics Of Soil-Aggregate Mixtures

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This paper reports the results of a laboratory study to investigate the effect of the geometric characteristics of coarse aggregate particles on the compaction characteristics of soil-aggregate mixtures. Six coarse aggregate materials with discernible geometric characteristics, including both pit-run gravel and crushed stone materials, were used in the study. The geometric characteristics of these materials were determined by the "particle index" test, a procedure developed at the University of Illinois particularly for the quantitative evaluation of these characteristics.

The results of this investigation show that the volume of the voids in a soil-aggregate mixture of a given gradation under a standard laboratory compactive condition decreases more or less linearly with decreasing values of the particle index of the coarse aggregates; that is, as the coarse aggregate particles become more spherical, rounded, and smoothly surfaced. The conclusion that the density of a soil-aggregate mixture varies not only with the gradation of the mixture but also with the geometric characteristics of the coarse aggregate fraction appears to be deserving of some consideration in the construction control of soil-aggregate roads.

• THE SERVICE behavior of a soil-aggregate material for roads and pavements is dependent on many factors. One of the important influencing factors is that of density or the void characteristics of the compacted soil-aggregate material. Experimentation both in the field and in the laboratory has indicated that the stability of a soil-aggregate material increases with an increase in density (1), so long as excessive pore water pressures are not developed (2). Moreover, dense soil-aggregate mixtures afford high abrasive resistance, shed the greater portion of rain water, and maintain a more uniform moisture content through the replacement (by means of capillary action) of the moisture lost through evaporation (3). A desirable density may be achieved through the use of that gradation of the combined aggregate that has the least voids. Thus, by careful gradation control an aggregate skeleton of high stability could be obtained from materials that otherwise would possess a much lower stability.

Almost every State has specifications covering suitable gradations and materials for soil-aggregate roads. The AASHO and the ASTM also have standard specifications for materials and mixtures suitable for uses as surfaces, bases, and subbases, according to the gradation, as well as the Atterberg limits, of the soil-aggregate mixtures. Many of these grading specifications cover materials of various kinds, including stone, gravel, or slag with natural or crushed sand and fine mineral particles passing a No. 200 sieve (4). Because the gradations of soil-aggregate mixtures are always determined by a sieve analysis which classifies the sizes of aggregate on the basis of its least section area, and inasmuch as long, pencil-shaped or other irregularly shaped particles may pass a sieve and be weighed with others of lesser volume and hence of smaller size,

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it is evident that aggregate materials with particles of different geometric characteristics may yield appreciably different density values even though they are identical in gradation.

In this paper the term "geometric characteristics" is used to include shape, angularity, and surface texture of aggregate particles. The term "shape" is used to refer to the form of an aggregate particle, whereas the term "angularity" is applied to the sharpness of the corners and edges of the particle. Thus, a cube and a tetrahedron are geometric solids of different shapes but, because the radius of curvature of their edges or corners is zero, they have equal degree of angularity. The term "surface texture" refers to the intimate details of the particle surface independent of shape and angularity. It is the property that measures the relative degree of smoothness or roughness of the particle surface.

OBJECTIVE AND SCOPE OF STUDY

In this investigation, a laboratory study was made to determine the effect of the geometric characteristics of coarse aggregates on the compaction characteristics of soil-aggregate mixtures. Six coarse aggregate samples with discernible geometric characteristics, including both pit-run gravel and crushed stone materials, were used in the study. The geometric characteristics of these materials were determined by the "particle index" test, a procedure developed at the University of Illinois particularly for the quantitative evaluation of these characteristics (5).

Each coarse aggregate was combined with various percentages of finer aggregate and soil materials to form seven different gradations. The compaction characteristics of these soil-aggregate mixtures were determined essentially according to AASHO Designation T-99-57. In this report the test data are analyzed and the effect of the geometric characteristics, as well as the gradation, of these materials on their void characteristics after compaction tests are presented.

