Open Graded Skid Resistant Bituminous Concrete Surfaces

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ABSTRACT

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The main purpose of this work was to search for an improved method of designing open-graded bituminous surface mixes with high voids for skid resistance under wet conditions. Several published methods and procedures were reviewed. The ideas and procedures from three of these methods were selected and a new procedure was developed which predicts voids in a given open-graded mix. The method is also fit for designing a mix with a definite desired void content. The predicted void contents were compared and correlated with specimens compacted by the Marshall procedure using crushed gravel and slag as aggregates with 85-100 penetration asphalt as binder. The method should be tried in field applications.

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DISCLAIMER

The opinions, findings and conclusions expressed in this publication are those of the authors and not necessarily those of the Michigan State Highway Commission or The University of Michigan.

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INTRODUCTION

Most highway engineers agree that the period of rapid highway expansion of the last twenty years is drawing to a close. In the next twenty years the problems of maintenance and reconstruction will be dominant. Thousands of miles of highways will need resurfacing to improve riding qualities and skid resistance, especially during wet weather, and to reduce the probability of hydroplaning during wet weather. A very promising bituminous concrete mix for these purposes is the so-called open-graded mix.

These open-graded mixes are designed with a relatively high porosity or void content, on the order of 15 percent or more. Because of the high porosity, the permeability is greatly increased and water can be readily displaced from under the tire and into the voids. This action results in increased skid resistance and decreases the probability of hydroplaning. At the same time the mixes must be so designed that there will be no rutting under the repetition of wheel loads. In other words, they must have satisfactory stability and flow characteristics to resist displacement by traffic. In addition, they must have the desired porosity at a unit weight which would result in little or no further compaction under traffic.

The present bituminous concrete mix procedures, such as the Marshall or Hveem methods, were developed for the design of dense (minimum porosity) mixes. These methods have proven unsatisfactory for the design of open-graded mixes because they are rather insensitive and inaccurate for determining the optimum asphalt content for this type of mix.

There are a number of methods in the literature dealing with the engineering design of open-graded mixes. Some are very recent and others are of less recent origin. All of them have one goal in common: to identify the fundamental properties of the components of a mix, and, with this information, predict how the mix is going to behave.

A number of the more recent investigations contain promising approaches to the open-graded mix design problem. Huang has developed a "particle index" (1) which is supposed to measure pertinent geometric characteristics of coarse and fine aggregates such as used in bituminous concrete. The Committee on Aggregates of the American Society for Testing and Materials is presently debating the introduction of this "index" into their standards for aggregates. This "index" concept has also been applied to mix design (2).

Another approach to defining the geometric properties of aggregates is the packing volume concept developed by Tons and Goetz (3). Ishai, Tons and others (4) (5) have extended this packing volume concept into the design of dense graded bituminous mixes.

Lees has made an extensive study of inter-particle void characteristics and the grading of aggregates (6) (7). He has developed a method of combining various sizes of aggregates to give a desired porosity.

Finally, the Federal Highway Administration (FHWA) has developed a method for designing open-graded mixes (8). This method employs a special vibratory compaction test to determine the voids in a narrowly-graded coarse aggregate. A procedure is presented to fill these voids with asphalt cement and finer aggregate so as to end up with the desired porosity.

The purpose of the research reported herein was to study and integrate the presently available knowledge into a new design procedure for open-graded bituminous mixes. This involved a review of the present methods, the performance of analytical and experimental work on the identification of the most important parameters affecting open-graded mix behavior and a laboratory investigation of the method adopted. Another goal was to computerize the method to the fullest extent possible. The report presents the results of this effort.

LITERATURE REVIEW

As mentioned before, Huang (1) has developed a particle index concept to measure the pertinent geometric characteristics of coarse and fine aggregates. As explained by Huang, "The particle index is based on the idea that the rate of voids change in a uniform-sized aggregate, when rodded in a standard rhombohedron mold, indicates 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. The value becomes progressively greater as the aggregate particles become more irregular in shape, angular, and roughly surfaced."

The test procedure involves rodding a one-size aggregate in a standard mold in three layers with 10 strokes per layer and, then, computing the percentage of voids. The procedure is repeated using 50 strokes per layer. The particle index (I_a) is computed from the following equation:

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

V_{10} = percentage of voids using 10 strokes per layer.

V_{50} = percentage of voids using 50 strokes per layer.

A = a constant based on the geometric characteristics of highly polished aluminum spheres. A value of 32.0 is presently used.

The particle index for a graded aggregate is computed as a weighted average of the one-size particle indexes. The method has been standardized by ASTM under Standard Method D 3398 now using a cylindrical mold instead of a rhombohedron mold.

The particle index concept shows promise as another tool in the selection of suitable aggregates for different purposes such as bituminous or portland cement concrete mixes. Its use in the design of bituminous mixes appears limited at this time.

Tons *et al.* (3) (5) developed a concept by which the geometric irregularities (shape, angularity and surface texture) of aggregate particles are unified and expressed quantitatively by basic volumetric parameters. They defined the packing volume of a particle (V_p) as the volume a rock particle occupies in a mass of monovolume (one-size) particles. The packing volume can be visualized as the volume enclosed by an infinitely thin membrane stretched around the peaks of the surface roughness as shown in Figure 1. Using the packing volume of a particle, the packing specific gravity (G_p) is defined as

$$G_p = \frac{W}{V_p}$$

where W is the dry weight of the particle.

Ishai and Tons (9) defined the surface voids under the membrane volumetrically as the specific rugosity (S_{rv}), in percent of the packing volume, as:

$$S_{rv} = 100 \frac{V_{sr}}{V_p} = 100 \left(1 - \frac{G_p}{G_{ap}}\right)$$

V_{sr} = volume on all surface voids between the packing volume membrane and the membrane of the apparent volume (Figure 2).

V_p = packing volume of the aggregate.

G_p, G_{ap} = packing and apparent specific gravities, respectively.

As can be seen from Figure 2, the specific rugosity can be divided into two components: the macro surface voids (S_{ma}) which are the voids between the bulk and packing volume membranes, and the micro surface voids (S_{mi}) which are the voids between the bulk and apparent volume membranes. These components can be expressed volumetrically as percentage of the packing volume by the following equations (12):

$$S_{ma} = 100\left(\frac{G_{ag} - G_p}{G_{ag}}\right)$$

$$S_{mi} = 100\ G_p\left(\frac{G_{ap} - G_{ag}}{G_{ap}\ G_{ag}}\right)$$

G_{ag} = bulk specific gravity of the aggregate.

Therefore, the specific rugosity expresses the total geometric irregularity of particles. The macro and micro surface voids can be used to distinguish between the larger surface voids which dominate the packing and interaction of particles in bulk, and the capillary surface voids which determine the amount of asphalt absorption (4) (10).

In order to compute the specific rugosity and the macro and micro surface voids, the packing, apparent and bulk specific gravities of the particles are required. The apparent and bulk specific gravities can be easily determined from ASTM Standard Methods C 127 and C 128. Ishai (10) developed a practical method for the direct determination of the packing specific gravity. The detailed procedure is given in the Appendix of Reference (11) and reproduced in Appendix 3.

The packing volume concept can also be used to partition the asphalt cement of a bituminous mixture into two components: (a) the rugosity asphalt which is the asphalt below the packing volume membrane, and (b) the flow asphalt which is the asphalt outside the packing volume membrane (Figure 2). For practical computations the interest is in weight of asphalt taken up by rugosity (B_{rw}). Then the amount of asphalt consumed by surface irregularities (macro rugosity) can be obtained by subtracting the absorbed (micro voids) asphalt (B_{ag}) from B_{rw}. The equations for B_{rw} and B_{ag} are as follows (12):

$$B_{rw} = \frac{100}{100-w}\left(w - 100\frac{G_b}{G_{mm}}\right) + 100\frac{G_b}{G_p}$$

$$B_{ag} = \frac{100}{100-w}\left(w - 100\frac{G_b}{G_{mm}}\right) + 100\frac{G_b}{G_{ag}}$$

where B_{rw} = amount of asphalt lost by rugosity, % by weight of aggregate.

B_{ag} = amount of asphalt absorbed, % by weight of aggregate.

G_b = asphalt specific gravity.

w = asphalt content, % by weight of total mixture.

G_{mm} = maximum specific gravity of the mixture.

G_p = packing specific gravity of the aggregate.

G_{ag} = bulk specific gravity of the aggregate.

Tons *et al.* (5) found that the unifying concepts presented above for geometric irregularity factors together with the related rugosity terms explained the behavior of one-size aggregates in bituminous mixtures. They determined that bituminous mixes made with one-size aggregates of different rugosity characteristics and with the same volume of flow asphalt had essentially the same strength. In other words, the strength was a function of the flow asphalt content and not the total asphalt content or specific rugosity.

Ishai and Tons (5) (10) determined that these same geometric irregularity factors and rugosity terms could be used to characterize and explain the behavior of dense-graded bituminous mixtures. The volume of the macro surface voids of the different size fractions in a graded mixture was found to be the basic parameter which determined the interaction between the coarse and fine particles. Measurements showed that the macro surface voids are not filled with just rugosity asphalt as in the case of one-size aggregate, but some of this asphalt is replaced by finer particles occupying the macro voids in larger particles. This interaction was defined quantitatively as the fines lost by rugosity (F_r).

It was found that both the fines lost by rugosity and the asphalt lost by rugosity are basic parameters which, at a given asphalt content, define uniquely the amount of flow asphalt in the mixture. The flow asphalt, in turn, was identified as a unifying parameter for mixtures made from different types of aggregates. For a given gradation and type of asphalt, the volume of the flow asphalt was found to be statistically constant at the optimum asphalt content for any mixture regardless of the type of aggregate. Unlike the findings for one-size aggregates, the strength of these mixtures were not the same at the similar flow asphalt content.

In summary, Tons _et al._ have developed a unified method, based on the packing volume concept, for determining the volume of asphalt required in a bituminous mix of given grading in order to have a desired volume of flow asphalt. This involves finding the specific rugosity and the rugosity asphalt for the various size fractions in the mix. The method did not furnish a way to estimate the grading and flow asphalt necessary for a desired strength.

Lees (6) has studied the voids in masses of one-size aggregates of different shapes in dense and loose packings. The purpose was to gain a better understanding of aggregate grading design especially for gap-gradings. A technique was developed for impregnating the voids in an aggregate mass with a plastic medium. The impregnated samples were very carefully sectioned so that the characteristics of the voids could be measured. From these measurements the critical ratio of occupation and the critical ratio of entrance were computed.

The critical ratio of occupation has been defined by Fraser (13) as the ratio of the diameter of the sphere occupying the void space between larger spheres to the diameter of the larger sphere. The critical ratio of entrance is the ratio of the diameter of the sphere that could pass through one of the openings between larger spheres to the diameter of the larger sphere.

Based on his studies, Lees concluded that, for the design of gap-gradings, the ideal structure would consist of one in which there is a step-like reduction in size of the aggregate fractions. To accomplish this each successively lower size should be between the critical ratio of entrance and critical ratio of occupation as determined from the loose packing characteristics of the next higher size aggregate fraction.

Lees (7) also studied the factors affecting the packing and porosity of aggregates. A general theory for the combining of aggregate fractions to obtain minimum porosity was developed. This theory is based on the previous work of Furnas (14) and Powers (15).

Furnas (14) studied the voids in aggregate systems made up of two-size particles. Figure 3, where the voids in the system are plotted against the percentage of the larger constituent, presents the results of this work. Each curve is for a different size ratio which is equal to the diameter of the smaller particles divided by the diameter of the larger size. The size ratio = 0 curve, which implies infinitely small or infinitely large particles, was plotted from theoretical consideration.

A study of Figure 3 shows that each size ratio has a combination of small and large particles which results in a minimum void content. Further, the minimum voids decrease as the size ratio decreases. For size ratios of 0.2 or less, the minimum voids are obtained with a combination of about 67 percent large particles and 33 percent small particles. The minimum point is less well defined and occurs with decreasing percentages of the larger particles for size ratios greater than 0.2.

Powers (15) suggested the use of a specific void content or void ratio graph, Figure 4, for the presentation of data such as shown in Figure 3. The specific voids are found from $\frac{n}{1-n}$ where n is the percent of voids in the mass. The abscissa of this graph is the percent of the smaller size aggregate in the two component system while the ordinate is the specific void content. One of the advantages of this method of plotting is that specific gravity differences are eliminated.

Another advantage is that the size ratio = 0 curve can be determined as two straight lines. One of these lines connects the specific void content for 100 percent of the smaller aggregate to the zero point on the right side of the graph. The other line is drawn from the specific void content for 100 percent of the larger aggregate (0 percent of the smaller size) to the -1.0 specific void content point. The intersection of these two lines determine the minimum theoretical void content and the mix proportions to produce this minimum.

Lees (7) performed a large number of experiments in which he combined aggregates of various sizes and shapes over a wide range of size ratios. He concluded that there are three basic parameters that control the combining of two-size aggregate mixes to obtain minimum voids. These parameters are: (a) the average of the two porosities of the individual constituents when compacted separately, (b) the difference in these two porosities, and (c) the particle size ratio. Using these three parameters, Lees developed graphs from which the required percentage of smaller particles to give the minimum porosity can be found.

A procedure to determine the voids at the minimum porosity was also developed by Lees. As can be seen in Figure 4, the maximum possible theoretical reduction in voids when two aggregates are mixed is at a size ratio = 0. For size ratios greater than zero, the reduction in voids is less than this theoretical maximum. Lees, therefore, defined the relative contraction as the ratio of the actual reduction in voids in a two component system to the theoretical maximum reduction.

From analysis of his experimental data, Lees found that the relative contraction is dependent upon the difference between the two porosities and the size ratio but independent of the average porosity. From these studies he constructed a graph from which the relative contraction can be determined. The voids at minimum porosity (C) can then be calculated from the following equation (7):

$$C = A - \text{relative contraction} \left[A - \frac{\left(P_{\text{larger}} \times P_{\text{smaller}}\right)}{100} \right]$$

A = the lower of the two porosities measured separately for the larger and smaller aggregates.

P_{larger} = the porosity measured separately for the larger aggregate.

P_{smaller} = the porosity measured separately for the smaller aggregate.

Lees (7) has proposed a method for extending the above results from two component systems to three or more component systems. The method is illustrated in Figure 5 for a four component system. As shown on the specific void content diagram on the left of Figure 3, the largest component, A, is combined with the next smaller component, B, by the procedure outlined in the previous paragraphs. In this way the percentages of A and B necessary to obtain the minimum porosity are determined.

The combination of A plus B is then considered as the large fraction and is combined with the next smaller component, C. New values of the porosity difference and average porosity are calculated, treating A plus B as one component. The size ratio is computed using a mean equivalent spherical diameter (E.S.D.) for the A plus B component from the following relationship proposed by Lees (7):

$$\text{E.S.D.} = \frac{1}{\sum_{i=1}^{n} \frac{p_i}{d_i}}$$

where p_i are the proportions by volume of particles of diameter, d_i, respectively. The percentages of A plus B, and C are then determined for the minimum porosity.

By the same procedure, A plus B plus C is taken as the large size and is combined with the smallest fraction, D. The percentages of the two sizes to give the minimum porosity are computed as before. In this manner, as many components as desired may be combined to obtain the minimum porosity. For each combination, the voids at minimum porosity can also be determined.

To summarize, Lees has studied very intensively the design of gap-graded mixes using one-size aggregate components. Based on these studies, methods have been devised that permit the design of mixes for not only a minimum porosity but also for a controlled porosity such as needed in open-graded bituminous mixes. He found that the basic parameters involved are the difference in the porosities, the average of the porosities and the size ratio of the components being combined.

Smith <u>et al.</u> (8) of the Federal Highway Administration have developed a method for the design of open-graded bituminous mixes. As explained in Reference (8), "The design procedure then is based on the concept that the open-graded asphalt friction course consists predominantly of a narrowly-graded coarse aggregate fraction (which is defined here as material that is retained on a No. 8 sieve) with a sufficiently high interstitial void capacity to provide for a relatively high asphalt content, a high air void content, and a small fraction of fine aggregate (which is defined as that material passing a No. 8 sieve). The coarse aggregate fraction provides the structure of the composite mixture while the fine aggregate fraction acts primarily as a filler within the interstitial voids."

The design method involves the compaction of the coarse aggregate by vibration in a standard mold using an electromagnetic vibrating rammer following a specified procedure. The voids in the coarse aggregate are computed from the results of this test.

The asphalt requirement, based on the weight of the aggregate, is determined from the following linear relationship:

$$\text{Percent asphalt} = 2.0\ (K_c) + 4.0$$

where K_c is a measure of the surface capacity. This surface capacity includes "absorption, superficial area, and surface roughness." The surface capacity is found by a test procedure that involves soaking oven-dry aggregate in No. 10 lubricating oil, draining and determining the percent oil retained. A graph is then used to find the volume of "K_c."

