

Voids in One-Size Surface Treatment Aggregates

JOHN L. SANER and MORELAND HERRIN

Respectively, Graduate Research Assistant and Professor of
Civil Engineering, University of Illinois

A fundamental concept used in the design of surface treatments is that the quantity of bituminous material needed is determined as the amount required to fill the voids between the aggregates to an optimum depth. This study was performed to determine the influence of aggregate characteristics on the void space in a one-size surface treatment aggregate. The laboratory investigation was conducted by spreading the aggregate one layer thick in a flat bottom pan and pouring known volumes of water into the container between the aggregate. By measuring the depth of the water and the volume of the voids, the percent voids could be computed.

The volume of the voids did not vary in direct proportion with the depth within the aggregate, as is assumed in current design methods. In general, the more rounded aggregates, such as the gravels, had a smaller volume of voids than the more angular crushed stone. In some instances, the difference in the percent voids produced by a change in shape of the aggregate was quite large. Regardless of the shape of the aggregate, the smaller aggregates had greater percent voids than the larger aggregates. The aggregate particles, when placed with their least dimension in a vertical direction, had less voids than when in random arrangement.

•IN DESIGNING surface treatments, perhaps the most important quantity to be computed is the amount of bituminous material that must be sprayed on the roadbed. In most of the existing design methods, this quantity is determined as the amount required to fill the voids between the aggregates to an optimum depth (Fig. 1). This fundamental concept was first stated by Hanson in 1935 (2). It is so simple and logical that it is used by most of the other design methods. Since there is a direct relationship between the voids space and the amount of bituminous material needed, this investigation has been performed to determine the influence of various aggregate characteristics on the void space in one-size surface treatment aggregates. Indirectly, this study should indicate which aggregate factors influence the amount of bitumen needed in a surface treatment construction.

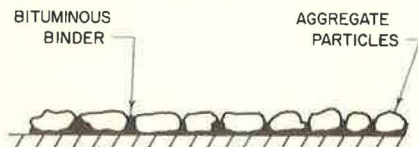


Figure 1. Cross-section of surface treatment.

VOIDS AS USED IN EXISTING METHODS OF DESIGNING SURFACE TREATMENTS

In his early investigations, Hanson (2) observed that the aggregate particles, when first dropped on the asphalt surface, are oriented in random directions; i. e.,

some are on edge, some are vertical, and others lie on their largest side. Hanson reported that the aggregates in this state had approximately 50 percent voids. After rolling and even under traffic loads, the aggregates tended to reorient themselves so that they presented their least dimension in the vertical direction. Under these conditions, Hanson reported, the voids between the aggregates were approximately 20 percent. Hanson and McLeod (6) indicate that this void volume is independent of the size of the cover aggregate, e.g., $\frac{1}{4}$, $\frac{1}{2}$, or $\frac{3}{4}$ in. Thus, it is thought by some investigators that the volume of voids in the surface treatment aggregate is only related to the position or orientation of the aggregate and is not influenced by the size or type of the aggregate.

Other investigators believe that the percentage of voids between the aggregate varies with the character or shape and surface texture of the aggregate. McLeod and engineers in Australia indirectly consider the shape by varying the amount of bituminous material needed to fill the aggregate voids to an optimum amount according to the type of aggregate (6). Other investigators, (1, 4, 5), indirectly consider the shape by determining the volume of the voids to be filled with bituminous materials directly by first placing aggregate in a large cylinder. Benson (1) and Kearby (4) weighed the aggregates and computed the percent voids by using the specific gravity of the aggregate. Mackintosh (5), on the other hand, measured the volume between the aggregate particles in the cylinder by determining the quantity of water needed to fill the voids. In both cases, the assumption is made that the aggregate in the one-stone thick layer will have the same arrangement and voids on the road surface as it will have in the cylinder. This assumption is probably not true. Benson (1) even acknowledges that this assumption is incorrect, but he uses it nevertheless.

No design method considers that the volume of voids may vary other than linearly with depth. For example, it is considered that, if a $\frac{3}{4}$ -in. aggregate (with 24 percent voids) is to be filled with bituminous material to one-half its depth, the volume of the voids to be filled would be $\frac{1}{2} \times 24 = 12$ percent. In other words, in design, it has always been assumed that the voids vary directly with the depth in the aggregate.

In summary, some investigators think that the percent voids in a layer of aggregate one stone thick is a constant value for all aggregates and is only related to the orientation of the aggregate. Other investigators think that the percent voids is related to the shape and, possibly, to the size of the aggregate. No design method, however, considers that the voids may vary with depth within the aggregate.

A number of aggregate characteristics, therefore, could possibly influence the volume of voids, but only the following factors were investigated in this study: (a) depth in the aggregate layer, (b) maximum size of the aggregate, (c) particle arrangement, and (d) shape of the aggregate. In addition, it should be noted that the investigation is limited only to one-size surface treatment aggregates.

PROCEDURE

The procedure used to determine the volume of the voids in the aggregate layer was relatively simple. After the aggregate was washed, it was allowed to soak completely immersed in water for at least 12 hr. Just before testing, the aggregate was dried until it was in a saturated surface dry condition. This soaking and drying was done to account for the absorbent powers of the aggregate. The aggregate was then spread one layer thick in a flat bottom container. Care was taken to place the aggregate, by hand, in the desired particle orientation.

Measured volumes of water were then poured into the container and allowed to flow into the void spaces between the aggregate particles. The depth of this known volume of water was measured. Depth measurements were made at regular intervals of water volume, starting at the lowest possible depth of water up to the point at which the aggregate layer was completely immersed. Data were verified by repeating this procedure, including a re-soaking and drying of the aggregate.

With the depth, the volume of water in the pan at that depth, and the surface area of the bottom of the pan known, the percentage voids could be calculated by the following simple computation:

$$\text{Percent voids} = \frac{\text{Volume of water at depth } d}{\text{Area of bottom of pan} \times \text{depth } d} \times 100$$

This method of computing percentage voids should not be confused with other methods. It is the percentage voids in the aggregate layer below the surface of the water, not a percentage of the total voids in the aggregate layer nor a percentage of the total volume of the whole aggregate layer. This particular method of defining percent voids was chosen because of its simplicity and because the total volume or the total depth of the aggregate layer cannot be defined exactly due to variations in aggregate particle size.

Not only are the data presented in terms of percent voids, but also as volume of voids in gallons per square yard. This was done in specific instances to present the data in a manner that is more useful for illustrating points.

EQUIPMENT

The equipment used for testing was very simple in design. The pan was constructed of $\frac{3}{8}$ -in. thick aluminum and was approximately 5 in. deep and 3 ft square. The bottom of the pan was flat and so rigid that no deflection took place. The instrument used for depth measurement was a standard penetrometer normally used in bituminous material testing. The penetrometer was removed from its base and the vertical rod on which it is raised and lowered was clamped with a C-clamp into one corner of the pan at a location where a few particles of aggregate had been removed. (Because of the large size of the test pan, the removal of the few aggregate particles had little effect on the results.) First the needle was gently lowered until it was just touching the bottom of the pan. After the dial was set at zero, the needle was raised and relowered until the point was just touching the surface of the water. This point could be seen relatively easily by looking at a light reflection on the surface of the water. The dial was then adjusted and measurements of the depth were taken and recorded in 0.1-mm increments. Each depth measurement was repeated to insure against errors.

CALIBRATION OF TEST EQUIPMENT

A micrometer was used to check the penetrometer's accuracy in measuring distances. The needle movement was measured by the dial and with the micrometer through various distances all starting with zero, as in the testing procedure. The penetrometer was found very accurate in its readings.

Proof was needed that this method of investigation did measure the volume of the voids and that some unknown factor did not create a significant error. A procedure was needed by which the percentage of voids could not only be measured, but also computed by simple geometry. For this purpose, polished aluminum spheres of $\frac{5}{8}$ -in. diameter were used as aggregate. The spheres were placed in the pan in a single layer with a close-packed arrangement. Void data given in Table 1 were then obtained by the procedure previously outlined. A plot of the theoretical and experimental data is shown in Figure 2. This figure reveals that the measured values of percent voids, at depths below that at which the minimum percentage of voids occurs, were about 3 to 4 percent greater than the theoretical values. At depths above the minimum, the measured values were about 3 percent lower than the theoretical ones. At the depth of minimum percent voids and above the depth of the spheres themselves (i. e., when the spheres were completely covered with water), the experimental data agreed very closely with the theoretical calculations.