TABLE 1

GENERAL PHYSICAL CHARACTERISTICS OF AGGREGATE MATERIALS

Characteristic	Gravel 61	Crushed Stone 178
Apparent specific gravity (AASHO T-85-60)	2.49	2.66
Absorption (AASHO T-85-45)	3.8	1.0
% wear in abrasion test (AASHO T-96-56)	31.5	28.7
% loss in soundness test (AASHO T-104-57)	13.0	14.1

TABLE 2

PARTICLE INDEX OF VARIOUS COARSE AGGREGATES

Sample Designation	Particle Index for Particle Size of		
	¾- to ½-In.	½- to ⅜-In.	⅜-In. to No. 4
Gravel:			
61(a)	7.1	8.0	6.9
61(b)	9.8	9.3	8.4
61(c)	10.7	10.6	10.6
Crushed stone:			
178(a)	13.4	12.4	12.6
178(b)	16.0	15.9	14.9
178(c)	16.9	17.4	16.4

MATERIALS TESTED

Coarse aggregate materials used in this investigation were obtained from two sources: a pit-run gravel, designated No. 61, from Greenup, and a crushed stone, designated No. 178, from Casey, both in central Illinois. The gravel was produced from outwash deposits of the Wisconsian stage of glaciation. It was composed of a large variety of materials, including limestone and dolomite, dark colored igneous rocks, quartzite, sandstone, and some chert. The crushed stone was obtained from

Figure 1. Coarse aggregate samples.

formations of Pennsylvanian age. The rock was a compact, fine-grained, hard, gray limestone. The general physical characteristics of these two materials are summarized in Table 1.

The preceding materials were typical road aggregates conforming to the specifications of the Illinois Division of Highways for soil-aggregate roads. Though both materials contained varying amounts of particles of different shapes, the crushed stone was characteristically more angular and rougher in surface texture than the gravel material. To provide materials with a considerable range of variation in their geometric characteristics, each material was separated into three distinct classes by visual examination according to the shape of particles. In this connection, the sample containing only bulky particles or grains of which the length, width, and height were about the same was designated shape a, that containing elongated pieces was designated shape b, and that containing flat particles was designated shape c. During the separation process, the soft, unstable particles in the gravel material, largely consisting of sandstone and limestone, were also removed to prevent aggregate breakage during the compaction test.

The preceding classification of aggregates with respect to shape was entirely arbitrary, and was made merely to provide coarse aggregate samples that were individually distinctive in their particle shape, angularity, and surface texture. The visual classification was performed by one operator and checked by another in order to maintain a reasonable degree of consistency. Typical examples of these two aggregates of various shapes are shown in Figure 1.

The total geometric characteristics, embracing shape, angularity, and surface texture, of these coarse aggregate materials were determined by the "particle index test." A detailed description of this test has been presented elsewhere (5). Essentially, the