The final step in the method is determining the optimum content of the fine aggregate fraction. This optimum content, on a volume basis, is equal to the volume of voids in the coarse aggregate minus the volume of asphalt minus the volume of the desired air voids plus the volume of the absorbed asphalt. The suggested value of the minimum desired air voids in the mix is 15 percent by volume. Further, the percent by weight of fine aggregate is limited to 15 percent. In other words, the purpose of the method is to determine whether 15 percent by weight of fine aggregate will result in a minimum air void content of 15 percent by volume. If not, the percent of fine aggregate must be reduced so as to give the minimum air voids.

Smith et al. (8) used the above method to design a number of mixes which were already constructed and were exhibiting satisfactory behavior. The results checked quite well with in-place designs. Therefore, it was concluded that the method is a substantial improvement over existing methods and gives reasonable results.

While the method shows promise for the design of open-graded mixes, its application at the present time is limited to the narrowly-graded coarse aggregate fraction presented. It cannot be extended to other gradings in a rational way. Also, the method for estimating the asphalt content would be questionable for aggregates with high surface irregularities and roughness such as slags.

The goal of this research is to use fundamental, quantitative values for open-graded mix design. It was found that using Smith's (FHWA) method as a guide, the procedures developed by Lees and Ishai-Tons could be combined for a mix design which predicts voids in open-graded mixes.

SOME FIELD OBSERVATIONS IN MICHIGAN

Open-graded mixes with high void contents have been used on the roads in Michigan and elsewhere. A brief listing and comments on installations in Michigan are given in Appendix 1. Their performance so far is very encouraging, with only minor problems which can be eliminated in the future.

In regard to water drainage mechanism during rain, the FHWA model does not appear to be applicable, especially in urban areas where curbs are often present (8). In such cases the rainwater cannot freely flow into the pavement void system and then laterally out on the shoulder as the curb is in the way. Also, it appears that the surface voids stay clean and open only in the wheel tracks, while at the edge of the pavement dust and sand particles (probably from winter sanding operations) have often clogged the surface voids and the pavement surface no longer looks porous. This may not be of great importance as long as the voids in the wheel tracks are clean and open and the tires can "pump" the water into the pavement at one place (under the contact area) and push it out along the periphery of the contact area. Thus, as long as the voids under the wheels can be preserved, wet weather hydroplaning should not be a problem for all but the most reckless cases. To control the amount of voids in such pavement requires proper mix design and control.

TYPICAL MIXES USED

In order to achieve high void contents, open-graded mixes are used. A typical gradation as suggested by FHWA (8) is as follows:

Passing	3/8" sieve	100 percent
Passing	#4 sieve	30-50 percent
Passing	#8 sieve	5-15 percent
Passing	#200 sieve	2-5 percent

The minimum specified void content is 15 percent, and, as described in the literature review, the mix is designed on a trial-and-error basis.

In Michigan, 31 A aggregate appears to be close to the desired gradation to obtain a porous mix.

PRELIMINARY LABORATORY WORK

The initial laboratory work was done on 1/2 to 3/8 inch aggregates from several sources to familiarize ourselves with the so-called particle index (I_a) as developed by Huang and recently adapted by ASTM to characterize types of aggregate pieces (ASTM D 3398). Again, the particle index can be calculated from the following equation:

$$I_a = 1.25\ V_{10} - .25\ V_{50} - 32,$$

where

I_a = particle index of aggregate,

V_{10} = porosity or voids in the dry aggregate rodded by a standard rod 10 times,

V_{50} = porosity or voids in the dry aggregate rodded by a standard rod 50 times.

The given aggregate is compacted in a standard container and the voids are calculated on a bulk specific gravity basis. For example, the V_{10} would be obtained as follows:

$$V_{10} = \left(1 - \frac{W_{10}}{S_B V}\right) 100,$$

where

V_{10} = voids in the aggregate after 10 roddings, in percent,

W_o = weight of the dry rodded aggregate in a standard container,

S_B = bulk specific gravity of the aggregate,

V = volume of the standard container filled with the aggregate.

As the equation shows, the V_{10} has a coefficient of 1.25 as compared to 0.25 for V_{50}. As the result of this, the V_{10} measurement is very important in this procedure while error in V_{50} has less effect on the I_a, Thus, at the outset, it was already apparent that I_a cannot be used as a fundamental parameter in mix design. The compaction and void measurements, however, are fundamental in mix design and therefore several tests were run using three one-size (1/2 - 3/8 inch) aggregates: dolomite, mine rock (basalt) and smooth beach pebbles (gravel). The dolomite had a tendency towards elongated particles, the mine rock was closer to cubical shape and the beach pebbles were round and smooth. A typical comparison for mine rock and beach pebbles is shown in Figure 6. As it can be seen, the mine rock has higher void volume between the particles due to its more irregular and rougher surfaces. Thus, the I_a for mine rock would be higher than for the smooth, round beach pebbles.

The problems encountered with the rodding method were:

(1) The rod penetrated considerably more in the rounded pebbles and less in the mine rock, using the same effort.

(2) Some crushing of the particles occurred.

(3) The V_{10} values varied more than the V_{50} values.

Although the rodding technique would have been the simplest to use to estimate (measure) voids in the aggregate, it was abandoned for a "vibratory" method which would accelerate each particle during compaction and hopefully cause less crushing. During the first "vibratory" experiments, the V_{10} point was simply replaced by porosity obtained from hand-placing of the aggregate in the standard container. The second V_{50} point was replaced by compaction using 8 blows on the side of the container. The rock was placed in 3 layers, and after each layer was placed, the container was rotated and hit 8 times with a standard rod from a standard distance. Again, typical curves for three aggregates are shown in Figure 7. The mine rock and the dolomite are quite similar, while the beach pebbles have a significantly lower void content.

These differences are primarily due to the fact that bulk specific gravity is used for the void calculations. If so-called packing specific gravity is substituted, the three aggregates look alike for most practical purposes as shown in Figure 8. The conclusion from this preliminary study was that the particle index is difficult to use for prediction of voids in a mix containing several one-size particle combinations and that the packing specific gravity may be helpful to unify and simplify the void calculations and predictions in graded aggregates and mixes. It was also concluded that a vibratory type of compaction of the aggregate instead of rodding gives more uniform results and less crushed particles.

PREDICTION OF VOIDS IN COMBINED AGGREGATES

Measuring voids in a one-size aggregate is a simple matter once the compaction procedure is standardized. The next important step is how to predict voids when aggregates from different sieves (sizes) are combined. As pointed out in the literature review, the work in this area has been done by a number of researchers but Lees has expanded the ideas to the application for bituminous mixes (7). A typical curve obtained in the laboratory using American Aggregate-Green Oaks gravel is shown in Figure 9. The minimum porosity (or voids) for the combination of two aggregate sizes can be calculated by knowing only the void content of each aggregate fraction. Using 3 known points, a computer program was generated to predict the voids for any combination of the larger and the smaller aggregate. In other words, if the voids in each aggregate fraction compacted by a given procedure are known, the voids in combined (mixed) dry aggregates can be predicted (for the same standard compaction).

In order to have the compaction of individual aggregate sizes (sieve fractions) equalized, a standard vibratory compaction method was adopted. A sketch of the setup is shown in Figure 10. As shown, a layer of aggregate about 3 inches thick was placed in the 6-inch mold and vibrated at 3600 cpm and under a 53-pound surcharge. Typical compaction curves for two sizes of gravel and slag are shown in Figure 11. Knowing the height of the specimen, the voids in the aggregate can be calculated.

After these curves were obtained, a correlation between the vibratory test voids of each aggregate fraction and a Marshall mix voids was attempted. Some preliminary data obtained from the MDSHT files indicated that <u>one</u> minute of the standard vibratory compaction as described above is approximately equivalent to the ram compaction used by the FHWA (8) and approximately to 35 blows by the Marshall machine (with asphalt added to the aggregate). The above mentioned "equivalence" simply means that a mathematical bridge is established between the voids in the vibrated, compacted aggregate and the voids in a compacted Marshall specimen using 35 blows. As will be seen later, 30 blows in the Marshall compaction using MDSHT compactor correspond closer to one minute of dry aggregate compaction by the vibratory method.

DESIGN OF MIX WITH DESIRED VOID CONTENT

The prediction of voids in a compacted bituminous mix without making and testing specimens is a desirable goal. To do this the following information is needed (more detailed procedure is given in Appendix 2):

(1) Aggregate fractions to be combined and used in a mix (1/2" - 3/8", 3/8" - #4, etc.).
(2) Voids in each fraction after compaction.
(3) Bulk specific gravity of each aggregate fraction (if not the same) and the asphalt.
(4) Equivalent spherical diameter for each fraction.
(5) Rugosity or surface roughness for the aggregate in each fraction.
(6) Asphalt absorbed by the aggregate.
(7) The desired filler/asphalt ratio.
(8) The amount of flow asphalt to be added to the mix.

The reason for requiring measurements on each aggregate fraction is to provide information for the computer so that these fractions can be combined in the right proportions to get prescribed (desired) voids in the final mix.

The established procedure is to first calculate the voids in a dry aggregate mixture exclusive of filler. It is assumed that filler is part of the binding agent or asphalt and a certain filler/asphalt ratio will be used in the mix. It is also assumed that for mixes with high void contents (above 12 percent) no significant dilation in the aggregate skeleton will be caused by the asphalt and filler added. An example of the procedure used in putting the mix together is given in Appendix 2.

LABORATORY WORK ON MIXES, PHASE I

The first open-graded crushed gravel mix using mix proportions as shown in Table 1 and asphalt content of 7.1% by weight of the mix was compacted using 50 blows and the UM Marshall compactor. The first results were encouraging as can be seen from Figure 12. The average measured void content of the compacted mix was 19.7%, while the predicted voids based on standard 1-minute vibratory compaction of the aggregates were 19.2%. The next step was to try an open-graded slag mix with mix proportions as shown in Table 3. From this mix the average measured void content was 13.2% as compared to 17.3% predicted (using 1-minute vibratory compaction for the aggregates). As seen in Figure 12, the difference is considerable. Various explanations for this discrepancy could be advanced, but the most convincing one was a higher degree of crushing of slag as compared to gravel in the Marshall compaction process (impact). To check this, asphalt was extracted from the Marshall specimens for slag and gravel and the new gradations and new average particle diameters were determined (see Tables 2 and 4). From this, new predicted void contents were computed. For the slag the actual expected voids dropped to 14.2 percent and for the gravel to 18.2. For the first trial, using such diverse and different aggregates as gravel and slag, the closeness of the predicted voids was indicative that the basic principles used in the design are promising.

SERIES OF MARSHALL TESTS, PHASE II

The second part of the laboratory testing program included some adjustments. Previous observations showed that the mix temperature should not exceed 250 F for the mixes used as the asphalt in the Marshall specimen will tend to migrate downwards during compaction and the result is a specimen with a non-uniform texture.

The loss of fines and the asphalt in the mixing pan has to be watched since it will affect the composition of the compacted specimen. In other words, the mixing bowl should be "buttered" to keep losses to a minimum. It was also suspected that different Marshall compactors will give different densities and voids. This does not matter, as long as the compacted product is initially correlated with the vibratory compaction of the dry aggregate fractions. Since this research is conducted for MDSHT it was decided to use their Marshall compactor for the next series of specimens. The first mix used was gravel with 85-100 penetration asphalt as given in Table 1. The aggregate and the asphalt were heated to 250 F and each Marshall specimen was mixed individually by hand. The first specimen was used to "butter" the mixing pan and discarded afterwards. Five asphalt contents were used as shown in Figure 13. The asphalt percentages by weight of mix ranged from 5 to 7.75 percent, while on rugosity-flow asphalt bases the range was between -6 and +6 percent including the filler. As pointed out in the literature review, asphalt in a mix can be divided into three categories: first, asphalt absorbed (lost) in the aggregate; second, asphalt needed to fill up the surface irregularities (roughness) of the aggregate; and third, free or flow asphalt. At 0% flow asphalt content (Figure 13), only the absorbed and particle roughness asphalts are present; at +6% flow asphalt, 6 percent of the asphalt by volume of the aggregate is added (filler is counted as part of asphalt); and at -6% flow asphalt, the amount equal to 6% is subtracted from the surface roughness asphalt. As it will be shown later, the advantage of the flow asphalt versus voids plot is that different aggregates such as gravel and slag can be plotted on the same scale between -6 and +6 percent, while on weight bases the asphalt contents are quite different for slag and gravel (see Figures 17 and 18).

Three Marshall specimens for each of the five asphalt contents were compacted in the MDSHT compactor using 50 blows on each side. In addition, 3 specimens each were prepared applying 35 and 20 blows respectively using +3 percent flow asphalt (see Figure 13). From this data it was apparent that the predicted void curves are close to parallel with the experimental points, and, in this region of voids, a straight line relationship exists between asphalt content and voids in a compacted mix. Furthermore, it was estimated from these tests that a 30-blow Marshall compaction should give approximately the same voids as predicted voids using 1-minute vibratory compaction for the aggregate adjusted for crushing of gravel particles during the Marshall compaction. Results on additional specimens using 30 blows on each are shown in Figure 14.

The work with an open-graded gravel mix was followed with a similar mix using slag. The mix proportions are given in Table 3. The predicted and actual void values are plotted in Figure 15. As it can be seen, the 30-blow compaction (MDSHT compactor) gave voids close to those predicted by the 1-minute dry aggregate compaction (see also Figure 16).

Figure 17 shows a plot of both the open-graded gravel mix and the slag mix. They were both initially designed to be very nearly the same. More extensive crushing of the particles during compaction in the Marshall mold may account for most of the differences.

Although the main goal in this work was to develop a method for controlling (predicting) voids in a compacted mix, Marshall specimen stability and flow values were also determined. The typical Marshall plots are shown in Figures 19, 20 and 21. As it can be seen there is no definite optimum strength and no peak density for such open-graded mixes.

The data for rugosity and asphalt absorption was obtained from previous work (12). The void calculations were based on actual weight and volume measurements of the specimens.

DISCUSSION

The purpose of this research was to look into the parameters which affect the design of open-graded bituminous concrete mixes for resurfacing pavements with a bituminous mix which provides water drainage and skid resistance under all weather conditions. The emphasis was placed on an analytical and general approach with the goal of being able to predict certain important properties of such open-graded mixes so that a minimum amount of work can give the designer numerical answers. By combining various ideas published in the literature, a method for predicting and controlling voids in open-graded mixes has been proposed and tested.

Void control is very important for all bituminous concretes, but especially so for open-graded friction courses. The information needed for predicting voids in a mix is described in Appendices 2 and 3. The main idea was to first establish basic standard measurements on the aggregate and the asphalt to be used in the mix. Then, without making any laboratory (or field) specimen, the voids were predicted. Next, Marshall specimens were made in the laboratory and the voids were correlated with the predicted voids. For instance, in our case, 1-minute vibratory compaction of the dry aggregate fractions and their corresponding voids was equivalent to approximately 30 blows in Marshall compaction using the

MDSHT compactor. This applies to gravel or slag (and should apply to any other aggregate) even though they are very different materials. However, since slag particles are crushed and degraded more during the Marshall compaction, the changes in aggregate gradation and average particle size should be mathematically accounted for when voids in the Marshall specimen are predicted as can be seen in Figure 15 by comparing curves 1 and 3. For the harder gravel used in this experiment, the degradation and average particle sizes did not change as much and a lesser shift in the predicted voids is expected (see Figure 13, curves 1 and 3). It is apparent that the type and length of the dry aggregate compaction will affect the voids in the combined aggregates and a different number of blows in the Marshall compaction will be needed to "simulate" the new condition. Also, the mix can be compacted by the kneading compactor (Hveem) or other methods and the vibratory compaction of the dry aggregate can be adjusted to predict voids for the new conditions. The final correlation that is really important is that of the actual compaction on the road. Since Marshall compaction has been correlated with actual pavement in many studies, one expects that correlation with Marshall data also gives a good estimate of the field case.

The other flexible point of this method is that desirable voids can be set say at 18 ± 0.1 percent. The computer will calculate what proportions of each aggregate size is needed to provide the 18 percent voids. Another variation on the theme is that the mix producer may have a definite grading that he wants to use. Without making a laboratory mix, predictions can be obtained whether the desired void content can be achieved with the given materials or what adjustments are needed in the mix.