A definite phenomenon caused the deviation of the experimental from the theoretical results at some depths, although there was a close agreement at others. At depths below which the minimum percent voids occurred, $\frac{3}{4}$ of the diameter of the perfect spheres, the water was clearly observed to be drawn up around the spheres by means of surface tension, causing a concave upward surface on the water between adjoining spheres. Since the depth measurements were taken at a location where one sphere had been removed and the water was not drawn up as much, the measured depth was less than the average water depth in the pan. This lower depth, caused by a smaller drawing up where the sphere was missing, is produced in much the same way that

water rises in a tube due to capillary action. The smaller the diameter of tube, the higher the capillary rise will be. The percentage voids computed was therefore too large. Above the depth at which the minimum voids occurred, an opposite effect was clearly observed. The water was held down around the spheres by surface tension, causing a concave downward surface on the water between spheres. This caused the depth at the location where the depth measurement was taken to be slightly greater than the average water depth in the pan. This larger measured depth caused the computed percentage of voids to be smaller than the theoretical.

TABLE 1
CALIBRATION OF EQUIPMENT^a

Trial 1		Trial 2		Trial 3	
Depth (in.)	Voids (%)	Depth (in.)	Voids (%)	Depth (in.)	Voids (%)
0.197	64.2	0.205	60.8	0.181	68.8
0.327	40.5	0.331	40.3	0.323	41.4
0.437	32.4	0.437	32.7	0.437	32.7
0.504	30.1	0.484	31.8	0.484	31.8
0.535	30.4	0.563	31.3	0.547	32.1
0.563	30.9	0.598	33.2	0.597	33.4
0.579	32.0	0.634	34.9	0.614	36.0
0.598	32.9	0.638	37.7	0.650	37.3
0.634	34.7	0.650	41.2	0.665	40.2
0.646	37.6	0.657	44.2	0.657	44.2
0.650	40.8	0.689	45.5	0.689	45.5
0.661	43.6	0.709	47.7	0.728	46.2
0.685	45.5	-	-	-	-
0.705	47.5	-	-	-	-

^aUsing $\frac{5}{8}$ -in. diameter spheres in close-packed arrangement.

At the depth at which the minimum percent voids occurred, the effect of the surface tension was negligible and there was essentially no drawing up nor holding down of the water between adjacent spheres. Therefore, exact readings of depth were taken and the computed percent voids compared very closely with the theoretical. Also, at depths of water above the top of the spheres, when the spheres were completely immersed, the surface tension did not have any effect between the adjacent spheres, and the experimental data compared closely with the theoretical.

The data taken on the aggregate samples might be assumed to be similarly incorrect. This is not believed to be true, because the effect caused by the surface tension of the water was not observed when the aggregates were tested. This phe-

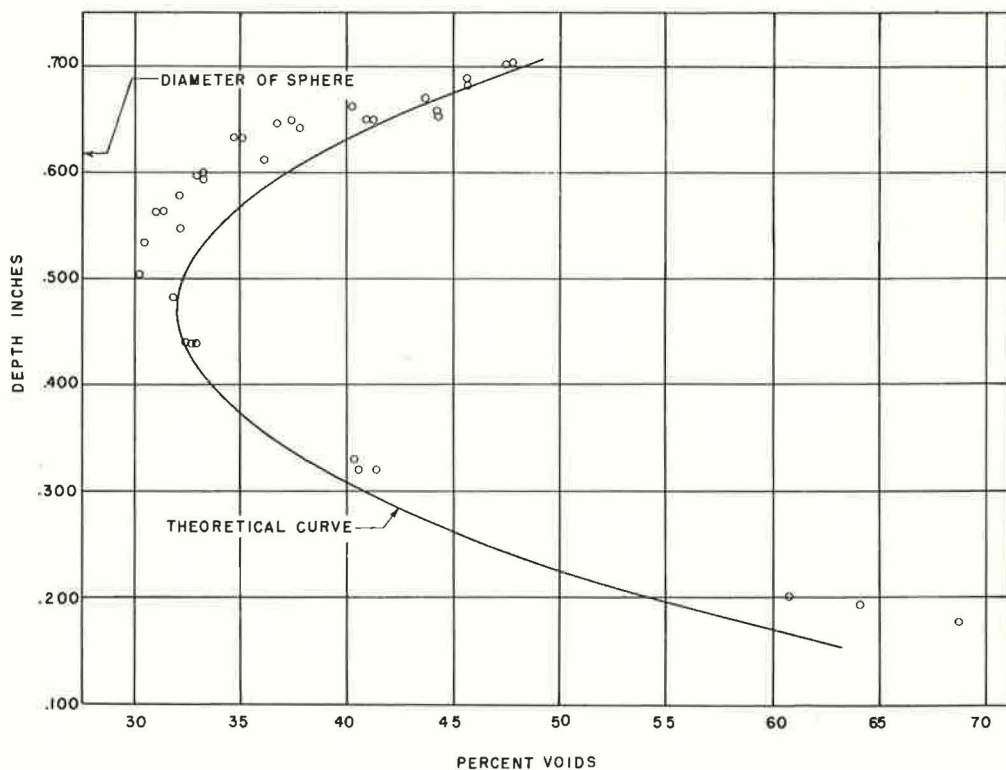


Figure 2. Calibration of equipment, $\frac{5}{8}$ -in. diameter spheres, close-packed arrangement.

nomenon of drawing up and holding down of the water by the polished aluminum spheres did not take place with the aggregate because the latter does not have the uniformity of shape nor the exceptional smoothness of surface usually necessary for this type of effect to take place. The measurements of depth taken with the various samples of aggregates should be very close to the average depth in the pan. Therefore, the computed values of percent voids in this investigation should compare very well with the actual percent voids in the aggregate layer.

AGGREGATES USED

In the investigation it was desired to determine what effect aggregate types and sizes had on the volume of the voids in an aggregate layer. A wide variety of types and sizes of aggregates were obtained. Seven different shapes of aggregates, ranging from crushed stone to rounded gravel, were used and are listed in Table 2. All of these aggregate samples were one size; i. e., they were materials retained between two sieves in a standard arrangement of sieves. The sizes used were 1/2 to 3/4 in., 3/8 to 1/2 in., 1/4 to 3/8 in., and No. 4 to 3/8 in. Because sieving does not allow a perfect sizing of aggregates of equal size, one size, as used here, does not mean a perfect uniformity of size. There was some variation in size within these aggregate samples. Table 2 gives other data pertaining to the aggregate, which are explained in the next section.

VARIATION IN PERCENT VOIDS WITH DEPTH WITHIN AGGREGATE LAYER

When the test procedure was being developed, questions arose as to what depth in the aggregate layer the percent voids measurement should be made, and if the percent voids at some particular depth would give an adequate parameter for describing the aggregate sample. To answer these questions, measurements were taken in intervals from the smallest possible depth to a point up to and a little beyond where the aggregate layer was completely immersed.

Figures 3 and 4 show how the percent voids and volume of voids varied with depth in the aggregate layer. Although the aggregate used in this example was a crushed limestone of 1/2 - to 3/4 -in. size, the results presented here are typical of those obtained from other sizes and types of aggregates.

The data presented in Figure 3 indicate that the percent voids varies with depth and has a minimum value that occurs at a depth slightly above one-half the maximum size of the aggregate (3/8 in.). Figure 4 shows that the plot of volume of voids vs depth is a smooth curve with the top and bottom parts of the curves approaching straight lines. If the volume of voids varies linearly with the depth within the aggregate layer, this curve should be a straight line. However, the relationship is not linear and, thus, the

TABLE 2
AGGREGATE TYPES AND PARAMETERS

Symbol	Type	Size	Parameters		
			Intersection Depth (in.)	Intersection Vol (gal/sq ft)	Min. Void (%)
No. 61	Gravel	1/2 - 3/4 in.	0.443	0.972	41.6
No. 178	Crushed stone	1/2 - 3/4 in.	0.479	1.076	48.3
75-25 ^a	Mixture Nos. 61 and 178	1/2 - 3/4 in.	0.457	0.881	36.0
50-50 ^a	Mixture Nos. 61 and 178	1/2 - 3/4 in.	0.440	0.880	42.8
No. 178 (a) ^b	Crushed stone ^b	1/2 - 3/4 in.	0.428	1.030	47.4
75-25	Mixture Nos. 61 and 178	3/8 - 1/2 in.	0.311	0.684	49.2
50-50	Mixture Nos. 61 and 178	3/8 - 1/2 in.	0.313	0.693	45.4
No. 61	Gravel	3/8 - 1/2 in.	0.376	0.827	45.2
No. 178	Crushed stone	3/8 - 1/2 in.	0.343	0.750	50.8
MC(a) ^c	Mine chat ^c	3/8 - 1/2 in.	0.354	0.861	50.2
Cr. Gr.	Crushed gravel	3/8 - 1/2 in.	0.317	0.817	50.8
No. 61	Gravel	No. 4 - 3/8 in.	-	-	48.0
No. 178	Crushed stone	1/4 - 3/8 in.	-	-	54.3

^aMixture (by weight) 75 percent No. 61 and 25 percent No. 178.