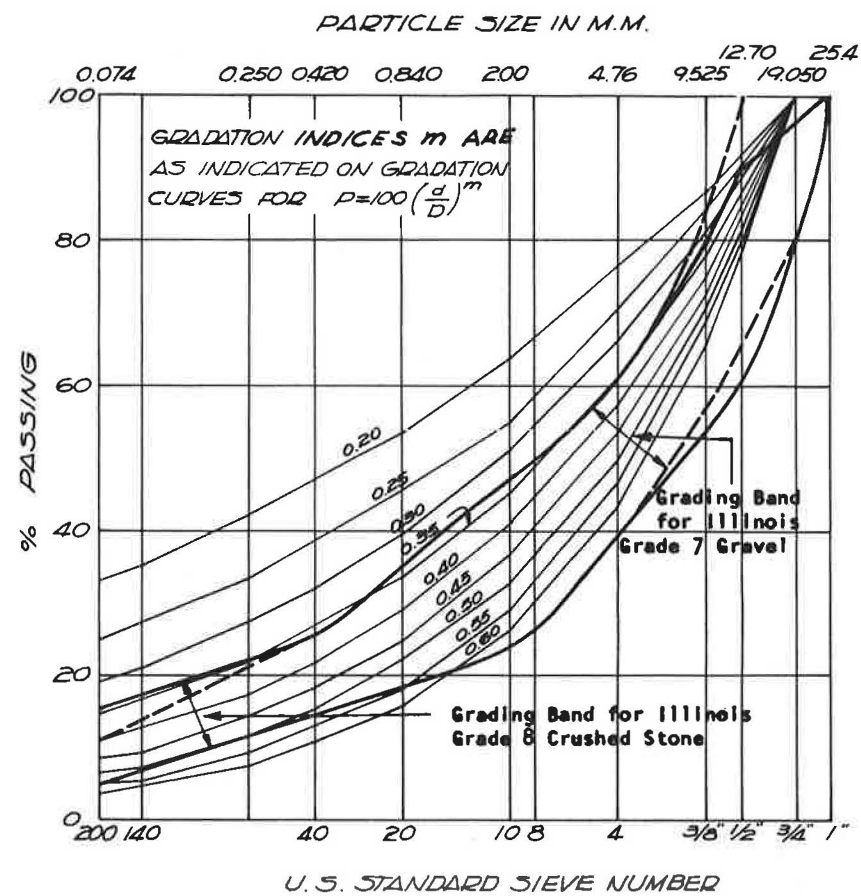

Figure 2. Particle size distribution of soil-aggregate mixtures.

test is based on the concept that the void conditions in a uniform-sized coarse aggregate when rodded in a standard rhombohedron mold show the combined features of shape, angularity, and surface texture of the aggregate. The result of this test is expressed as the particle index of the aggregate, for which a mass of single-sized, highly polished aluminum spheres is taken as zero. Typical index values of the aggregates that have been tested in the aggregate laboratory at the University of Illinois range from about 4 for a gravel composed of rather spherical particles with rounded corners and smooth surface to about 20 for a crushed limestone of flakey particles with angular corners and edges and a very rough surface.

The results of the particle index for the six aggregate samples are given in Table 2. The tests were performed according to the standard procedure in which each sample was separated by sieves into the following sizes: passing the ¾-in. and retained on ½-in. sieve, passing the ½-in. and retained on ⅜-in. sieve, and passing the ⅜-in. and retained on No. 4 sieve. These values were used later in determining the particle index of the coarse aggregates in a soil-aggregate mixture containing particles of all the three sizes. The particle index of such a mixture was the weighted average of the particle index for each size group based on the grading of the mixture.

Particle index values in Table 2 show that, for the crushed stone or the gravel of the same nominal size, the particle index is greatest for the flat particles (shape c) and smallest for the bulky particles (shape a). For the crushed stone or gravel samples belonging to the same size and shape group, the general fact that the crushed stone exhibited a much greater value of particle index than the gravel material was attributable

TABLE 3

ATTERBERG LIMITS OF SOIL-AGGREGATE MIXTURES

Gradation Index	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)
0.20	31.0	19.3	11.7
0.25	28.6	18.4	10.2
0.30	26.8	18.0	8.8
0.35	24.0	14.6	9.4
0.40	21.9	15.3	6.6
0.45	19.7	12.0	7.7
0.50	18.9	14.0	4.9
0.55	17.6	14.2	3.4
0.60	16.9	14.3	2.6

to its greater particle angularity and rougher surface texture. The different particle index values of the three particle sizes of an aggregate sample belonging to the same arbitrary shape group indicate that the total geometric characteristics of these arbitrarily selected particles were not unvarying.

The portion of the material passing the No. 4 sieve for this investigation was obtained from several sources. The material for the No. 4 to No. 140 sieve range was obtained from a stream gravel deposit located in the Bloomington moraine area near Penfield, Ill. For the No. 140 to No. 200 sieve material, Ottawa sand was obtained from a commercial source. The minus No. 200 binder material used was a greenish-brown silty clay from the B-horizon of the Flanagan, Catlin, Drummer soil association area in Urbana, Ill.

To control the gradation of the materials fully, the soil-aggregate mixtures to be used in the compaction tests were artificially prepared from gradation curves based on the mathematical expression for grain-size distribution developed by Talbot and Richart (6):

$$p = 100\ (d/D)^m \qquad (1)$$

in which

p = percentage of material passing sieve with opening of d;
D = maximum size of particles of the given soil-aggregate mixture; and
m = variable exponent, termed "gradation index."