Other Marshall data besides void content are shown in Figures 19, 20 and 21. It is important to point out that the slag mixes appear to be stronger than the gravel mixes. There is a question of what should be the minimum required Marshall stability for such thin resurfacings. In regular bituminous concrete construction, 500 and 750 pounds Marshall stability has been set as minimum for medium and heavy traffic, respectively. It is a well-known fact that thin bituminous layers are "confined" by the truck tire and the old surface below. Therefore, stability values below 500 or 750 pounds may be acceptable. In areas where traffic braking and acceleration forces are frequent, such as intersections, it may be advisable to use higher stability mixes. Slag aggregate may be helpful here.

The exact prediction of stability similar to the voids is not possible at this time. The trends in stability are somewhat similar and opposite to the voids (see Figures 19 - 21). However, the effect of crushing and degradation of particles is not as easy to predict in the case of stability as it was for voids. More work is needed on this problem.

The flow values obtained in the Marshall test are on the low side, but probably acceptable.

The asphalt contents chosen for the laboratory test specimens were based on 0 flow asphalt as the central point.* Using the aggregate rugosity approach for calculating the asphalt requirement in the mix, gravel, slag or other mixes can be placed on a more comparable footing. At this time 0 to 3% flow asphalt could be used as a starting point for open-graded friction courses. For the crushed gravel mix this would result in about 6.4% by weight of the mix (see Figure 14 for 0 flow asphalt) and about 10.8% by weight of the mix for the slag aggregate (see Figure 16, 0 flow asphalt). The suggested asphalt content for the above gravel mix appears to be identical to that presently used by the MDSHT in some field experiments. However, the 10.8% for slag is high as compared to 8 - 9% by weight used in some installations in Michigan. Such lower asphalt content will increase the voids and decrease the stability of the compacted slag mixes.

The filler in this work has been treated as being part of the asphalt, not part of the aggregate. This is due to the theory that a filler particle is so small that it gets into all crevices of the larger particles just like asphalt (except in the finest capillaries where only asphalt is assumed to be absorbed). The data seems to confirm this assumption.

It was also assumed that the filler and the asphalt do not dilate the aggregate skeleton and act strictly as void filling substances. This appears to be a good approximation for open-graded mixes and should be watched for dense, low void cases.

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*Reminder: The flow asphalt also includes the filler.

Three sizes of aggregate were used in this work, namely: 3/8" - #4, #4 - #16, and #16 - #100. All particles smaller than #100 sieve were included as filler. This grading was chosen for convenience and for better control of the mix proportions. Essentially, the mixes are close to Michigan 31 A and the FHWA gradation reported in Reference 8. Any other gradation or sieve size designation can be used.

CONCLUSIONS

The conclusions are based primarily on work with crushed gravel and slag mixed with 85-100 penetration asphalt to make open-graded bituminous mixes with voids varying between 12 and 24%. The basic concepts are expected to apply also for other aggregates in open-graded mixes. The most important conclusions resulting from this study are:

(1) Voids (porosity) in individual aggregate fractions obtained from a standardized vibratory compaction procedure can be used to predict voids when the different fractions of aggregate are combined in different proportions.

(2) By using packing volume and rugosity concepts, asphalt, filler and aggregate can be combined and the voids in the mix can be predicted.

(3) Voids obtained from Marshall compaction were correlated with the predicted voids.

(4) If a certain percentage of voids are desired, the required proportions of aggregate, filler and asphalt can be predicted without making and running Marshall or other test mixes.

RECOMMENDATIONS

The following recommendations for further study are offered:

(1) The predicted voids have been correlated with voids in specimens compacted by the Marshall method. The next step would be to try field installations using mixes designed by the proposed method and aggregates similar to those used in this study. Both of the aggregates used (gravel and slag) were close to the MDSHT 31 A grading.

(2) The amount of aggregate degradation or crushing during rolling in the field as compared to that during Marshall compaction should be checked since degradation was found to influence the prediction of voids.

(3) Experiments with different aggregates and additives, such as rubber, should be tried to find out their influence on the prediction of voids.

(4) Further research on the predicting of strength or stability is required and could prove to be very beneficial.

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BIBLIOGRAPHY

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TABLES

TABLE 1

ORIGINAL COMPOSITION OF GRAVEL MIX WITH 3% FLOW ASPHALT

		% Ingredients in Compacted Form			
	E.S.D.	by Volume			by Weight
Fraction #1 3/8"-#4	.700	61.73	39.74	39.74	54.16
Fraction #2 #4-#16	.268	35.08	22.58	22.58	30.77
Fraction #3 #16-#100	.055	3.19	2.05	2.05	2.80
		100.00			
Filler				3.79	5.17
Asphalt				12.69	7.10
Voids			35.63	19.15	0.00
Total			100.00	100.00	100.00

TABLE 2

COMPOSITION OF GRAVEL MIX WITH 3% FLOW ASPHALT AFTER MARSHALL COMPACTION

		% Ingredients in Specimen			
	E.S.D.	by Volume			by Weight
Fraction #1 3/8"-#4	.650	50.80	32.70	32.70	44.28
Fraction #2 #4-#16	.326	42.70	27.47	27.47	37.19
Fraction #3 #16-#100	.0989	6.50	4.42	4.42	5.98
		100.00			
Filler				4.03	5.45
Asphalt				12.76	7.10
Voids			35.41	18.62	0.00
Total			100.00	100.00	100.00

TABLE 3

ORIGINAL COMPOSITION OF SLAG MIX WITH 3% FLOW ASPHALT

		% Ingredients in Compacted Form			
	E.S.D.	by Volume			by Weight
Fraction #1 3/8"-#4	.594	57.95	35.88	35.88	45.21
Fraction #2 #4-#16	.313	37.05	22.94	22.94	31.67
Fraction #3 #16-#100	.068	5.00	3.10	3.10	4.54
		100.00			
Filler				4.77	7.10
Asphalt				15.98	11.48
Voids			38.08	17.33	0.00
Total			100.00	100.00	100.00

TABLE 4

COMPOSITION OF SLAG MIX WITH 3% FLOW ASPHALT AFTER MARSHALL COMPACTION

		% Ingredients in Compacted Form			
	E.S.D.	by Volume			by Weight
Fraction #1 3/8"-#4	.586	45.80	29.29	29.26	35.21
Fraction #2 #4-#16	.290	44.10	28.20	28.20	37.17
Fraction #3 #16-#100	.081	10.10	6.43	6.43	9.00
		100.00			
Filler				5.02	7.13
Asphalt				16.94	11.48
Voids			36.09	14.15	0.00
Total			100.00	100.00	100.00

FIGURES

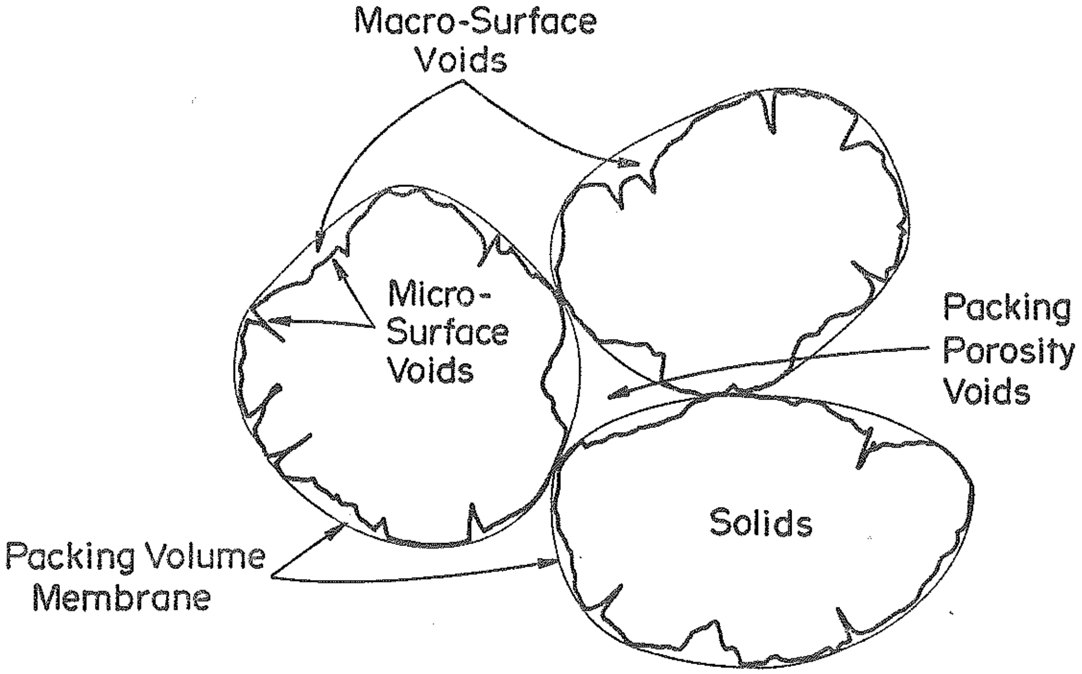

Figure 1. Sketch defining terms used in packing volume concept.

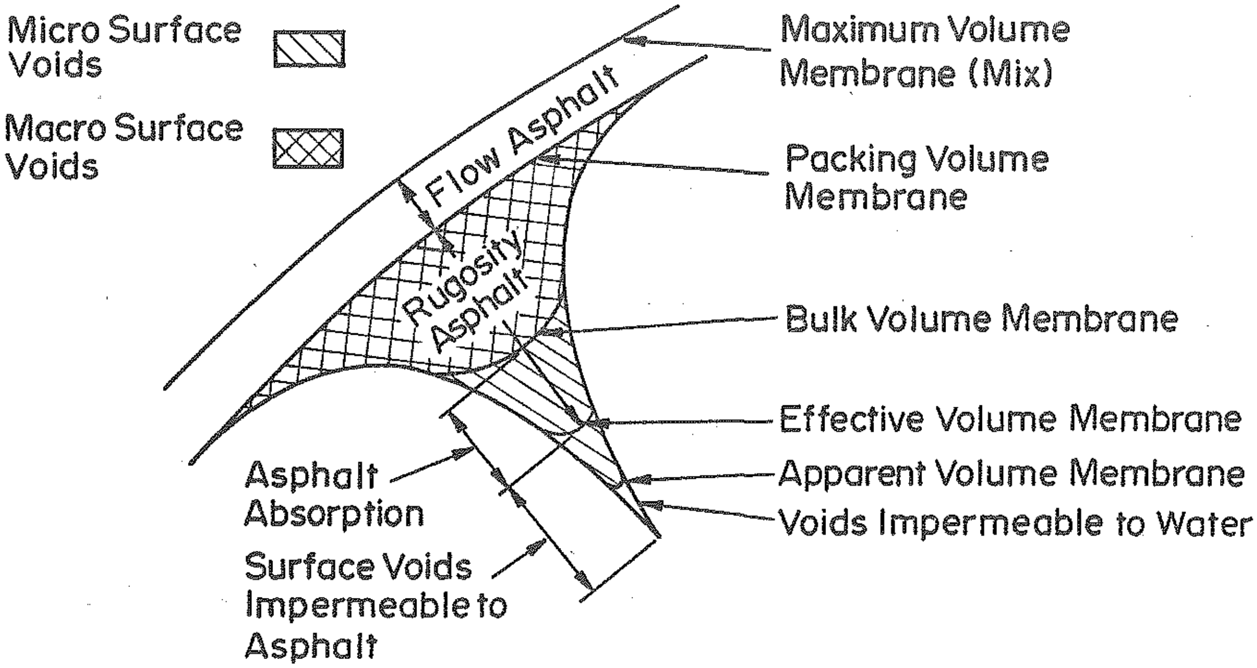

Figure 2. Sketch defining terms used in rugosity concept.

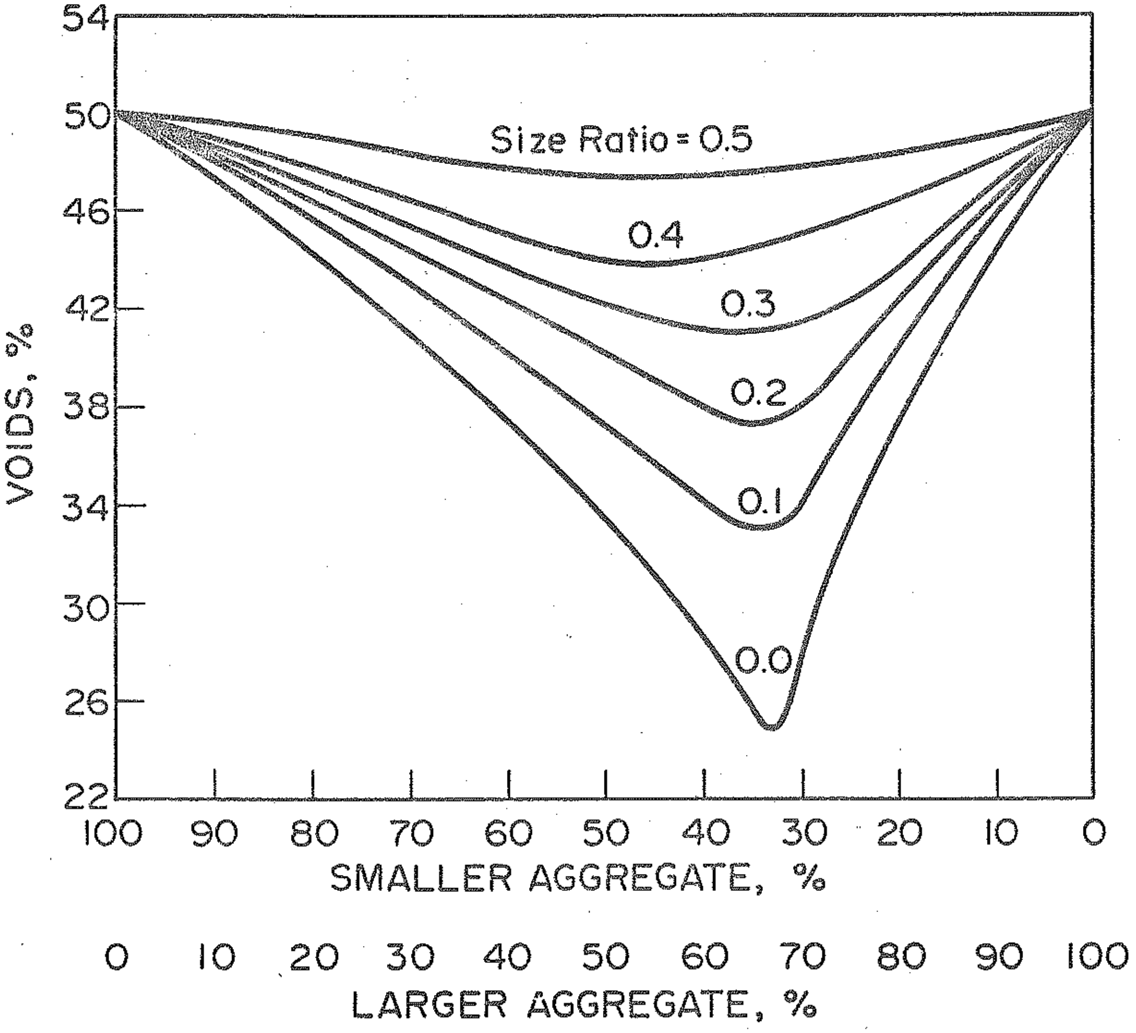

Figure 3. Relationship between voids and proportions of aggregate size, from reference (14)

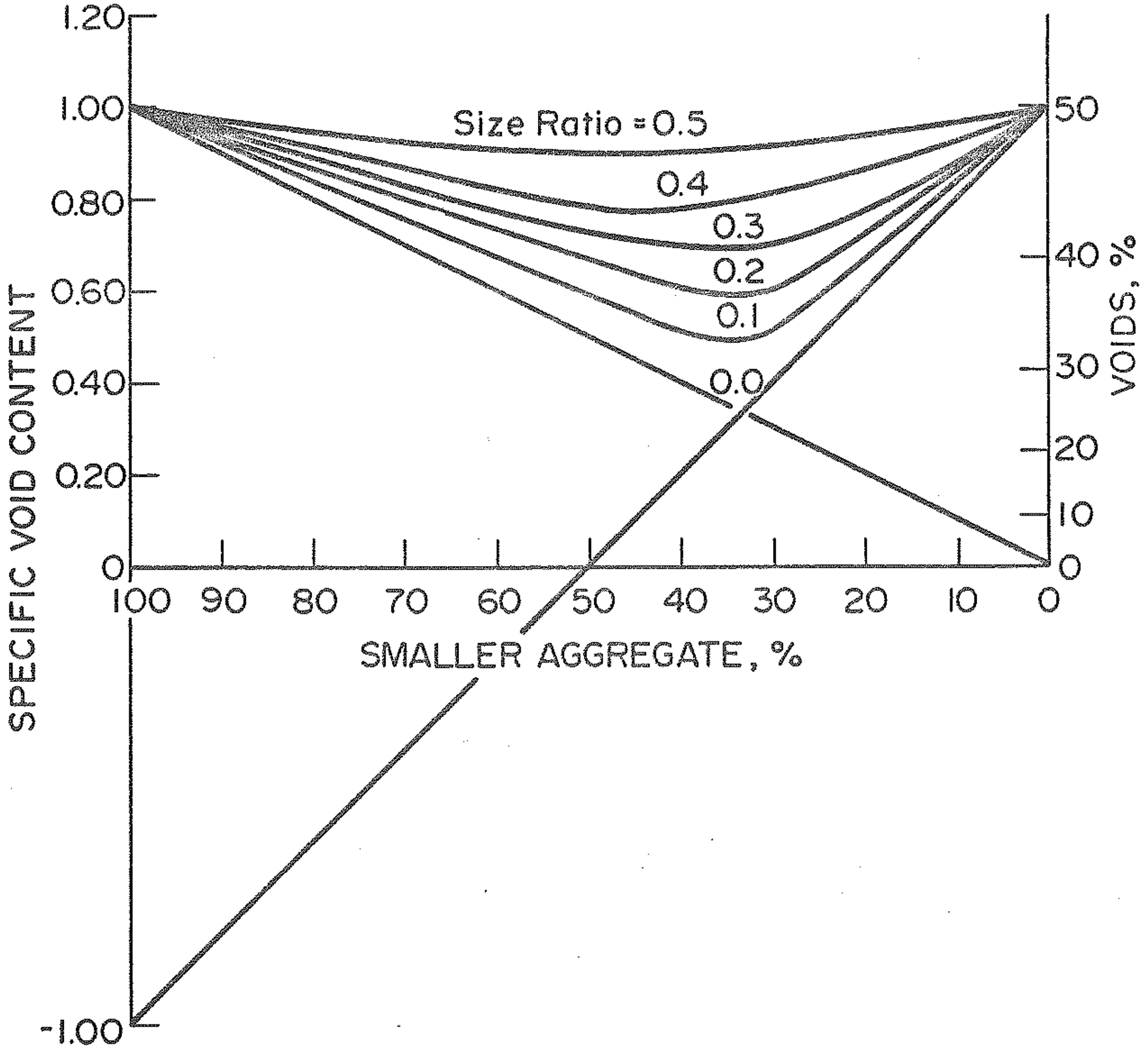

Figure 4. Specific void content curve for two-component aggregate system, from reference (15).