^bCrushed stone No. 178 is stone as received from plant; No. 178 (a) is stone No. 178 sorted to contain more cubical particles.

^cMine chat sorted to contain more cubical particles.

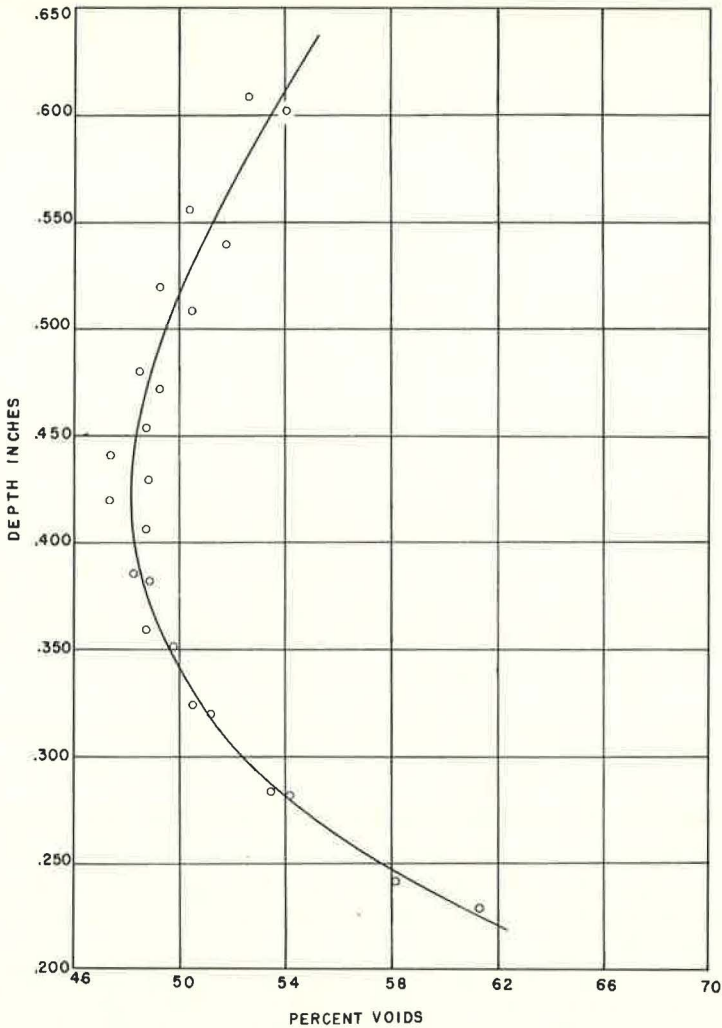


Figure 3. Variation in percent voids with depth, crushed stone No. 178, $\frac{1}{2}$ - to $\frac{3}{4}$ -in. size.

volume of voids does not vary in direct proportion with depth. This is a major difference from what has been assumed in many current methods for designing surface treatments.

The variations in percent voids and volume of voids with depth were studied to determine if some value could be used as a parameter in describing the aggregate. Three aggregate parameters were investigated. From the curve of percent voids vs depth, the minimum value of percent voids was used as one parameter. From the curve of volume of voids vs depth, two other parameters were determined by the following method. The straight portions of the curve were extended until they intersected as shown in Figure 4. The coordinates of this intersection were then used separately as parameters; i. e., one parameter is the volume of voids at this intersection and the other is the corresponding depth. The values of these parameters for the various aggregates are given in Table 2. The use of these parameters is more fully explained in the discussion of the variation in percent voids with shape.

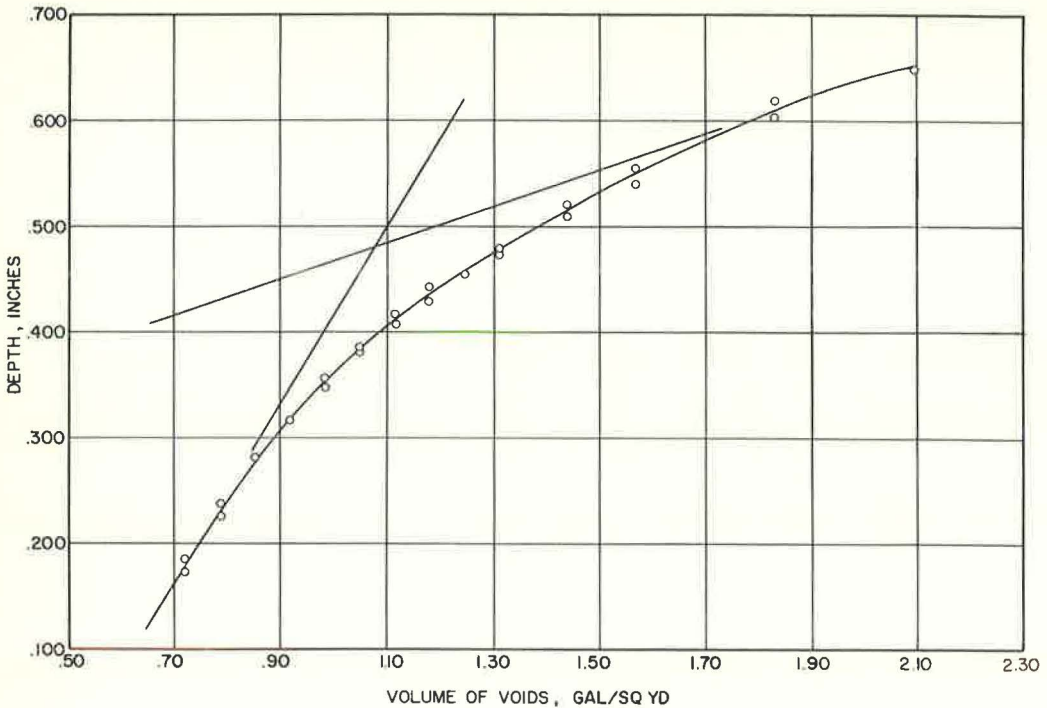


Figure 4. Variation in volume voids with depth, crushed stone No. 178, $\frac{1}{2}$ - to $\frac{3}{4}$ -in. size.

VARIATION IN PERCENT VOIDS WITH SIZE OF AGGREGATE

Tests were performed on two types of aggregates at three different sizes of each type: $\frac{1}{2}$ to $\frac{3}{4}$ in., $\frac{3}{8}$ to $\frac{1}{2}$ in., and No. 4 to $\frac{5}{8}$ in. The aggregate types used were an angular crushed stone and a rounded gravel. The results of this series of tests are shown in Figures 5 and 6.

Regardless of the type, the smallest size aggregates had greater minimum percent voids than the largest sizes. This difference is quite significant, in some instances as great as 8 percent. Also, a comparison of Figures 5 and 6 indicates that the shapes of these curves are similar. A difference in aggregate type does not seem to have any effect on this phenomenon of increasing voids with decreasing size of aggregate, except perhaps on the magnitude of the increase.

VARIATION IN PERCENT VOIDS WITH PARTICLE ARRANGEMENT

We should first define aggregate particle arrangement. Hanson (2) observed that aggregate particles, when first spread on the asphalt surface in a surface treatment construction, will be oriented in various directions. In other words, there will be a random arrangement of the particles. Hanson also observed that after the surface treatment had been compacted by rolling and by traffic, the aggregate particles were all oriented with their least dimension in a vertical direction. These two particle arrangements, the random arrangement and the least dimension arrangement, were used in this study.