In this investigation, the maximum size D was limited to the ¾-in. size, and the gradation indexes included 0.20, 0.25, 0.30, 0.35, 0.40, 0.45, 0.50, 0.55, and 0.60 The particle size distribution curves for various values of gradation index used in this investigation are shown in Figure 2. Also presented in the figure are the grading bands specified by the Illinois Division of Highways for grade 7 gravel and grade 8 crushed stone, which give the grading limits that have been found in Illinois to give satisfactory results in practice for the types of aggregate materials used in this investigation. Also, the curve with a gradation index of 0.50 represents the ideal grading curve for maximum density developed by Fuller. Although it was originally developed for concrete aggregates, nearly all the gradation specifications now in use approximate, with variable tolerances, this curve.

Table 3 gives the liquid limit, plastic limit, and the plasticity index of soil-aggregate mixtures having different gradation indexes. Because these physical constants were determined on the portion of the mixtures passing the No. 40 sieve, these values were the same for all mixtures having the same gradation index. This similarity of the liquid limit and the plasticity index of the soil fines for the soil-aggregate mixtures involving six different coarse aggregates, but having the same gradation, permitted direct comparison of the test results in terms of the particle index or the geometric characteristics of the coarse aggregate particles.

COMPACTION TEST

The compaction test was conducted on the soil-aggregate mixtures essentially according to Method C of AASHO Designation T-99-57. The standard mold used in this test is 4.0 in. in diameter and 4.59 in. in height, with a volume of 1/30 cu ft. The rammer is 2 in. in diameter having a flat circular face and weighing 5.5 lb. In the standard procedure, the sample is compacted in three equal layers, each by 25 uniformly distributed

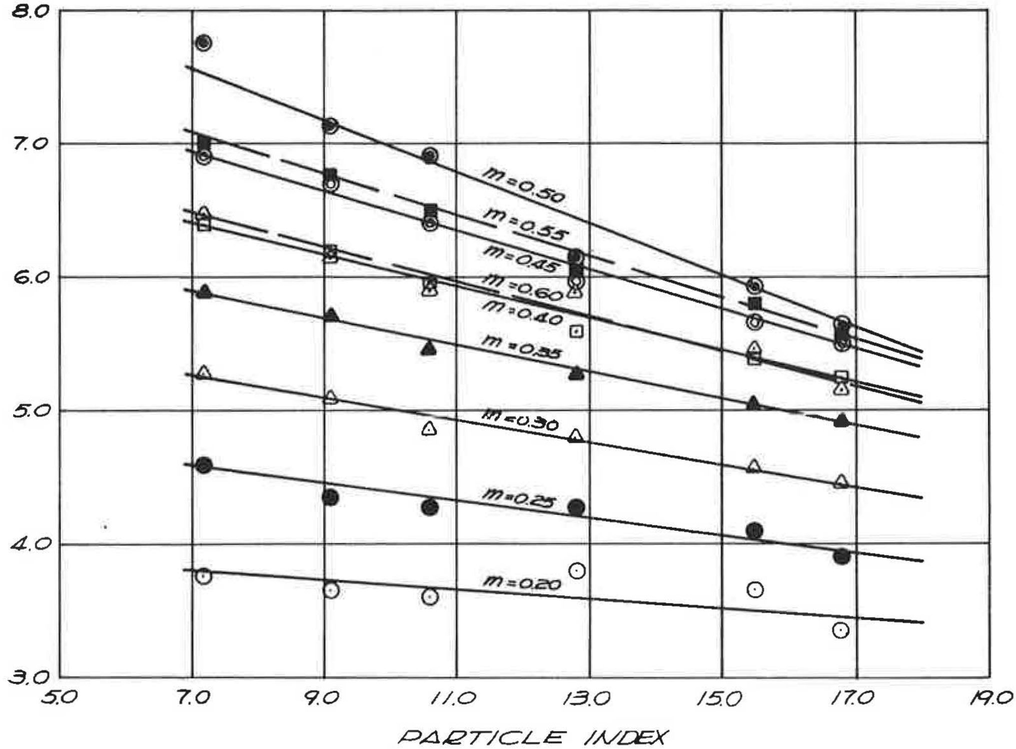

Figure 3. Relation between compaction characteristics of soil-aggregate mixtures and particle index of coarse aggregates for various mixture gradations.

blows from the rammer, dropping free from a height of 12 in. above the elevation of the material to be compacted. The moisture content of the specimen is determined by taking a small moisture sample from the center of the compacted material, after the specimen has been weighed and removed from the mold, and then drying it in an oven to constant weight.