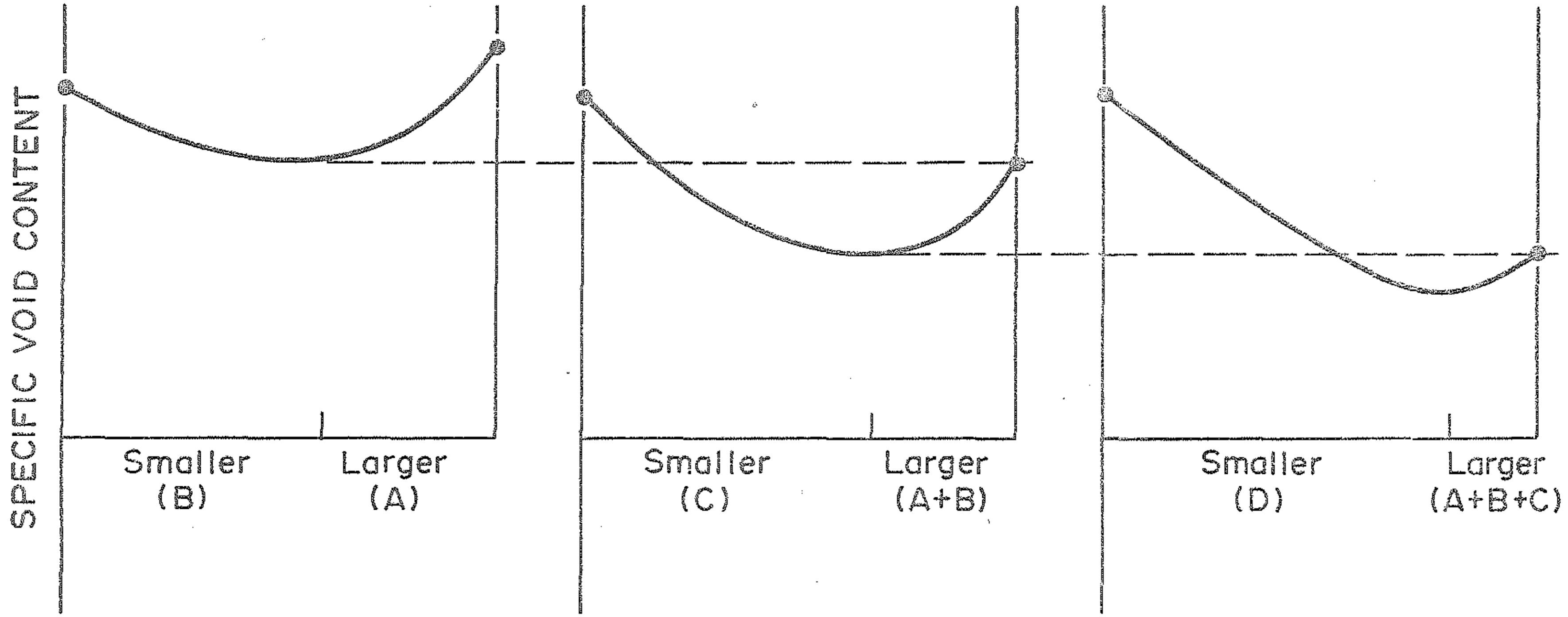

Figure 5. Sketch showing method of using two-component blend design concept for multi-component system, from reference (7).

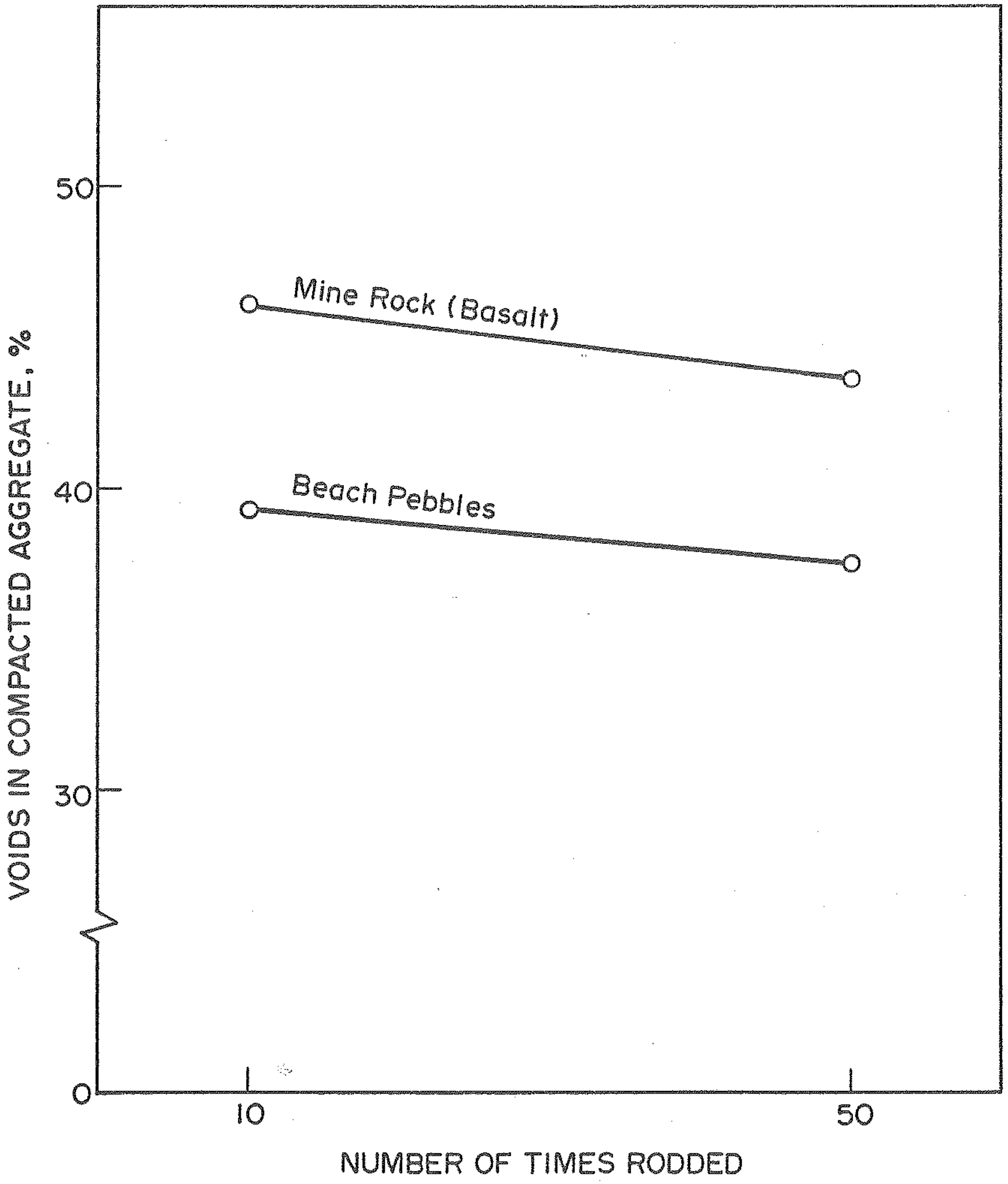

Figure 6. Decrease in voids in "one-size" aggregates due to rodding compaction (similar to ASTM D 3398). Bulk specific gravity used in void calculations.

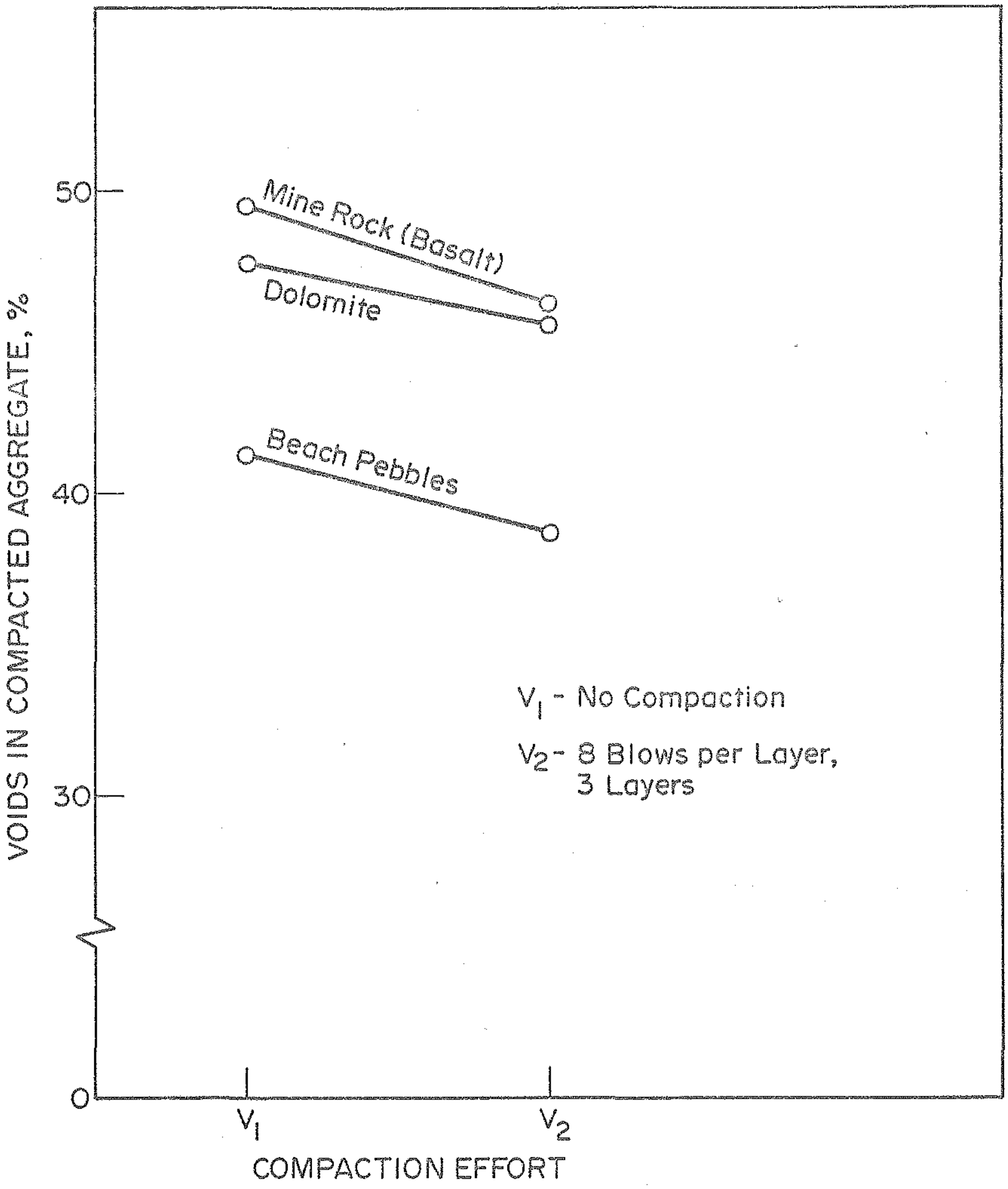

Figure 7. Decrease in voids in "one-size" aggregates due to vibratory blows to the side of the container. Bulk specific gravity used in void calculations.

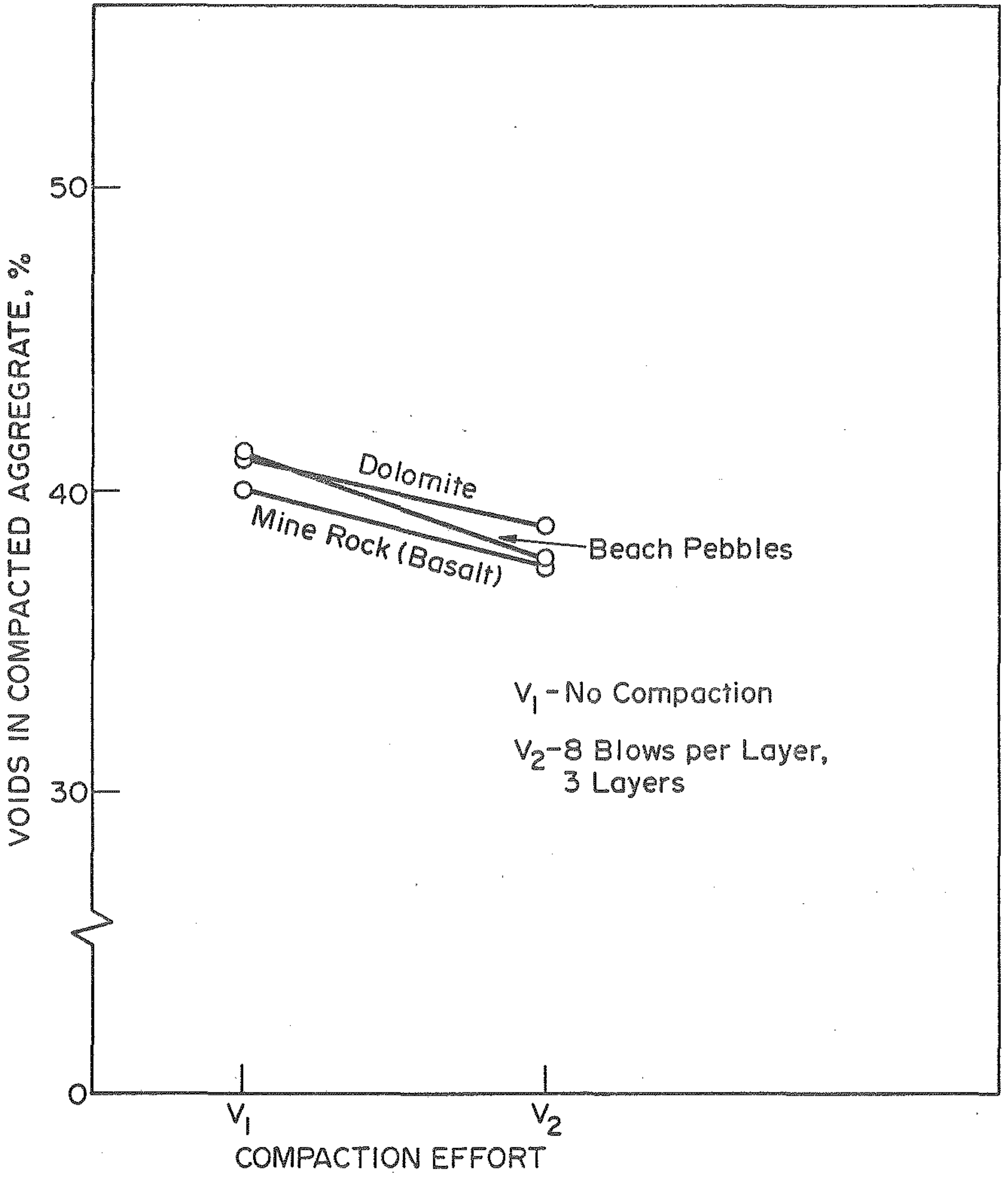

Figure 8. The same as Figure 7 except that packing specific gravity was used for void calculations.