To study the effect of arrangement, tests were performed on three aggregate samples. The samples were a $\frac{1}{2}$ - to $\frac{3}{4}$ -in. crushed stone (type a), a $\frac{3}{8}$ - to $\frac{1}{2}$ -in. and a No. 4 to $\frac{5}{8}$ -in. gravel. Each sample was tested with the aggregate in both arrangements. The least dimension arrangement was carefully prepared by hand placing and orientating every aggregate particle in the pan so the least dimension was in the vertical direction. The random arrangement was prepared by sprinkling handfuls of the aggregate from a small

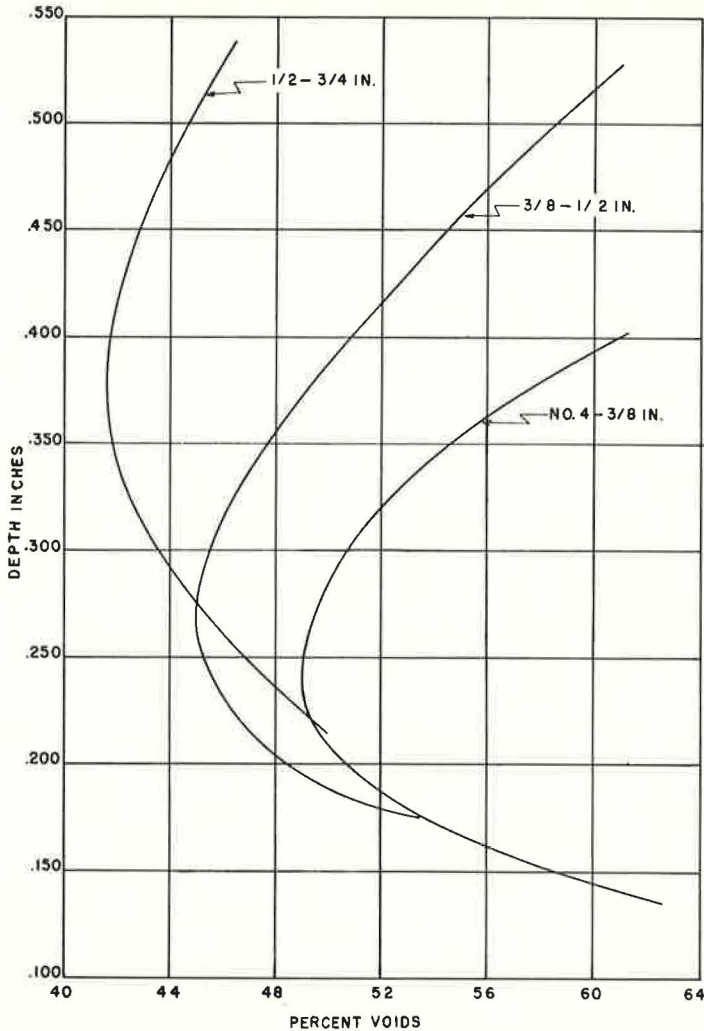


Figure 5. Variation in percent voids with depth for three sizes of gravel No. 61.

height onto the surface of the pan. In both arrangements, care was taken to keep the layer of the aggregate one particle thick.

The results obtained from these series of tests, shown in Figures 7, 8 and 9, indicate that arrangement has some effect on the percentage voids, but regardless of the type or size of aggregate, this effect is relatively small. In the random arrangement, the minimum percent voids is only approximately 4 percent greater than the minimum voids in the aggregate with the least dimension arrangement.

The decrease in the percentage of voids is considerably less than the percentage decrease often attributed to particle reorientation in actual construction. The decrease in percent voids that takes place when a surface treatment is compacted by rolling in the field may not be caused primarily by particle reorientation, but by some unknown factor, possibly resulting from a breakdown or degradation of the aggregate. This investigation was limited, however, to one-size aggregate and no definite statement can be made concerning the effect of aggregate gradation on the percentage voids. This is an area needing further investigation and study.

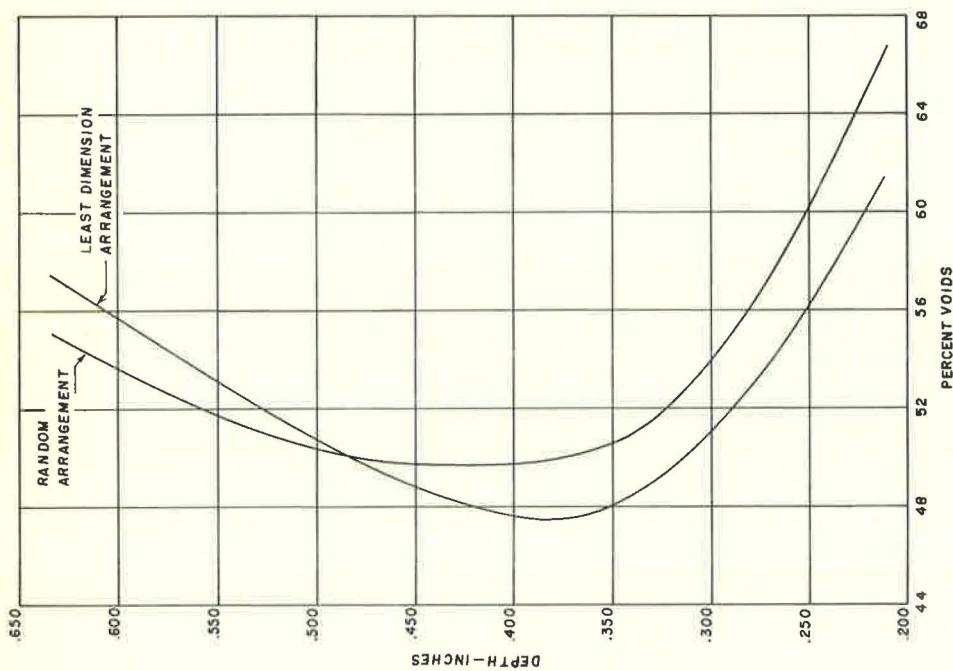


Figure 7. Variation in percent voids with depth for two different particle arrangements, crushed stone No. 178 (a), $\frac{1}{2}$ - to $\frac{3}{4}$ -in. size.

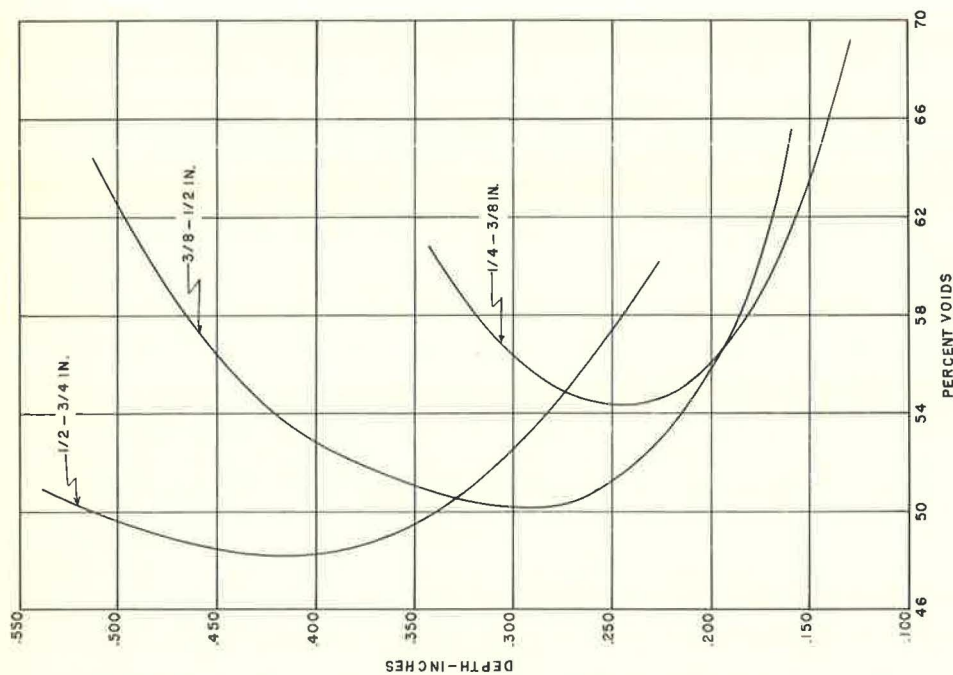


Figure 6. Variation in percent voids with depth for three sizes of crushed stone No. 178.