Owing to the large quantity of aggregate materials in most soil-aggregate mixtures in this investigation, a variation from the standard method of determining moisture content was found necessary. To determine the moisture content more accurately, the entire soil-aggregate mixture, rather than a small moisture sample, was used for its determination. In this connection, the soil-aggregate sample was oven dried before mixing with water. By knowing the oven-dry weight of the soil-aggregate sample and being careful to prevent evaporation and not to lose any material during the compaction process, the moisture content of the soil-aggregate mixture was determined before each compaction trial simply by dividing the amount of water that had been added by the original oven-dry material expressed as a percentage.

The preceding procedure was first suggested by Ziegler (7) and was used with considerable success in this investigation. It permitted the use of a relatively small quantity (3,000 g) of soil-aggregate sample for a complete test. In addition, the moisture-density relationship curve was determined within the comparatively short period of time of approximately 3 hr.

In the determination of the weight-volume relationships of the soil-aggregate mixtures, corrections were made for the volume of water that was absorbed by the aggregate particles during the compaction test. This portion of water varied with the kind of aggregate material as well as the general shape of the particles. Generally speaking, the absorption of the three crushed stone samples was more or less the same (1.0 percent) but was much lower than that of the gravel samples. Among the gravel samples,

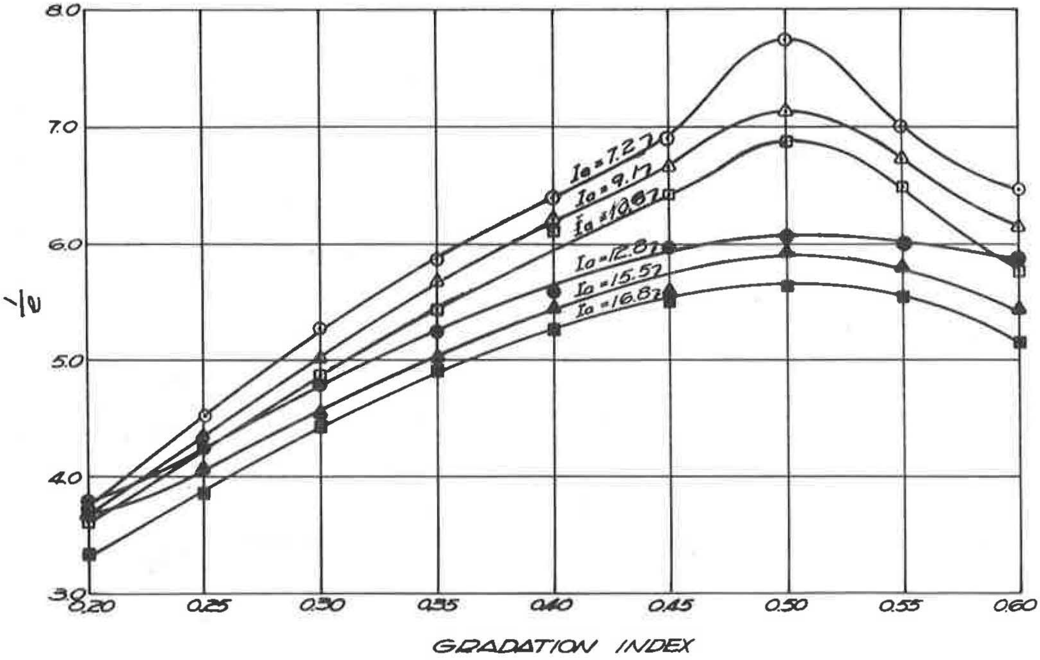

Figure 4. Relation between compaction characteristics and mixture gradation for soil-aggregate mixtures containing coarse aggregates of varying particle index.

the one with flat particles had the highest absorption (5.0 percent) and that with the bulky particles the lowest absorption (3.0 percent). Because only the volume of water in the void space of a soil-aggregate mixture was used in the volumetric analysis, the amount of water absorbed by aggregates, which had been predetermined in the laboratory, was excluded from the total water added in the determination of the void characteristics of the mixtures.