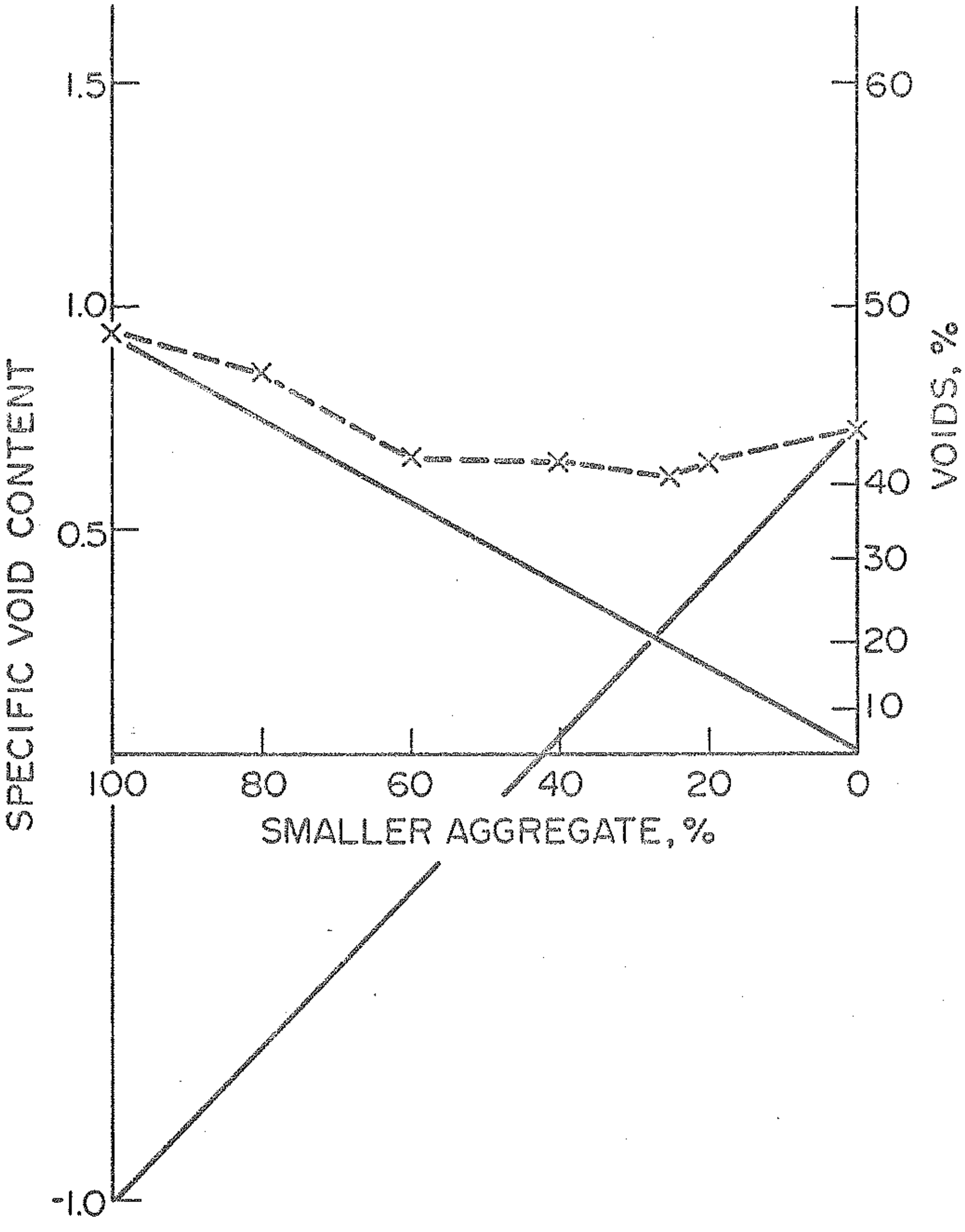

Figure 9. Specific void content curve using 1/2"-3/8" crushed gravel as larger and #4-#8 crushed gravel as smaller aggregate.

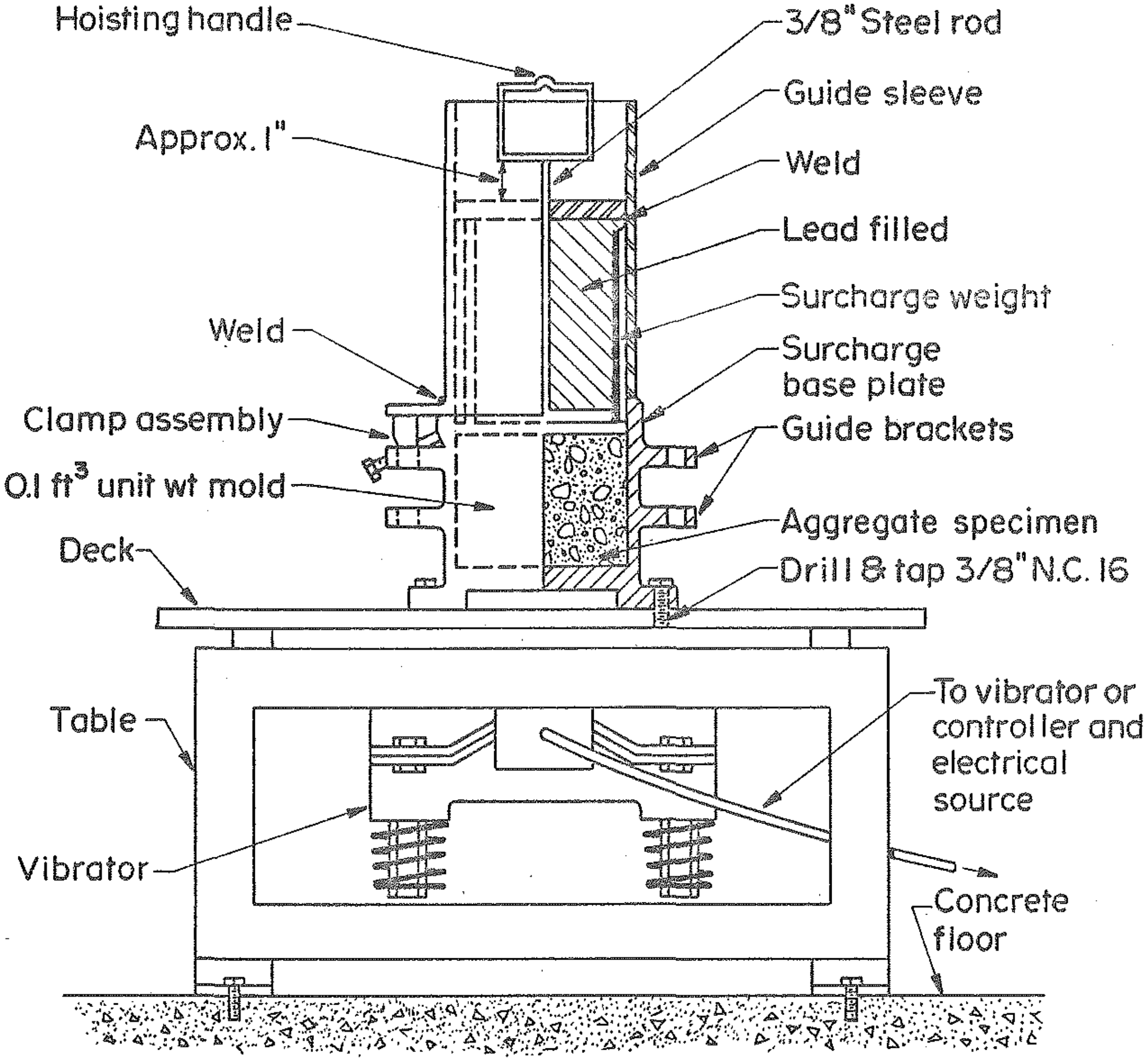

Figure 10. Vibratory compaction machine for dry aggregates, ASTM D 2049.

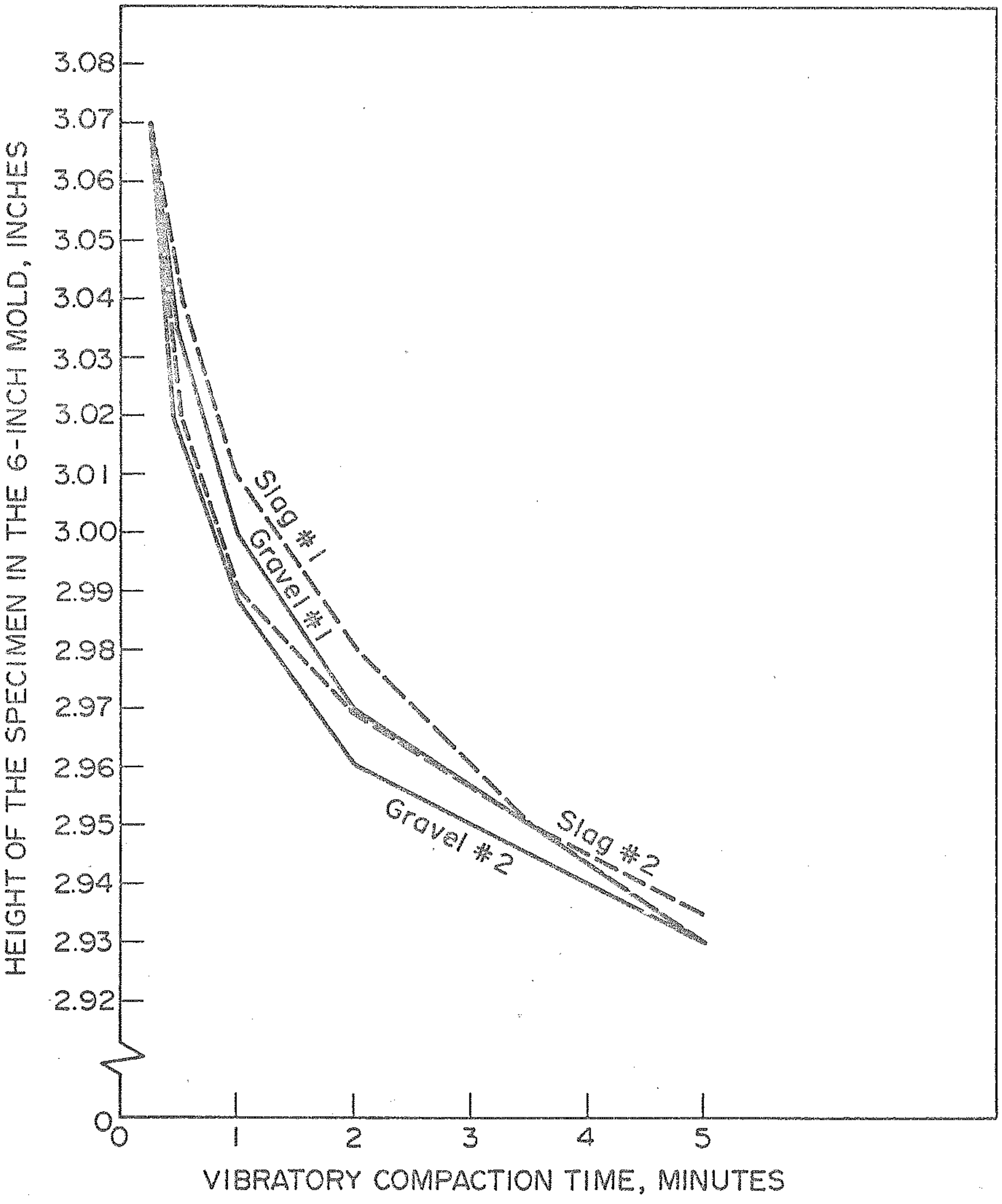

Figure 11. Vibratory compaction curves for gravel and slag fractions #1 and #2

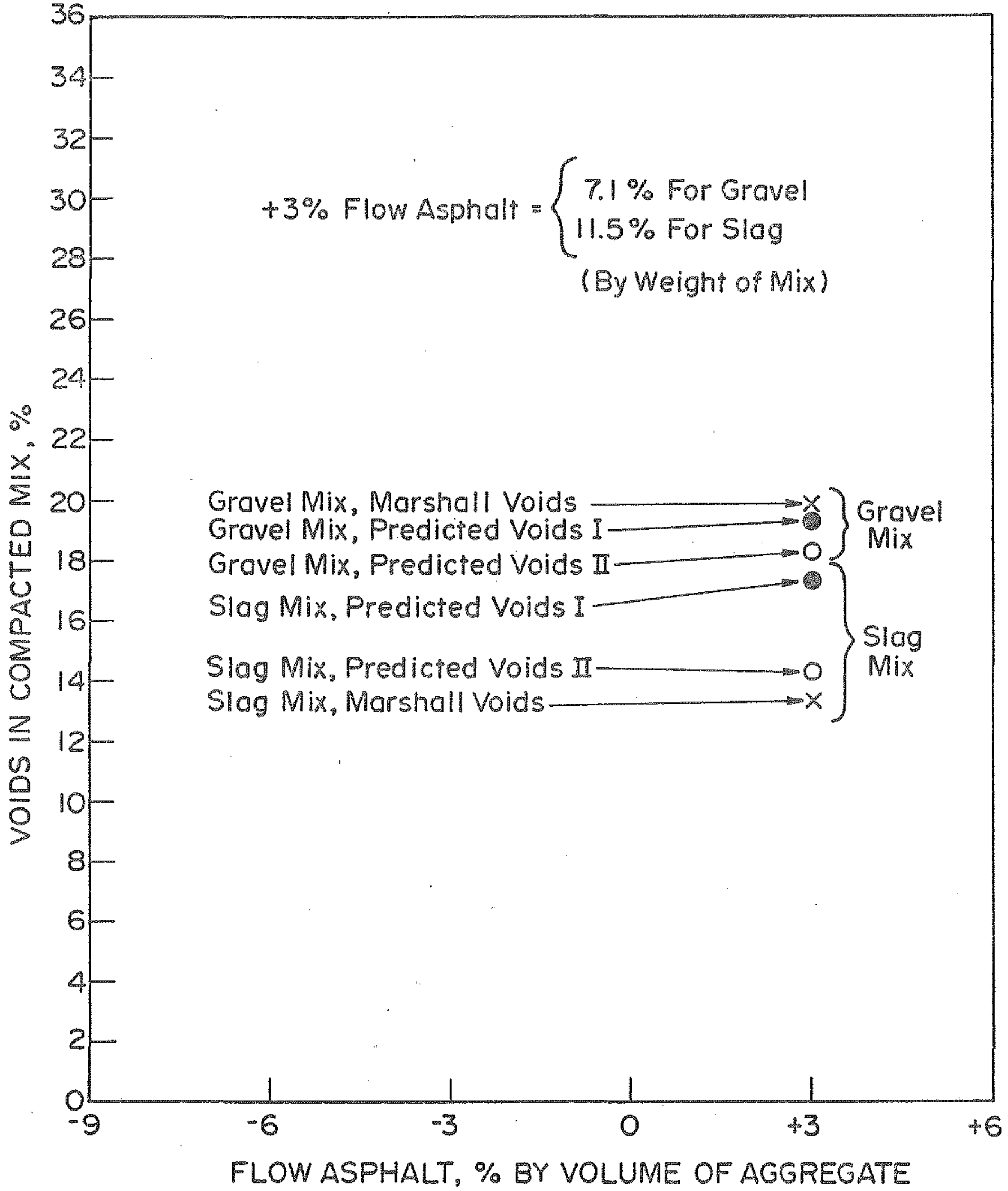

Figure 12. Voids in Marshall specimens compared with predicted voids using original (I) and after compaction by Marshall (II) gradations. Gravel and slag mixes, 50 blows UM compactor.