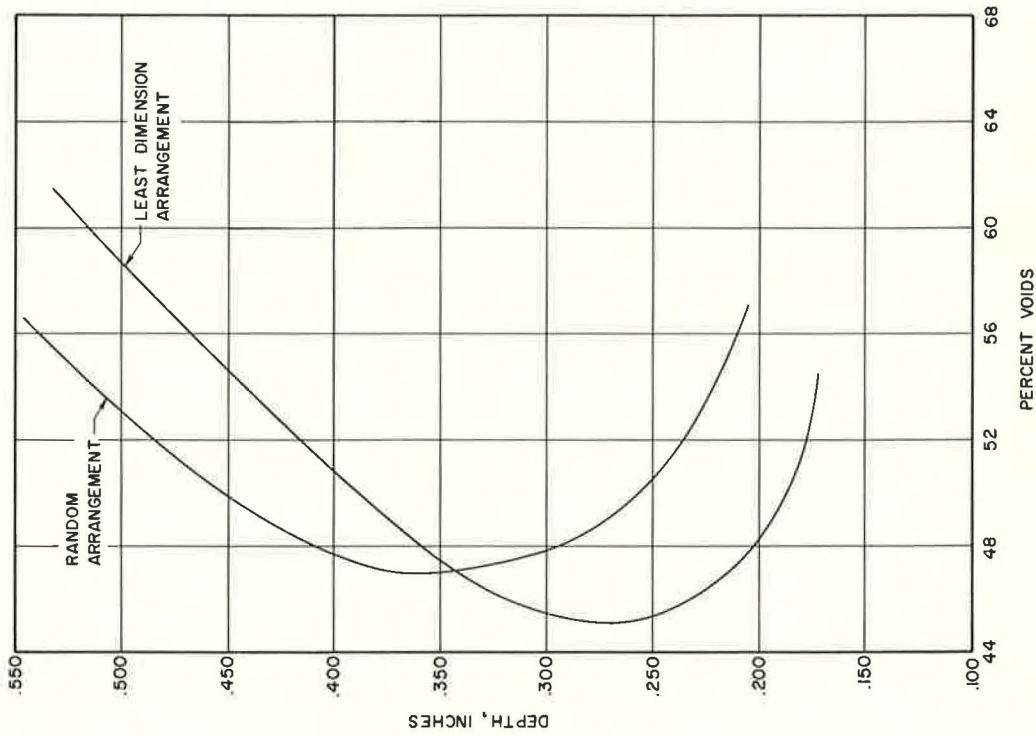


Figure 8. Variation in percent voids with depth for two different particle arrangements, gravel No. 61, $\frac{3}{8}$ - to $\frac{1}{2}$ -in. size.

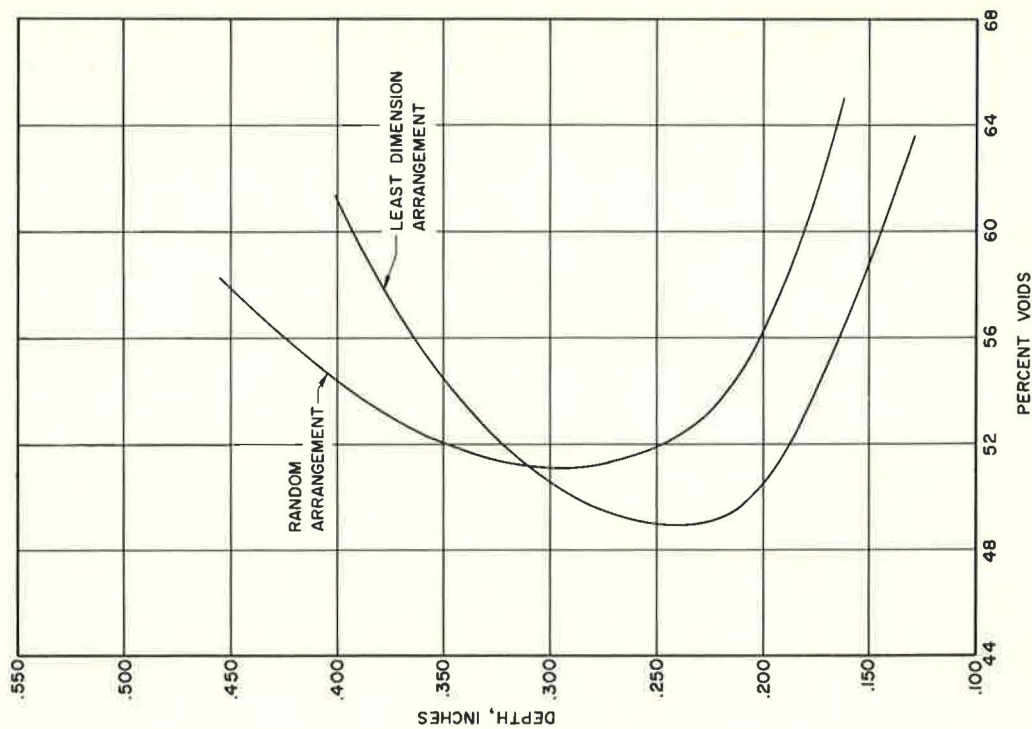


Figure 9. Variation in percent voids with depth for two different particle arrangements, gravel No. 61, No. 4 to $\frac{3}{8}$ -in. size.

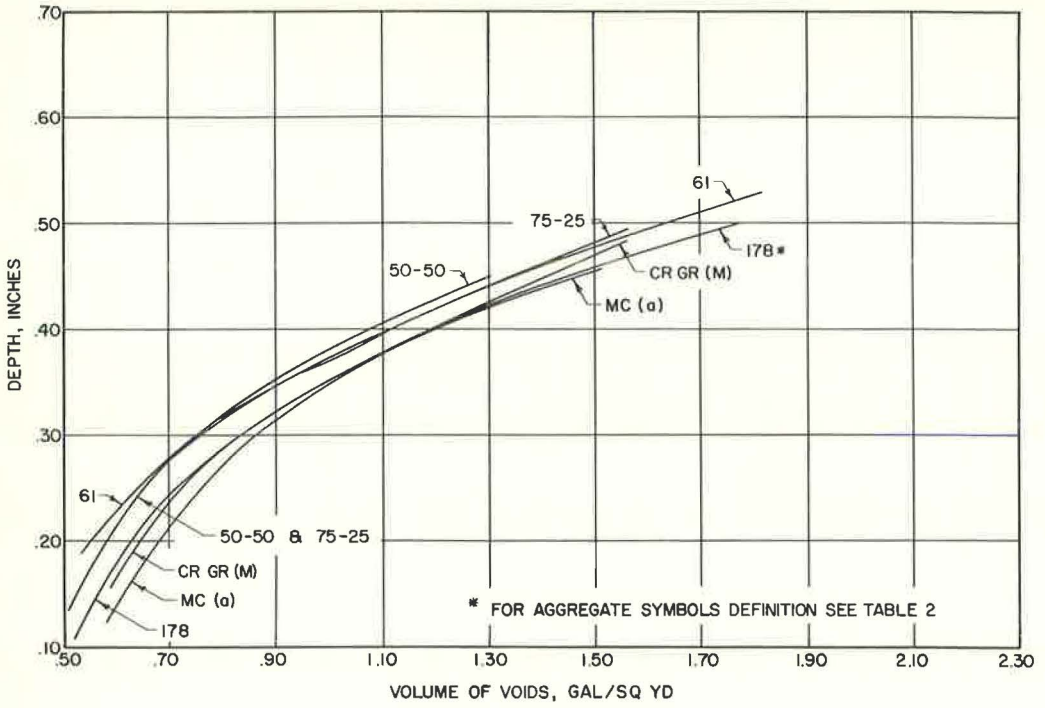


Figure 10. Variation in volume voids with depth for different aggregate types, $\frac{1}{2}$ - to $\frac{3}{4}$ -in. size.