RESULTS

From the results of the compaction tests, the void characteristics of each mixture were analyzed at maximum dry density and optimum moisture content. In the presentation of these data, use has been made of the reciprocal value of the void ratio:

$$e = V_v/V_s \quad (2a)$$

in which

V_v = total volume of voids; and
V_s = the volume of solids.

Hence,

$$1/e = V_s/V_v \quad (2b)$$

The reciprocal of the void ratio affords a convenient basis for comparing the compaction characteristics of soil-aggregate mixtures containing particles of different specific gravities. A low reciprocal value of the void ratio indicates a low solids content per unit volume of compacted soil-aggregate mixture.

Figure 3 gives the relation between the reciprocal voids ratio of various soil-aggregate mixtures and the particle index of their coarse aggregates. The particle index for each mixture is the weighted average of the values for the three sizes of aggregate particles given in Table 2 on the basis of their weight percentages. The plot clearly demonstrates that the particle index or the geometric characteristics of the coarse aggregates

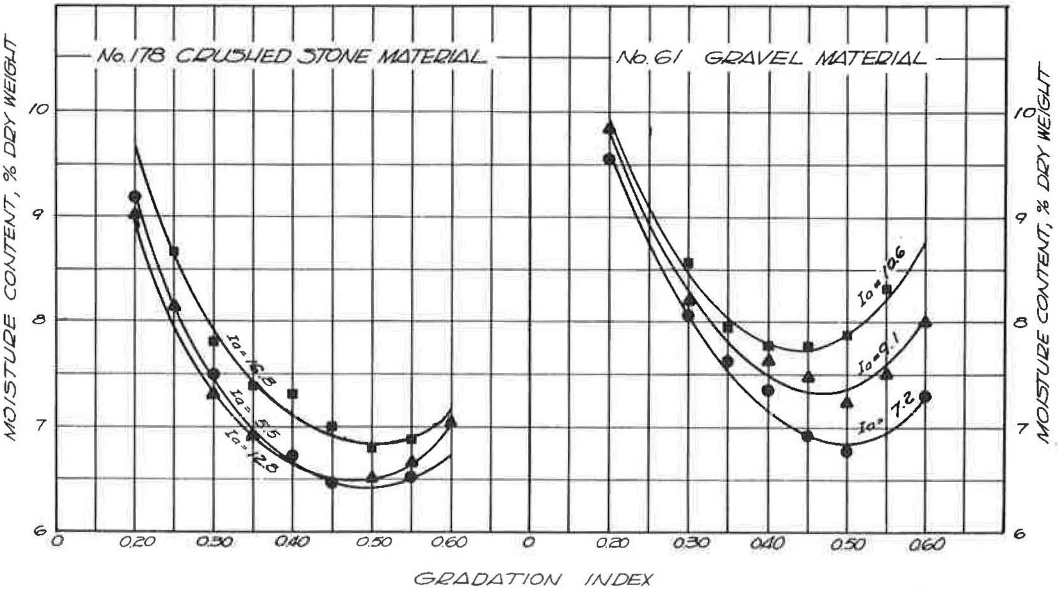

Figure 5. Relation between moisture content and mixture gradation for soil-aggregate mixtures containing coarse aggregates of varying particle index.

in the mixture was an influencing factor on the resultant void characteristics of the compacted sample. More specifically, the volume of the voids in the soil-aggregate mixtures of a given gradation under a standard laboratory compaction condition increased more or less linearly with increasing values of the particle index of the coarse aggregates. It must be noted that the particle index reflects the combined features of shape, angularity, and surface texture of an aggregate mixture, and that the value becomes progressively smaller as the aggregate particles become more spherical, rounded, and smoothly surfaced. It is obvious that aggregate particles with a small particle index would slip more readily over one another when exposed to a compactive effort than would the aggregates with a larger particle index. Hence, the former would form a more closely knit aggregate pattern and thus contain less void space than the latter.