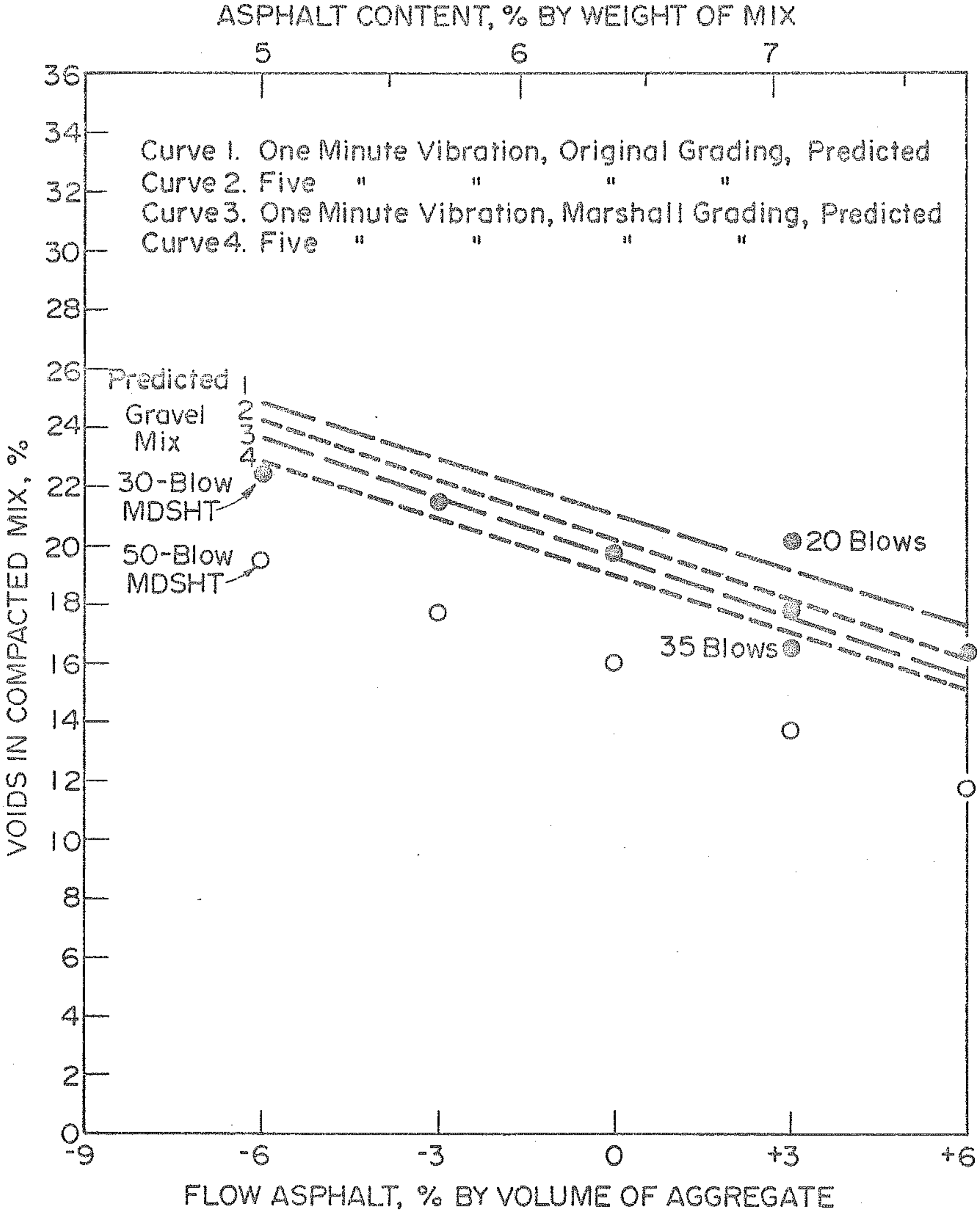

Figure 13. Voids in Marshall specimens compared with predicted voids using different aggregate compaction times and change in gradation. Crushed gravel and MDSHT compactor.

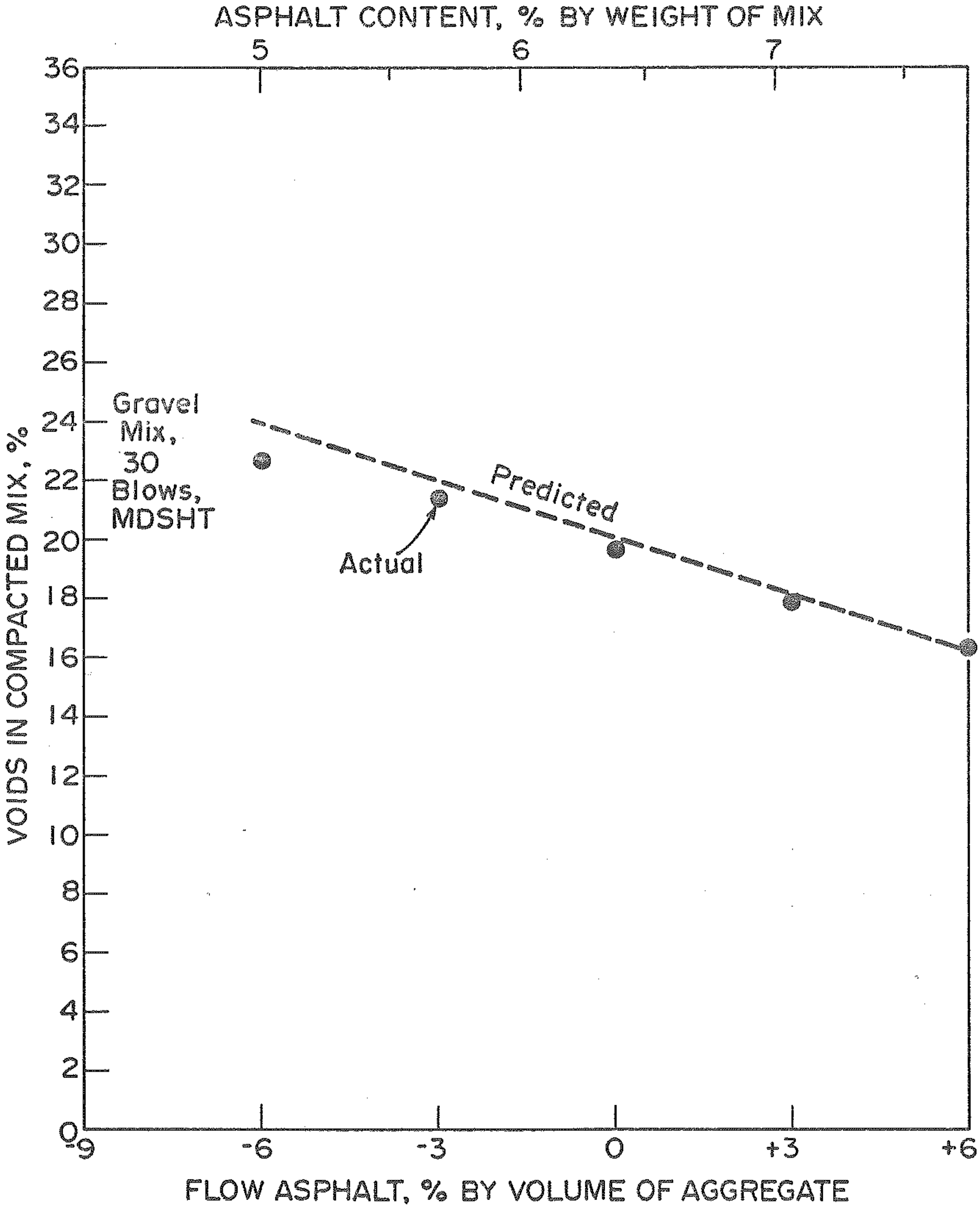

Figure 14. Voids in Marshall specimens compared with predicted voids using one-minute aggregate compaction and gradation obtained from Marshall specimens. MDSHT compactor, 30 blows.

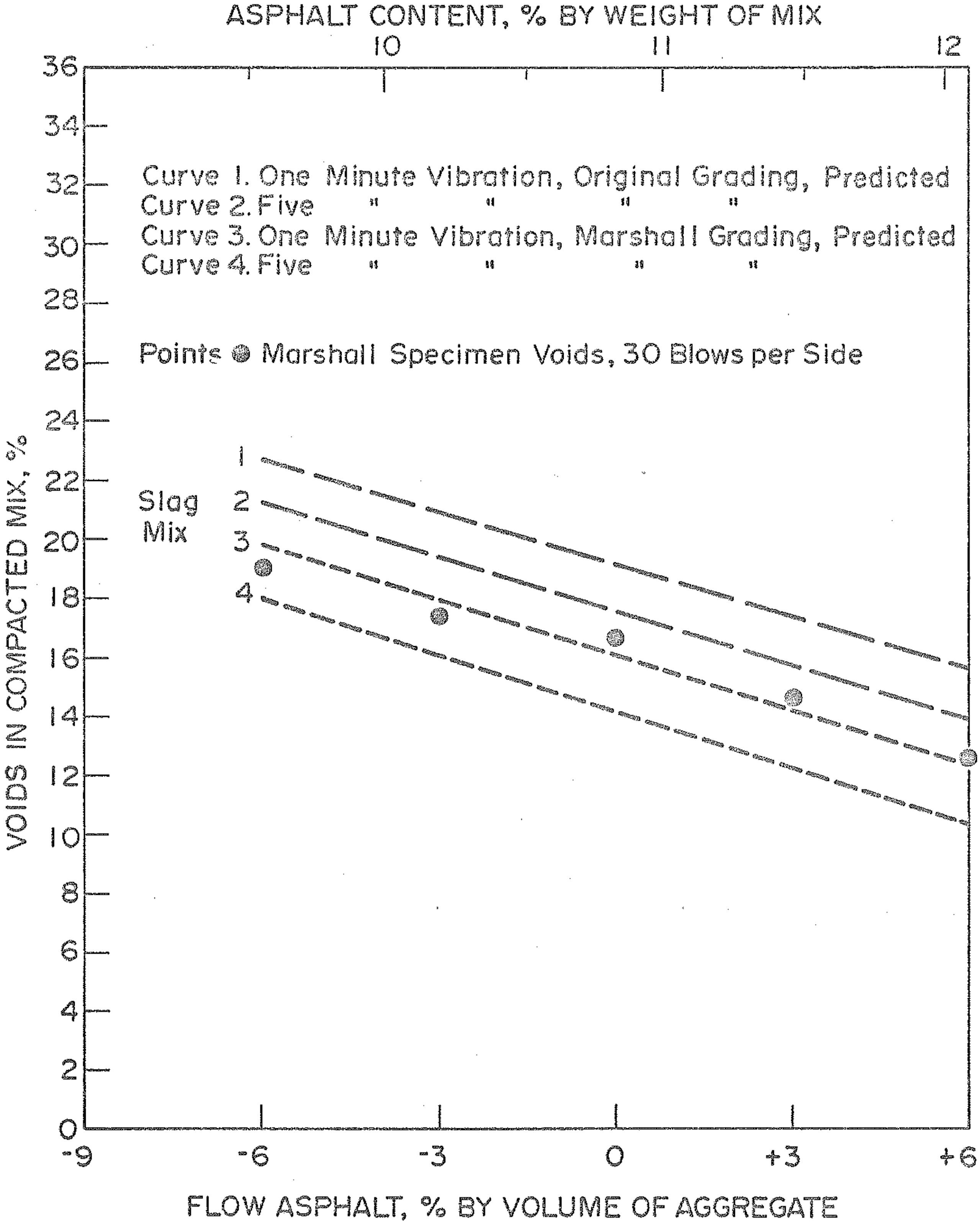

Figure 15. Voids in Marshall specimens compared with predicted voids using different aggregate compaction times and change in gradation. Slag aggregate and 30-blow MDSHT compactor.

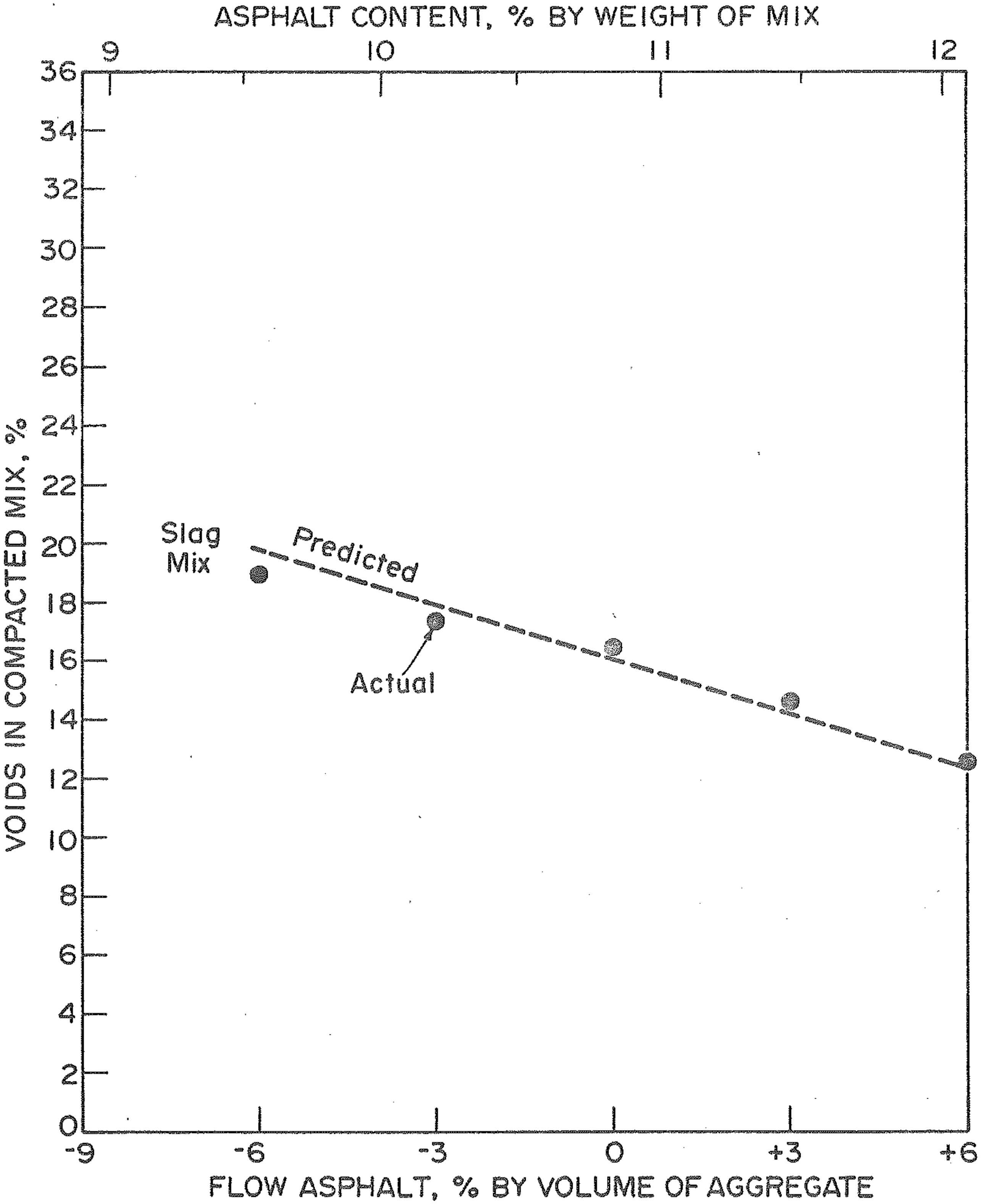

Figure 16. Voids in Marshal specimens compared with predicted voids using one-minute aggregate compaction and gradation obtained from Marshall specimens. MDSHT compactor, 30 blows.