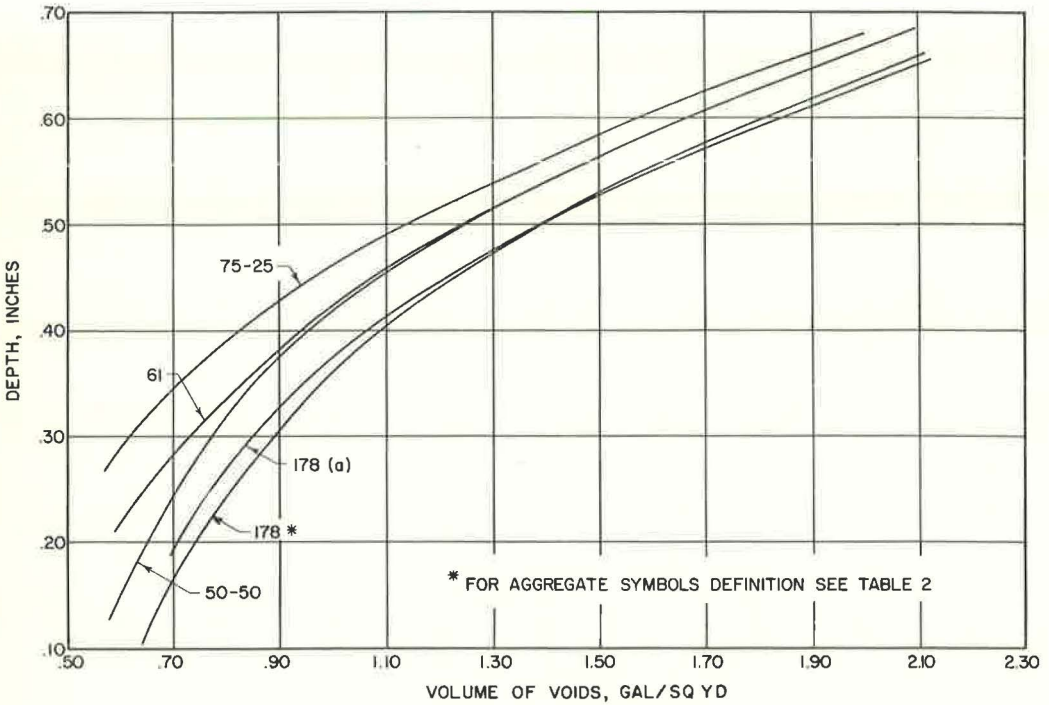


Figure 11. Variation in volume voids with depth for different aggregate types, $\frac{1}{2}$ - to $\frac{3}{4}$ -in. size.

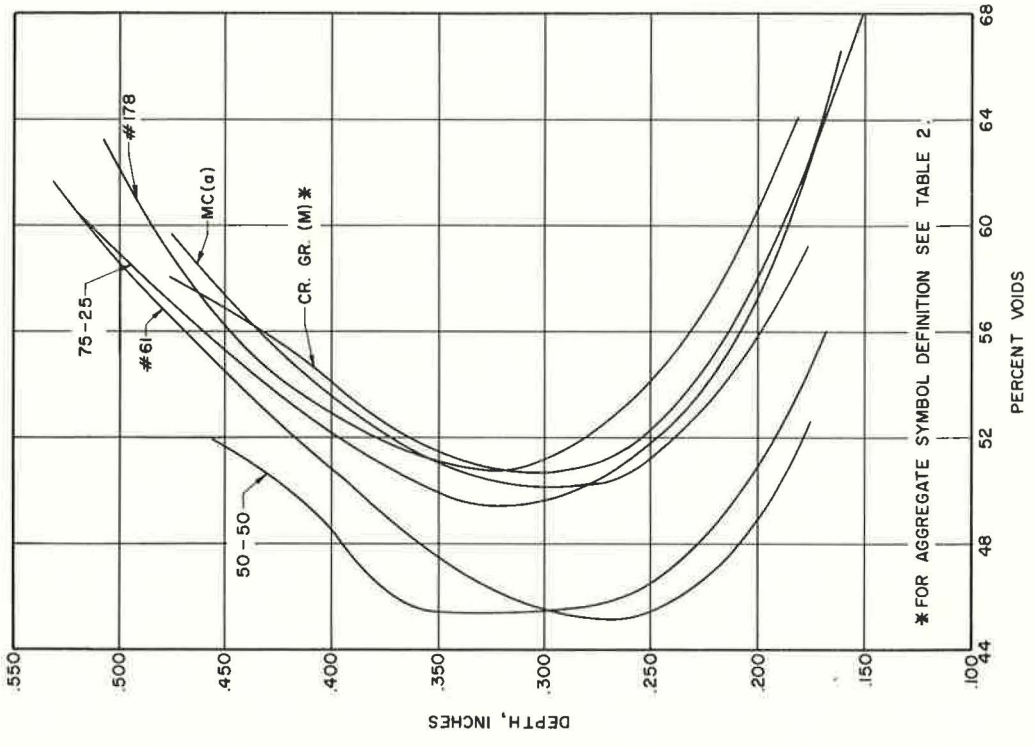


Figure 12. Variation in percent voids with depth for different aggregate types, $\frac{3}{8}$ - to $\frac{1}{2}$ -in. size.

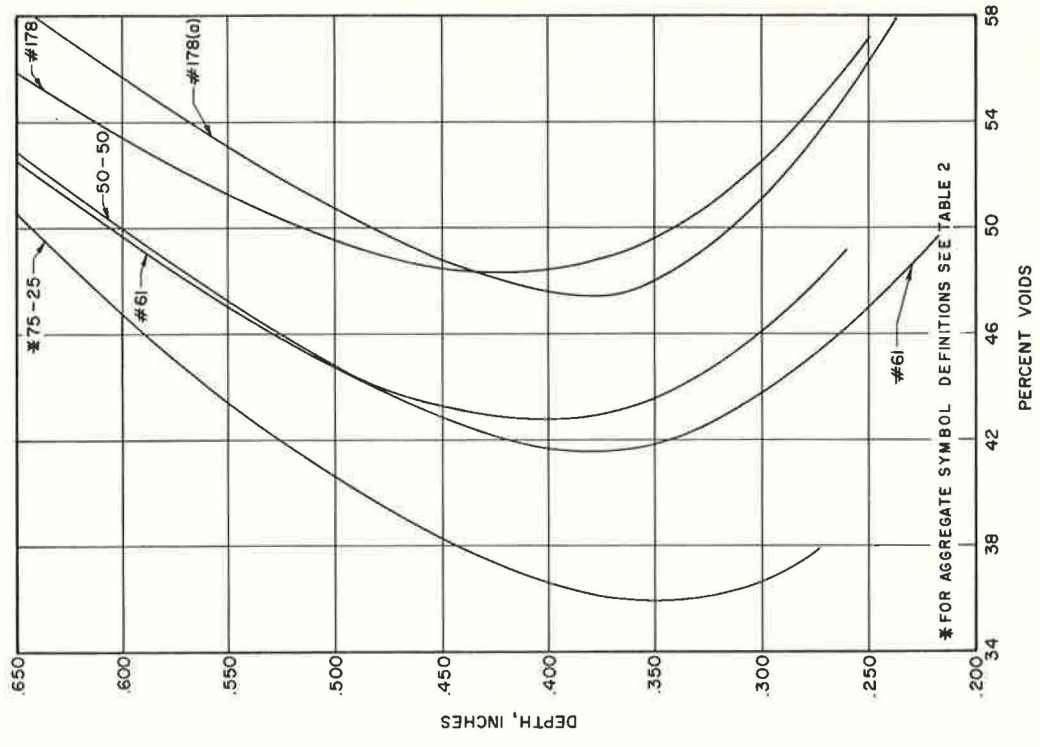


Figure 13. Variation in percent voids with depth for different aggregate types, $\frac{1}{2}$ - to $\frac{3}{4}$ -in. size.

VARIATION IN PERCENT VOIDS WITH SHAPE

Two questions need to be answered: Is the shape of the aggregate a significant factor in determining the quantity of voids for surface treatment design? If it is significant, how can the shape be accounted for in determining the amount of void space?