Also, the significance of the particle index of the coarse aggregates on the resultant void characteristics of the compacted samples appears to increase with increasing values of gradation index until the optimum value of 0.50 is reached. After this point is reached, the significance becomes less apparent with further increases in gradation index values. This relationship is indicated by the change in slope of the lines in Figure 3 for increasing values of gradation index.

Figure 4 shows the reciprocal void ratios of various soil-aggregate mixtures are plotted against their corresponding gradation indexes. The data indicate that, for the soil-aggregate mixtures containing coarse aggregates of given geometric characteristics, there was one gradation value at which minimum void space in the compacted soil-aggregate sample was consistently obtained. This particular value of gradation index as indicated from this series was equal to 0.50. This gradation seems to represent the most desirable number of particles of any particular size in the mixture such that the voids within any particle size were filled by those of a smaller size, regardless of the geometric characteristics of these particles. This gradation index represents the ideal grading curve for maximum density developed by Fuller. Also, similar results have been shown by previous investigators (8).

Figures 3 and 4 also show that the minimum void space for a given soil-aggregate mixture under a particular compactive condition may be obtained by adjusting the gradation of the mixture. However, this minimum void space obtainable from a soil-aggregate mixture containing coarse aggregates of a given particle index is definitely limited as indicated by the straight line representing the gradation index of 0.50 in Figure 3. Further, the lines in that figure representing the various gradations tend to converge toward the higher values of particle index. Any adjustment in gradation in this range of higher particle index values will, therefore, have little influence on the resultant void characteristics of the compacted samples.

Figure 5 shows the influences that the particle index and the gradation had on the optimum moisture content of various soil-aggregate mixtures. There is a general trend in this plot indicating that soil-aggregate mixtures containing coarse aggregates with a smaller particle index also required a smaller optimum moisture content for effective laboratory compaction. Although Figure 4 shows that the void space is a minimum for a gradation index of 0.5 for all soil-aggregate mixtures, the curves in Figure 5 indicate that optimum moisture content for this gradation is also a minimum and that, with an increase in void space on either side of the optimum gradation index 0.50, there is a corresponding increase in optimum moisture content for effective compaction. Because the presence of moisture in the sample tends to facilitate the rearrangement of the soil and aggregate particles into a condition of minimum void space, it would be expected that mixtures containing particles that were more spherical, rounded, and smoothly surfaced required less moisture to reach this condition. It may also be realized that at a gradation index of 0.50, the particular combination of aggregate and soil particles is such that a minimum of void space is inherent in the composition of the sample. If the void space in the sample is thus naturally minimized at a gradation index of 0.50, it stands to reason that a minimum of water will be present in the sample at this gradation as compared to other gradations.

SUMMARY AND CONCLUSIONS

In this investigation, use has been made of standard laboratory compaction procedure with certain modifications in an attempt to gain information concerning the effect of the geometric characteristics of coarse aggregate particles, as indicated by the "particle index," on the void characteristics of compacted soil-aggregate mixtures. The coarse aggregate materials employed in this study included both pit-run gravel and crushed stone materials. The soil-aggregate materials were artificially prepared according to a mathematical expression to yield nine different and fully controlled gradations. From the results of the testing, the following conclusions have been drawn:

1. The geometric characteristics of the coarse aggregates, as indicated by the "particle index," have a definite bearing on the resultant void characteristics of a compacted soil-aggregate mixture. There appears to be an almost linear relationship between void content in a compacted sample and the particle index of the coarse aggregate. The percentage of voids in a compacted sample increased with increasing values of particle index.
2. For the soil-aggregate mixture containing coarse aggregates of given geometric characteristics, there is an optimum gradation index at which maximum dry density is achieved under a given compactive effort. For a mixture with a ¾-in. maximum aggregate size, this gradation index is equal to 0.50. The optimum moisture content is also a minimum for this gradation.

The data in this investigation indicate convincingly that there is more to consider than gradation in the evaluation of void characteristics and that a definite relationship exists between the particle index of the coarse aggregates and the void characteristics of the compacted soil-aggregate mixture. For a soil-aggregate mixture containing coarse aggregates of given geometric characteristics under a particular compactive effort, it is possible to increase its maximum dry density by varying its gradation. However, the maximum density obtainable is much limited for a mixture containing coarse aggregates having a very high particle index.

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