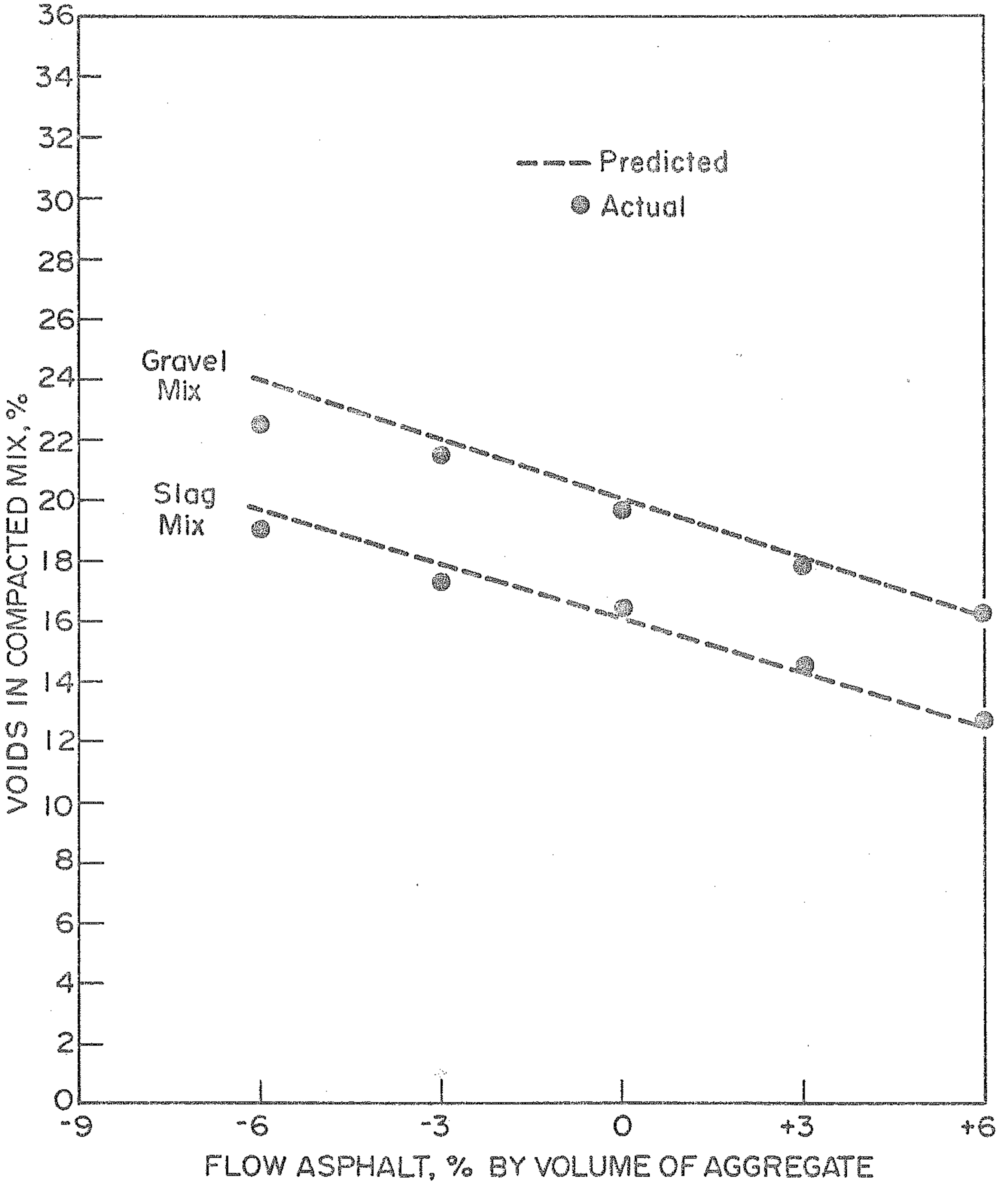

Figure 17. Voids in Marshall specimens compared with predicted voids using one-minute aggregate compaction and gradation obtained from Marshall specimens. MDSHT compactor, 30 blows.

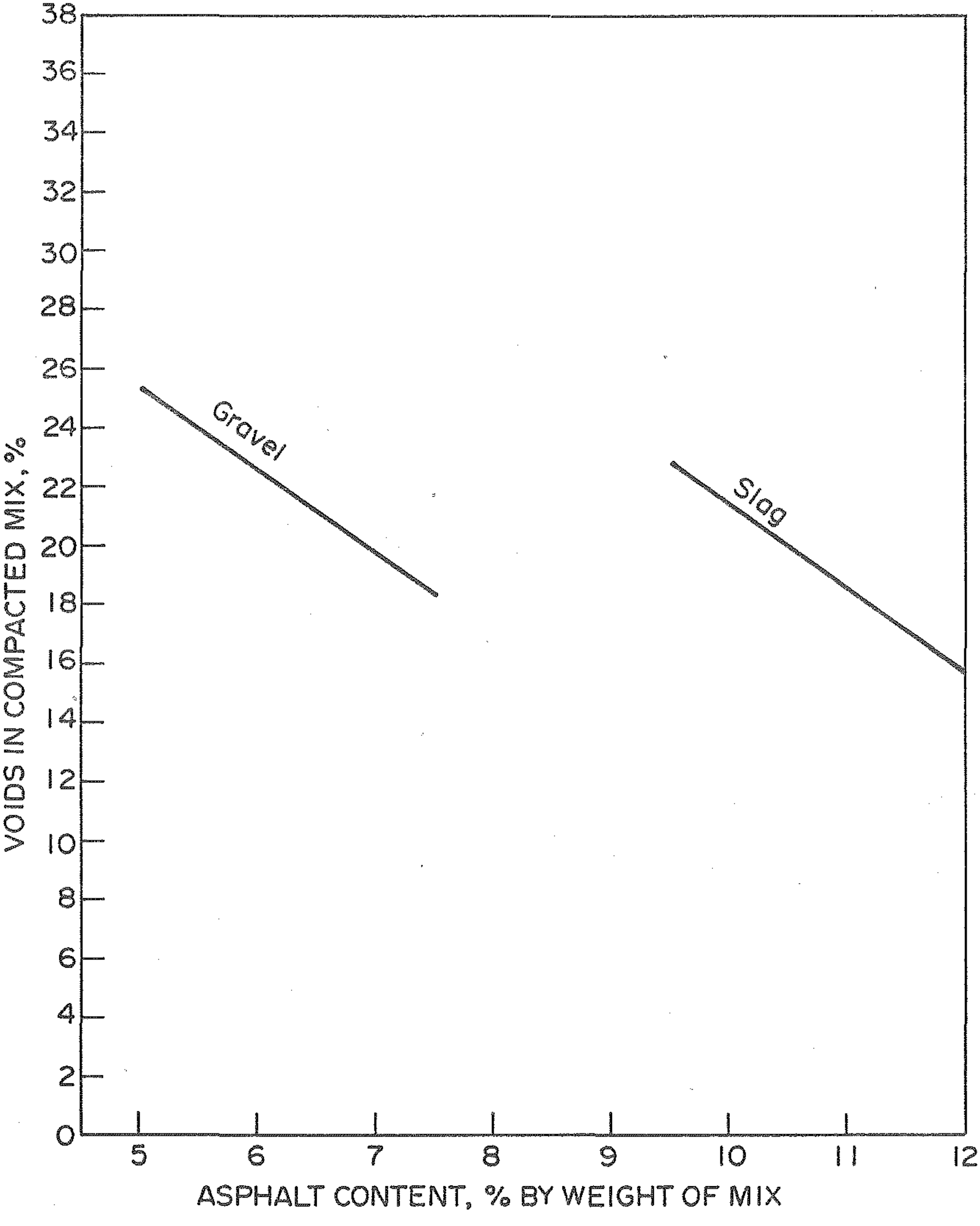

Figure 18. Predicted voids for gravel and slag mix, using one-minute compaction for the aggregates and no crushing factor.

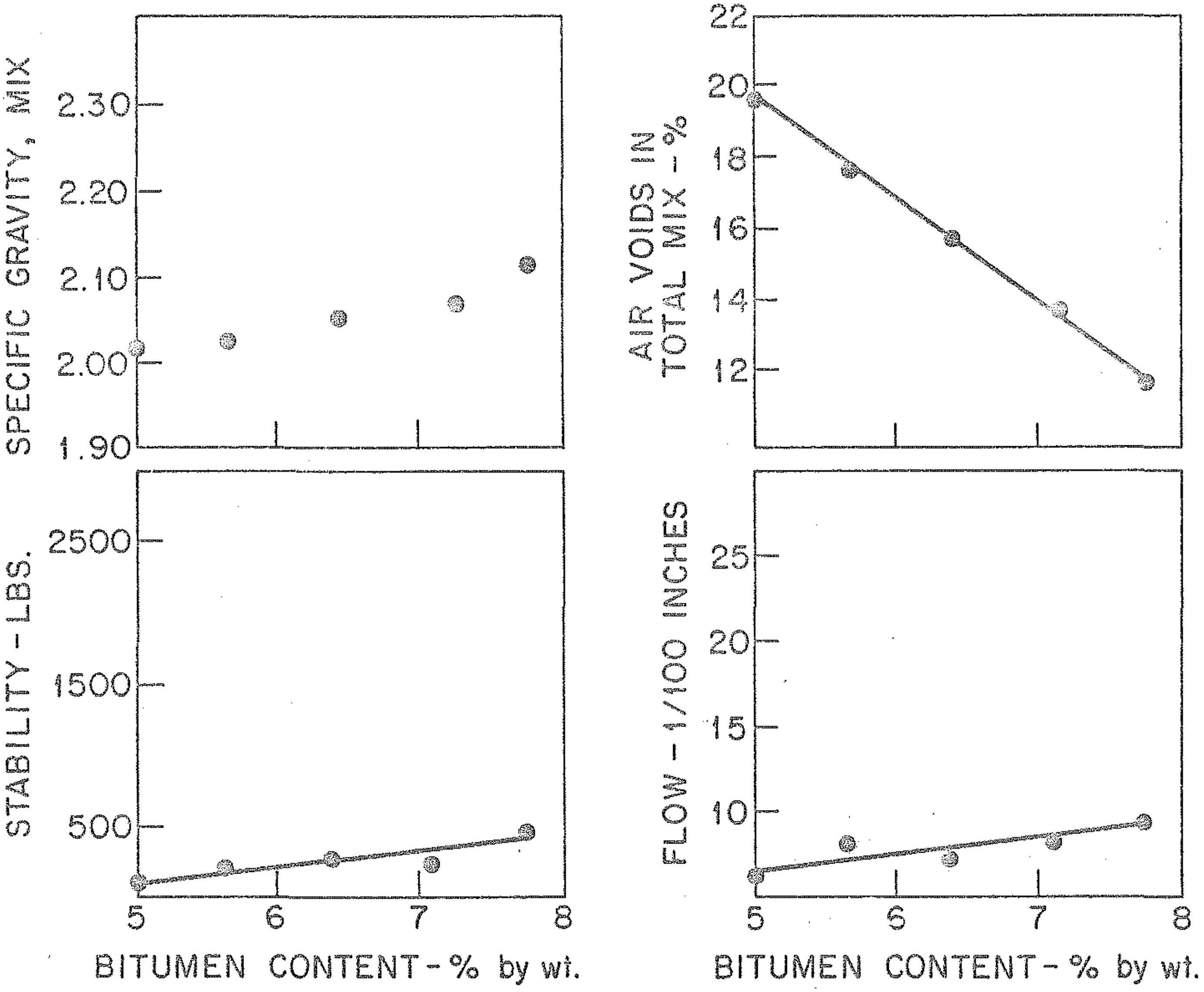

Figure 19. Marshall data for 50-blow compaction using MDSHT compactor, open graded gravel mix.

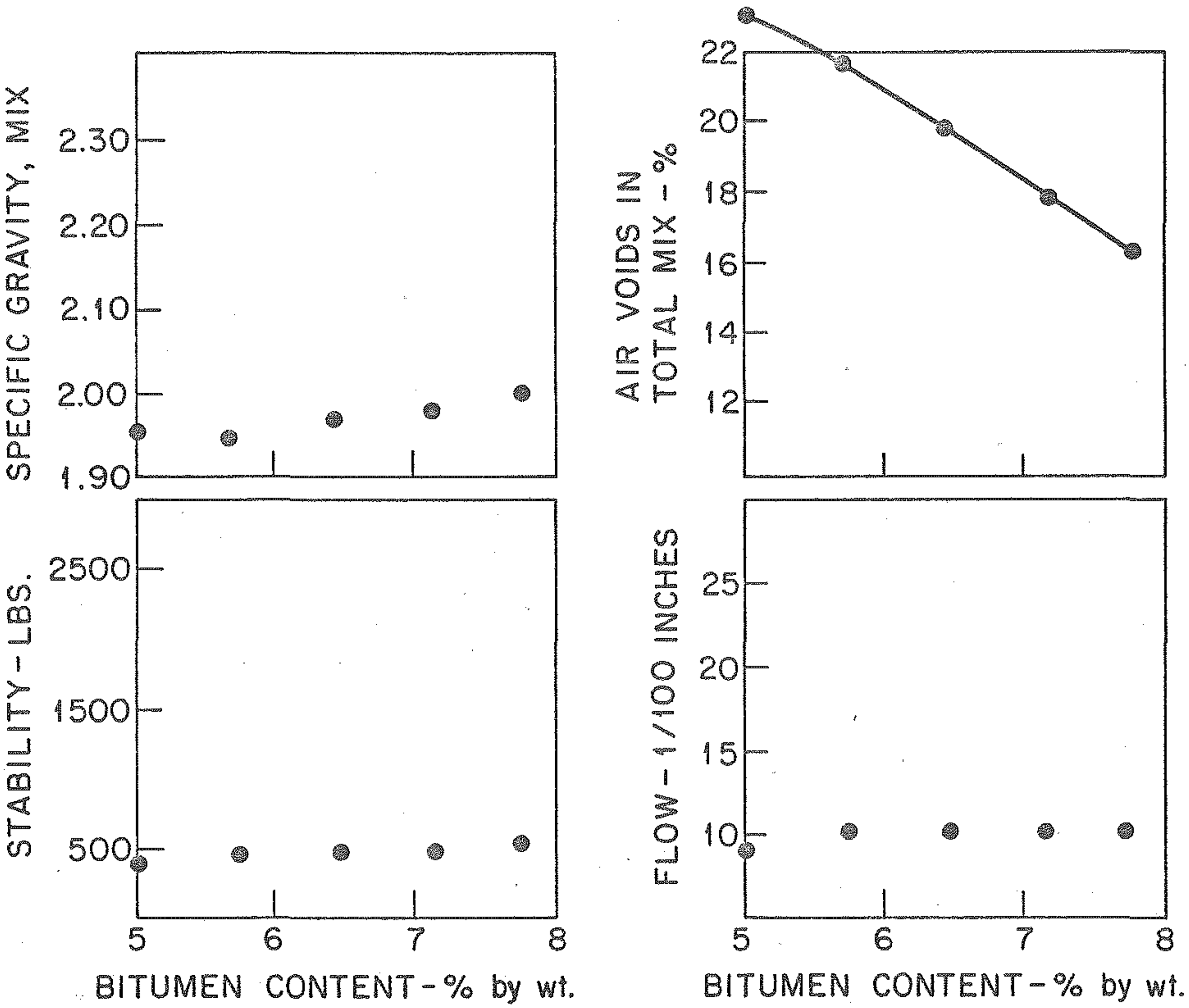

Figure 20. Marshall data for 30-blow compaction using MDSHT compactor, open graded gravel mix.

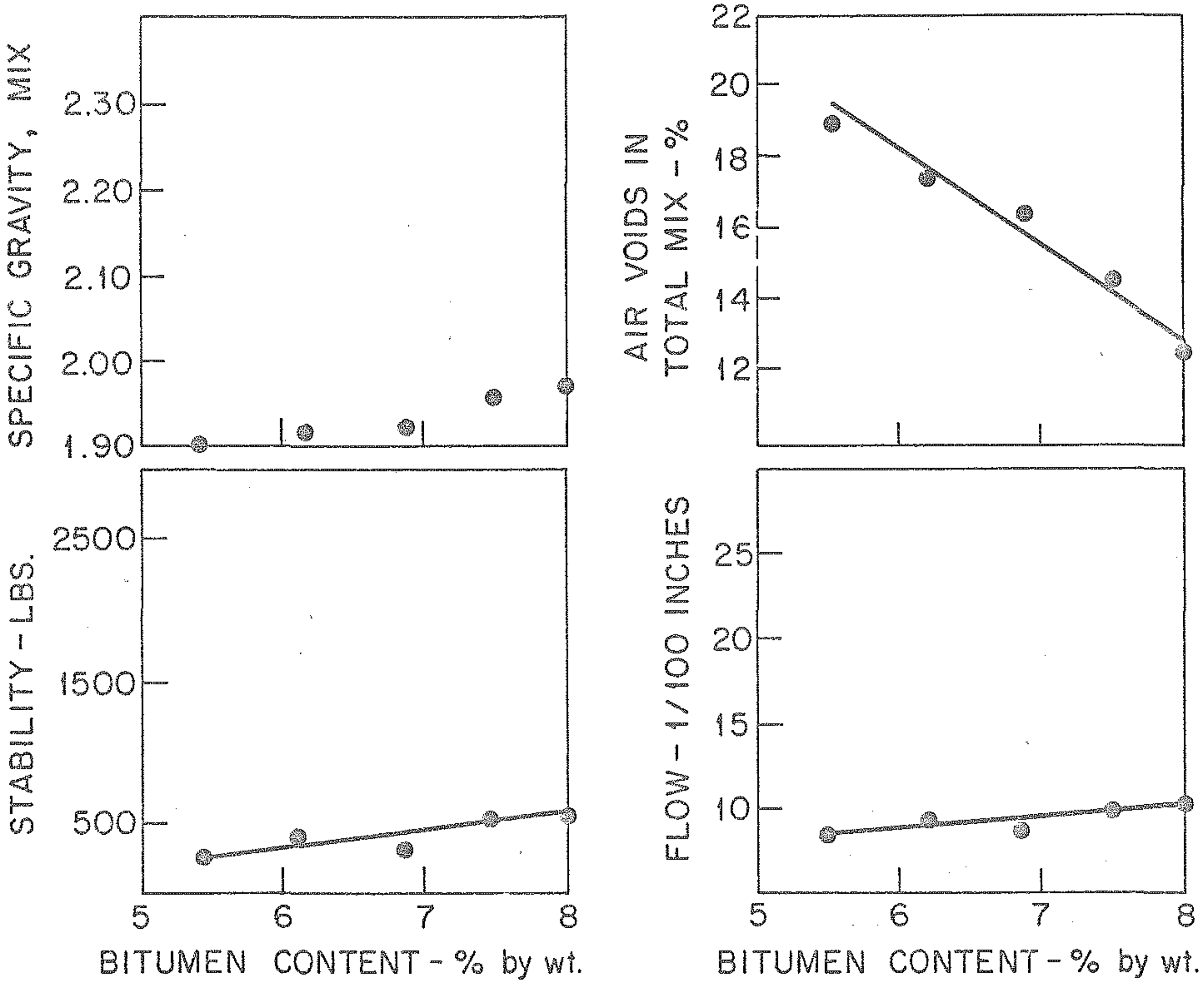

Figure 21. Marshall data for 30-blow compaction using MDSHT compactor, open graded slag mix.