Some believe that differences in shape have little effect on the amount of void space in an aggregate layer. The data collected in this experiment indicated that this is not

TABLE 3
AGGREGATE SHAPE FACTORS

Aggregate		Shape Factor			
Symbol	Size (in.)	Compacted Voids (%)	Loose Voids (%)	Particle Index	Flakiness Index (%)
75-25	1/2-3/4	39.5	48.0	12.4	6.42
50-50	1/2-3/4	40.7	50.1	14.0	7.75
No. 61	1/2-3/4	37.9	46.5	12.2	7.60
No. 178	1/2-3/4	43.4	52.3	17.4	5.97
No. 178 (a)	1/2-3/4	42.8	50.8	13.4	-
75-25	3/8-1/2	-	-	13.6	10.10
50-50	3/8-1/2	42.0	51.2	15.0	10.04
No. 61	3/8-1/2	40.6	47.8	13.7	7.67
No. 178	3/8-1/2	43.8	52.6	18.4	8.64
MC (a)	3/8-1/2	41.8	48.2	-	-
Cr Gr (M)	3/8-1/2	40.6	48.4	-	-

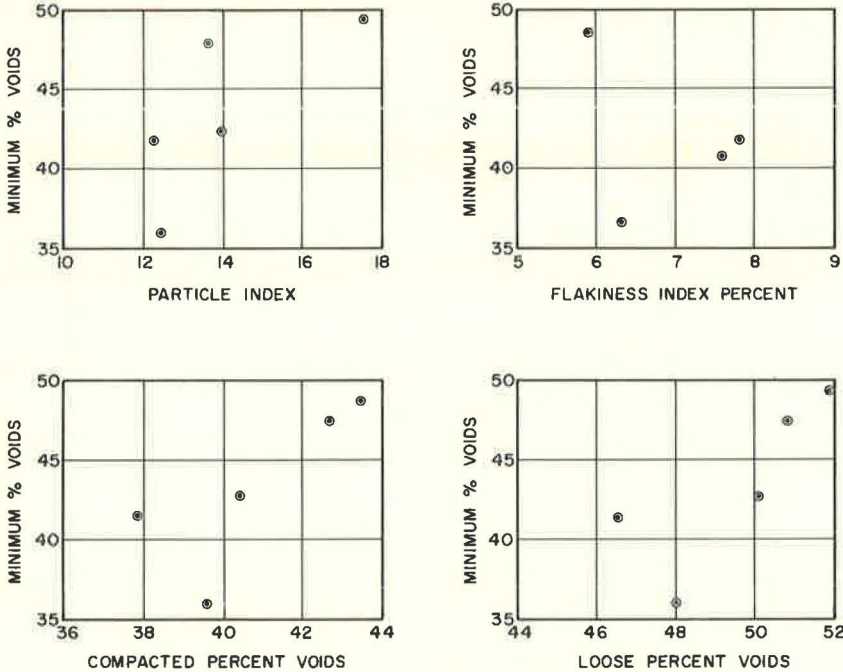


Figure 14. Variation of shape factors with minimum percent voids, 1/2- to 3/4-in. size.

true because a significant difference was found. This difference is illustrated in Figures 10 and 11 which show the variation of the volume of voids, in gallons per square yard, with depth, in inches, for aggregate samples of $\frac{3}{8}$ - to $\frac{1}{2}$ -in. and $\frac{1}{2}$ - to $\frac{3}{4}$ -in. size, respectively. The various curves in each figure represent aggregates of different shapes. In the $\frac{1}{2}$ - to $\frac{3}{4}$ -in. aggregate (Fig. 10), the difference between the greatest and the smallest value of volume of voids for the different aggregate samples was about 0.27 gal/sq yd. In the $\frac{3}{8}$ - to $\frac{1}{2}$ -in. aggregate, the difference was about 0.12 gal/sq yd. These are very significant differences in the amount of void space in an aggregate layer and, therefore, the shape of the aggregate should be considered in determining the quantity of voids.

In examining Figures 10 and 11, the range of values for the volume of voids may seem to be high when compared to values used in actual construction. The volume of voids ranges from values of 0.50 gal/sq yd to 2.10 gal/sq yd. These data are for a one-size aggregate and would most likely not be as high if the aggregate were a less uniform size or a graded aggregate. Also, the upper limit of the values of volume of voids may appear to be extremely high. Again, it must be realized that these data were obtained when the aggregate layer was completely immersed, and that by this method of investigation, when depths used are greater than the maximum size of the aggregate, there will be large values of volume of voids measured.

The data presented in Figures 10 and 11 are also presented in Figures 12 and 13 in terms of percent voids. A definite difference in the percentage of voids for the different aggregate shapes can be noted. The difference between the upper and lower values of minimum percent voids for the $\frac{1}{2}$ - to $\frac{3}{4}$ -in. aggregate samples was about 12 percent, whereas for the $\frac{3}{8}$ - to $\frac{1}{2}$ -in. aggregate samples the difference was about 6 percent.

Figures 10, 11, 12 and 13 show a general trend of the variation in voids with shape. The percentage voids in the crushed stone was approximately 6 percent greater than in the gravel. In other words, the more rounded aggregates, such as the gravels, have a smaller percentage of volume of voids than the more angular crushed stone aggregate.

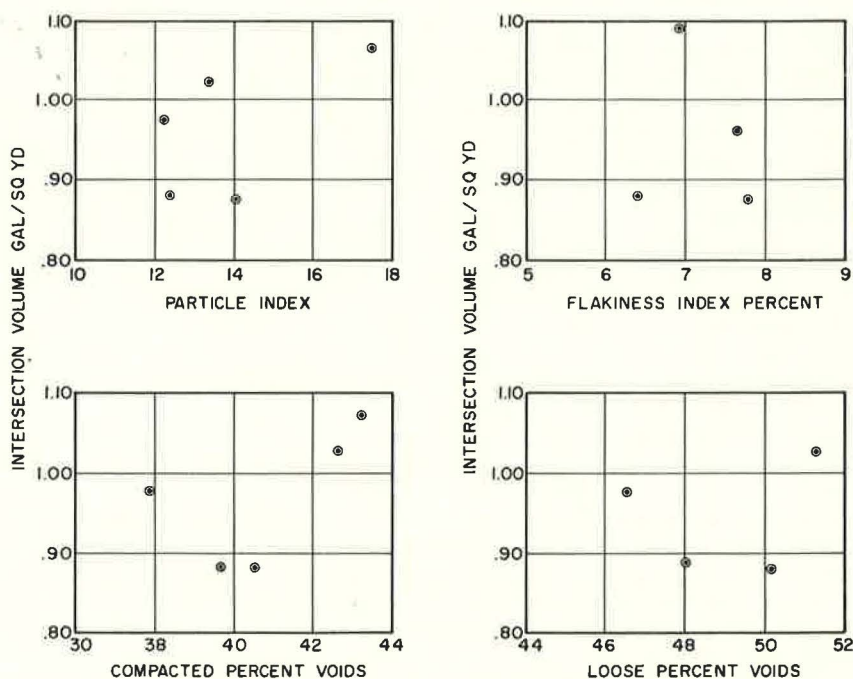


Figure 15. Variation of shape factors with intersection volume, $\frac{1}{2}$ - to $\frac{3}{4}$ -in. size.

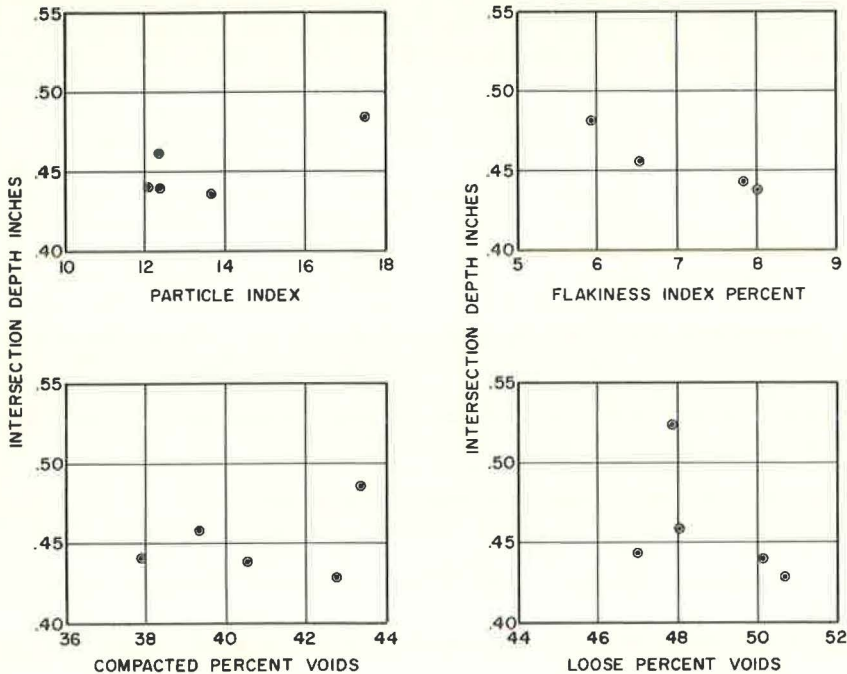


Figure 16. Variation of shape factors with intersection depth, $\frac{1}{2}$ - to $\frac{3}{4}$ -in. size.

An attempt was made in this investigation to determine a method that would compensate for aggregate shape in determining the volume of voids in an aggregate layer. This was done by attempting to correlate aggregate parameters with some shape factor. The parameters are the minimum percent voids and the intersection coordinates previously defined in the section on variation in percent voids with depth within the aggregate layer. The intention was to correlate the parameters with some easily obtainable shape factors so that these shape factors could be used in design to account for the differences in the volume of voids produced by various aggregate shapes.

The shape factors used were particle index, flakiness index, compacted percent voids and loose percent voids. The particle index of an aggregate is determined by a test developed by Huang (3). The test to determine the particle index is fairly time consuming and tedious, but has been used with fairly good results for soil-aggregate mixtures. The flakiness index is a British standard test developed by the County Roads Board of Victoria, Australia (British Standards Institution 812). It is a numerical index used primarily to determine the average least dimension of an aggregate, but it does take shape somewhat into account. The compacted and loose percent voids are simply the percent voids in the aggregate when it is placed in a $\frac{1}{10}$ -cu ft cylinder in its densest and loosest state. The numerical values of these four shape factors for the various types of aggregate are given in Table 3.

The relationships between these four shape factors and the three aggregate parameters of minimum percent voids, intersection volume, and intersection depth are shown in Figures 14, 15 and 16, respectively, for $\frac{1}{2}$ - to $\frac{3}{4}$ -in. aggregates. Data for aggregate of other sizes are similar to the data presented in these figures. None of these plots indicate that a logical relationship exists between the aggregate parameters and shape factors which could be used in a design method. Apparently none of these aggregate shape factors can adequately differentiate between the change in voids produced by different aggregate shapes.

Although no relationship was found in this investigation that would account for the variation in shape in determining the volume of voids, it is believed that the shape of

the aggregate must be considered in surface treatment design. If no significant relationship can be found utilizing aggregate shape factors, it may be desirable to utilize a direct measurement of the void space. Some design methods already utilize a direct measurement of void space by measuring the voids in the aggregate when placed in a hollow cylinder (1, 5). These methods do not give a true measurement of the void space because the aggregate in a surface treatment is in a single layer and not in a closely packed arrangement as it is when placed in the cylinder. Procedures similar to the one developed in this study could possibly be used to measure directly the volume of the voids in a single layer with some adaptation of the equipment for field use. Direct measurement could then possibly account for shape and differences in aggregates.

SUMMARY AND CONCLUSIONS

From the analysis of the data the following conclusions can be drawn concerning the influence of various factors on the void space in a one-size, one-particle thick, aggregate layer.

1. Contrary to the assumption made in many current procedures for designing surface treatments, the volume of voids does not vary linearly with depth within the aggregate layer. The relationship is curvilinear and varies with different aggregates.

2. The percent voids vary with aggregate size; as the aggregate size is decreased, the percent voids are increased.

3. The volume of voids tends to decrease as the particles are reoriented from a random placement to a position with their least dimension in a vertical direction. The decrease in volume is relatively small.

4. Aggregate samples of different shapes have significant differences in percent voids. This difference can be as much as 6 percent if the aggregate shape is changed from a rounded gravel to an angular crushed stone.

5. There is apparently no relationship between the aggregate parameters developed and used in this study and any of the following aggregate shape factors: particle index, flakiness index, voids in the compacted state or voids in the loose state. It seems that none of these aggregate shape factors can adequately differentiate between the change in voids produced by different aggregate shapes.

6. A suitable shape factor needs to be developed for design purposes that will tend to relate the volume of the voids to the shape of the aggregate. If this development is not possible, a direct measurement of the void space may be necessary.

ACKNOWLEDGMENTS

The research for this paper was conducted as part of the Illinois Cooperative Highway Research Project No. IHR-75, Basic Properties of Seal Coats and Surface Treatments. This project is conducted by the Engineering Experiment Station of the University of Illinois, in cooperation with the Division of Highways of the State of Illinois and the U. S. Bureau of Public Roads.

REFERENCES

1. Benson, F. J. Seal Coats and Surface Treatments. Proc. 44th Ann. Road Sch., Purdue Univ., Eng. Ext. Dept., Ser. No. 95, p. 73, Apr. 1958.
2. Hanson, F. M. Bituminous Surface Treatments of Rural Highways. Proc. New Zealand Soc. of Civ. Eng., Vol. 21, p. 89, 1934-1935.
3. Huang, Eugene Y. A Test for Evaluating the Geometric Characteristics of Coarse Aggregate Particles. Proc. ASTM, Vol. 62, 1962.
4. Kearby, J. P. Test and Theories on Penetration Surfaces. Highway Research Board Proc., Vol. 32, pp. 232-237, 1953.
5. Mackintosh, C. S. Rates of Spread and Spray in Bituminous Surface Dressing of Roads. Civ. Eng. of South Africa, Vol. 3, No. 10, p. 183, 1961.
6. McLeod, Norman W. Basic Principles for the Design and Construction of Seal Coats and Surface Treatments With Cutback Asphalts and Asphalt Cements. Proc. AAPT, Vol. 29, Suppl., 1960.

Discussion

RICHARD L. DAVIS, Technical Representative, Koppers Co., Inc., Tar and Chemical Div. — The authors are to be congratulated on writing a paper about voids in surface treatment aggregates. Although a tremendous amount of surface treatment work is done each year, the principles of good design for surface treatment construction are not very well understood. The measurement of the voids or space in surface treatment aggregates available for binder deserves study. The authors' finding that aggregate shape factors now in use cannot adequately differentiate between the change in voids produced by different aggregate shapes is very interesting.

The authors point out that the volume of voids does not vary linearly with depth within the aggregate layer for one-size aggregate, and they mention that it is usually assumed that the voids vary linearly with depth in most surface treatment design methods. Most surface treatment design methods, and specifically Hanson's design method, are concerned with the estimation of the voids or space in the mineral aggregate which will be available for bituminous material when the surface treatment has reached equilibrium under the compaction of traffic, rather than with the original void space. The voids in the mineral aggregate at equilibrium with traffic, although related to the original voids in the mineral aggregate, also depend on several other variables. Two of these are (a) the extent to which the aggregate voids are reduced when the aggregate particles are forced down into the old surface, and (b) the extent to which the aggregate voids are reduced when the aggregate particles are broken or degraded under the action of traffic.

Inasmuch as these two variables usually reduce the voids in a one-size aggregate to less than half the original value, and the contribution of each variable depends on a number of factors such as the resistance of the underlying surface to indentation and the resistance of the stone to degradation, the originators of surface treatment design methods have used a linear relationship in their design methods as is often done in complex situations when the true relationship is not very well understood.

The authors also state that voids increase as the aggregate size is decreased. Having had some experience with the method used by the authors to determine voids in the aggregate and being aware of the increasing difficulty of keeping the aggregate particles close together as the size of the particles become smaller, I can understand that greater void space was found with decrease in particle size. However, since the findings of many other investigators indicate that there is no change in void space with size of aggregate particles, it would appear desirable that the authors check their findings carefully for some explanation of the difference between their results and those of others.

This writer hopes that the authors will continue their work and that a practical, effective method of designing surface treatments will result.

JOHN L. SANER and MORELAND HERRIN, Closure—The discussion by R. L. Davis is sincerely appreciated. The authors will attempt to clarify the questions arising from this discussion. Mr. Davis points out that Hanson's design method is concerned with the void space in the mineral aggregate which will be available for bituminous material when the surface treatment has reached equilibrium under the compaction of traffic, rather than with the original void space. The authors agree that this concept is correct. The authors further agree that the reduction in voids is also due to other variables such as aggregate particle embedment and aggregate degradation. All that the authors were trying to point out in the paper is that only a small part of the reduction is due to particle reorientation from a random arrangement to a least dimension arrangement.

Mr. Davis also doubts the evidence obtained by the authors that the percent voids increases with decreasing aggregate size. He attributes this to the increasing difficulty of keeping the aggregate particles closer together as the size of the aggregate particles becomes smaller. The authors, in testing, did not notice this increasing difficulty. Even if this were true, would this not take place in the actual surface treatment?

Another factor that may have influenced test results, and one that had bothered the authors, was the effect of the surface tension of the water. It had been assumed from observing the water during testing that this effect was negligible because of the random shape, random size, and surface texture of the aggregate particles. It was decided to check this assumption by testing an aggregate sample with a solution containing a wetting agent. The wetting agent used for this purpose was a 0.1 percent solution of detergent which reduced the surface tension to approximately one-tenth of its original value. The results obtained in testing the aggregate with the solution differ little from those obtained when testing with the water. This serves to prove that the authors' assumption of the negligible effect of surface tension is correct.