APPENDICES

APPENDIX 1

MICHIGAN INSTALLATIONS - OPEN GRADED SKID RESISTANT BITUMINOUS CONCRETE MIXES

1975

(1) M-25, Essexville, two intersections, the surface was placed directly on portland cement concrete.

(2) M-125, Monroe, slag aggregate, placed on bituminous leveling course.

(3) M-24, Lapeer, placed on bituminous leveling course.

(4) Holland Ave., Saginaw, placed on bituminous leveling course.

(5) I-75, Zilwaukee Bridge approach, placed on bituminous surface.

(6) Van Dyke and 14 Mile Road in Warren, placed directly on portland cement concrete.

APPENDIX 2

PROCEDURE FOR DESIGN OF MIX WITH CONTROLLED VOID CONTENT

The steps in the mix design for open-graded - skid resistant bituminous concrete surfaces are as follows:

(1) Chose asphalt, aggregate and aggregate gradation (fractions).

(2) Measure bulk specific gravity for each aggregate fraction.

(3) Determine voids (porosity) of each fraction (without asphalt) using standardized compaction procedure corresponding to standardized number of blows for mix in the Marshall procedure.

(4) Determine the Equivalent Spherical Diameter (ESD) for each aggregate fraction.

(5) Determine the rugosity for each aggregate fraction.

(6) Determine the amount of asphalt absorbed by the aggregate.

(7) Select the amount of filler to be used and set filler/asphalt ratio.

(8) Select the amount of flow asphalt

(9) Calculate voids using a computer program.

(10) If voids are too high or too low, change aggregate proportions (or asphalt) and repeat calculations until right voids are obtained. (This is all paper-work and no additional laboratory work is needed.)

MORE DETAILED DESCRIPTION OF EACH STEP

Initially, the type of aggregate and asphalt has to be chosen for a given job (for instance, crushed gravel and 85-100 penetration asphalt). Once this has been decided, the following information on the aggregate and the asphalt is needed for prediction of voids in a mix:

(1) The aggregate <u>fractions</u> which are to be combined for the open-graded mix need to be designated (1/2" - 3/8", 3/8" - #4, #4 - #16, etc.). For all practical purposes any fraction division can be chosen. For some materials such as slag, the bulk specific gravity and other properties change considerably with decrease in particle size. In such cases the more sieve fractions that are used, the more precise the prediction.

(2) The <u>bulk specific gravity</u> is needed for each fraction used in a mix. For the crushed gravel the specific gravity of each fraction used in this experiment did not change. For the slag, the larger size aggregate had a considerably lower bulk specific gravity. If the computer is "asked" to combine different fractions in different proportions, the knowledge of the specific gravity for each fraction instead of a combination of sizes is very desirable.

The specific gravity of the asphalt should also be measured.

(3) Once the sieve fractions are chosen, the aggregate from each sieve is compacted in a vibratory compactor as described by ASTM D 2049, and this compactor is available in the MDSHT Laboratory. Briefly, the mold is fastened to the vibrator, the aggregate is poured into the mold, leveled off, and a surcharge of 53 pounds is placed on the top of the sample. Then the frequency is set on 3600 cpm and the power switch is turned on. The sample is then vibrated for one minute and the volume of the compacted aggregate is determined. Using the sample weight and bulk specific gravity, the voids in the aggregate (at 1-minute compaction) can be calculated by using the previously mentioned equation:

$$n = \left(1 - \frac{W}{SV}\right) \times 100,$$

where

n = voids in the compacted aggregate, in percent,

W = weight of the aggregate, grams,

S = bulk specific gravity of the aggregate,

V = volume of the compacted aggregate, in cc.

The amount of aggregate placed in the mold should be such that the compacted specimen height is around 3 inches.

(4) For each size the equivalent spherical diameter (ESD)

must be measured. This can be done by picking 500 particles at random and weighing them. From this the ESD can be calculated as follows:

$$V_{av} = \frac{W_t}{500\ S},$$

$$ESD = \sqrt[3]{\frac{6\ V_{av}}{\pi}},$$

where

V_{av} = average volume of the particle, in cc,

W_t = total weight of the 500 rocks, grams,

S = bulk specific gravity of the aggregate,

ESD = equivalent spherical diameter.

(5) The <u>rugosity</u> or surface roughness of the aggregate can be measured using the procedure published in Reference (12). A copy of this procedure is included in Appendix 3. However, rugosity values for a number of aggregates were determined and tabulated in the above reference and copies of this tabulation are attached to Appendix 3.

(6) The amount of <u>asphalt absorbed</u> by the aggregate is a routine measurement needed in any mix design. Absorption values for several aggregates are given in Appendix 3.

(7) The <u>filler/asphalt</u> ratio is simply the volume of filler (not weight) divided by the volume of asphalt. For the experiments described in this paper, this ratio was 0.3, but any other reasonable number could be used.

(8) The amount of flow asphalt added to the mix is based on volume. In this report the filler volume is counted as part of the flow asphalt. Since the filler/asphalt ratio was 0.3, this means that the flow asphalt contains 77 percent pure asphalt and 23 percent filler by volume. The amount of flow asphalt could be adjusted somewhat to fit voids and stability requirements, but 3% (more or less) may be a desirable quantity.

From the above list of 8 information points, only 3 are new and require some work. These are as follows:

#3, determining voids in each fraction,

#4, obtaining average diameters for each fraction,

#5, determining rugosity for each fraction.

Of the above three requirements, #4 is the easiest to obtain, requiring only a small amount of time. The voids determination (#3) is also relatively simple. The determination of rugosity may require a more sophisticated effort, but once rugosity for a certain aggregate source has been obtained, it can be used repeatedly. Also, rugosities for a number of aggregates in Michigan are available.

ACTUAL MIX DESIGN EXAMPLE

For the example, a crushed gravel mix similar to that used in laboratory comparisons is given. First, however, is a list of the numerical information used:

(1) Three aggregate fractions were combined with mineral filler and asphalt. The list is as follows:

Fraction #1,	3/8" - #4
Fraction #2,	#4 - #16
Fraction #3,	#16 - #100
Filler	passing #100
85-100	asphalt

(2) The specific gravities of each component were:

#1 - 2.67

#2 - 2.67

#3 - 2.67

Filler - 2.67

Asphalt - 1.02

(3) Aggregate fractions #1, #2 and #3 were densified by a vibratory compactor for one minute, 53# surcharge and the voids (porosity) were as follows:

#1 - 42.00

#2 - 41.29

#3 - 37.65

Voids for filler were not needed, since they are assumed to be a part of the asphalt.

(4) From each of the 3 fractions, 500 particles were selected at random and their equivalent spherical diameters were:

#1 - .700 cm
#2 - .268 cm
#3 - .055 cm

(5) The rugosity values for the three fractions were obtained from Tables 6 to 11 (Row CG, Column B_{rw}, Appendix 3), by interpolation where necessary. The final values used were:

#1 - 7.72
#2 - 11.55
#3 - 12.03

(6) The absorbed asphalt was also estimated using Tables 4 to 9, Row CG, Column B_{ag}. The values obtained were:

#1 - .55
#2 - .50
#3 - .87
Filler - .26

(7) From research done by various investigators, the filler/asphalt ratio = 0.3 appeared to be reasonable.

(8) The amount of flow asphalt was set at +3 percent by volume of #1, #2 and #3. The flow asphalt was not pure, but it contained 77 percent virgin asphalt and 23 percent filler (by volume) to make the filler/asphalt ratio = 0.3.

For this example a bag of 31 A crushed gravel aggregate was sieved and the relative proportions of fractions #1, #2 and #3 were kept as they were. The following volumetric percentages were used:

#1 -	61.73%
#2 -	35.08%
#3 -	3.19%
Total	100.00%

The first part of the mix design procedure included a computer program which calculated the voids for the combined aggregate percentages. The void content for the above blend (using 1-minute vibratory compaction as a basis) was 36.71 percent. Using these voids as a starting point, asphalt and filler were added and the final mix proportions were obtained as follows:

	Using 100 cc Bulk Vol. cc			Weight in grams
1	61.73 x 63.29/100 =	39.06 cc	x 2.67 =	104.32 g
2	35.08 x 63.29/100 =	22.21 cc	x 2.67 =	59.27 g
3	3.19 x 63.29/100 =	2.02 cc	x 2.67 =	5.39 g
Air		36.71 cc		0
	Total	100.00 cc		168.98 g

	B_{rw}		Macro + Micro in g
1	7.72 x	104.32/100 =	8.05
2	11.55 x	59.27/100 =	6.85
3	12.03 x	5.39/100 =	.65
Air	0	0	
		Total	15.55 g

	B_{ag}		Micro in g
1	.55 x	104.32/100 =	.57
2	.50 x	59.27/100 =	.30
3	.87 x	5.39/100 =	.05
Air	0	0	
		Total	.92 g = .90 cc

Macro = 15.55 - .92 = 14.63 g
Macro Voids Vol. = 14.63/1.02 = 14.34 cc
Flow Vol. = $\frac{63.29 \times .03}{1.02}$ = 1.86 cc
Total 16.20 cc

$(\text{Flow} + \text{Macro})_{1,\ 2,\ 3}$ = .77 x 16.20 = 12.47 cc = 12.72 g

Filler = .23 x 16.20 = 3.73 cc = 9.96 g

Micro in Filler = 9.96 x .26/100 = .03 g = .03 cc

Total Asphalt = $(\text{Flow} + \text{Macro} + \text{Micro})_{1,\ 2,\ 3} + (\text{Micro})_{\text{filler}}$ =
12.47 + .9 + .03 = 13.4 cc = 13.67 g

Absorbed Asphalt = .9 + .03 = .93 cc = .95 g

Composition

1	39.06 cc	=	104.32 g
2	22.21 cc	=	59.27 g
3	2.02 cc	=	5.39 g
Filler	3.73 cc	=	9.96 g
Asphalt	12.47 cc	=	12.72 g
Absorbed Asphalt	0 cc	=	.95 g
Voids	20.51 cc	=	0
Total	100.00 cc		192.61 g

Proportions by Weight

1	54.16
2	30.77
3	2.80
Filler	5.17
Asphalt	7.10
Total	100.00

The predicted voids in the mix under 30 blows of Marshall compaction is 20.51 cc or 20.51 % in the above calculation.

APPENDIX 3

THE POURING TEST METHOD

General

The pouring test was used for direct measurement of the packing specific gravity (G_p) of one-size[1] aggregate particles.

Equipment

The equipment and material used were as follows:

1) Pouring setup, which consisted of (see Figure 22):
    a. supported bin with adjustable orifice funnel
    b. stainless steel container (standard volume)
    c. large pan for collecting particles
2) Steel ruler for aggregate leveling purposes.
3) Scoop for handling particles.
4) Stainless steel bowls for handling and weighing particles.
5) Balance, 3 kg capacity. Sensitive to 0.1 g.
6) Uniform clean, smooth glass beads in different sizes.

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[1] One-size aggregates are defined as sieved fractions which pass through top sieve and retain on bottom sieve which are different by a factor of 2.

The specific setups used for different fractions were as follows (see also Figure 22):

In the first stage:

Dimension \ Fraction	1/2 in.-5/8 in.	#3-#4	#8-#10	#20-#30
D (cm)	10.0	10.0	7.5	7.5
a (cm)	7.5	5.5	1.5	1.5
b (cm)	12.5	15.0	9.0	9.0
H (cm)	20.0	17.5	20.0	20.0
Ø (cm)	12.5	10.0	5.0	5.0
h (cm)	6.5	7.5	9.5	9.5
Glass beads size (mm)	6.0	6.0	3.0	3.0

As modified in the second stage:

Dimension \ Fraction	1/2 in.-5/8 in.	#3-#4	#8-#10	#20-#30	#60-#80	#200-#270
D (cm)	16.0	16.0	16.0	8.5	8.5	8.5
a (in)	3	1-7/16	5/8	7/16	3/8	5/16
b (cm)	12.0	12.0	12.0	12.0	12.0	12.0
H (cm)	21.0	21.0	21.0	21.0	21.0	21.0
Ø (cm)	12.2	10.3	8.4	6.4	6.4	6.4
h (cm)	15.2	11.8	9.5	7.3	7.3	7.3
Glass beads (mm)	16.0	6.0	3.0	0.5	0.25	0.075

Testing Procedure

The following procedure was used for one-size fractions:

1) Fill the conical bin with the one-size glass beads, up to the fixed standard height specified.

2) Open the funnel orifice to allow free pouring of all particles into the stainless steel container.

The conical bin must contain enough material to achieve overflow (about 1.3 times the capacity of the container).

3) Level the particles pile down to the top of the container by a steel straightedge.

4) Weigh the content of the container (test response).

5) Collect all particles and repeat the same procedure for the number of replications desired.

6) Repeat the same procedure (steps 1 through 5) for all comparative aggregate fractions.

Calculations

Based on the known specific gravity of the glass beads used as a standard, the packing specific gravity of a given fraction can be calculated by using the equation given in Table 5. An example and a working sheet, similar to those used (including actual data for #8 - #10 fraction) can also be seen in Table 5.

TABLE 5

AN EXAMPLE OF A WORK SHEET USED IN THE POURING TEST

POURING TEST FOR #8 -#10 FRACTION

Bin Diameter (D): 16.0 cm
Funnel Orific Diameter (a): 1.59 cm (5/8 in)
Aggregate Head (b): 12.0 cm
Pouring Height (H): 21.0 cm
Container Diameter (Ø): 8.4 cm
Container Height (h): 9.5 cm

Average Diameter of Glass Beads: 3 mm
Specific Gravity of Glass Beads: 2.2305

$$^{*}\quad G_{px} = \frac{G_{ps}}{\Sigma W_s} \Sigma W_x = Q \Sigma W_x \qquad Q = \frac{G_{ps}}{\Sigma W_s} = \frac{2.2305}{733.92} = 3.0392 \times 10^{-3}$$

Test Data

Sample	Weight in Grams (ΣW)						Packing Sp. Gr. Factor-Q	Packing Sp. Gr. G_{px}
	Test Replications					$\Sigma W_s, \Sigma W_x$ Average		
	1	2	3	4	5			
G. Beads	733.9	733.8	734.0	734.2	733.7	733.92	3.0392×10^{-3}	
LS/A	722.9	724.1	724.1	723.8	725.2	724.04		2.201
LS/B	725.9	725.1	723.7	724.3	723.9	724.53		2.202
BP/A	824.2	823.0	824.1	825.2	825.8	824.46		2.506
BP/B	824.3	823.9	824.8	823.1	824.1	824.04		2.504
MR/A	746.0	744.9	745.2	744.8	745.7	745.32		2.265
MR/B	743.1	745.8	743.7	745.1	744.7	744.48		2.263
OL/A	765.9	761.7	761.8	762.1	762.8	762.86		2.318
OL/B	764.7	763.8	766.8	762.9	764.3	764.50		2.323
SS/A	593.1	593.1	593.2	593.4	592.7	593.10		1.803
SS/B	592.1	592.1	592.8	592.2	593.3	592.50		1.801
NG/A	754.3	754.2	754.0	755.2	756.0	754.47		2.294
NG/B	753.3	755.2	753.3	754.6	752.9	753.86		2.291
SL/A	631.1	629.8	631.2	628.9	630.2	630.24		1.915
SL/B	629.1	630.2	629.7	631.3	630.9	630.24		1.915
CG/A	680.1	679.0	678.9	677.9	678.7	678.92		2.063
CG/B	679.4	677.7	676.7	677.9	677.5	677.84		2.060

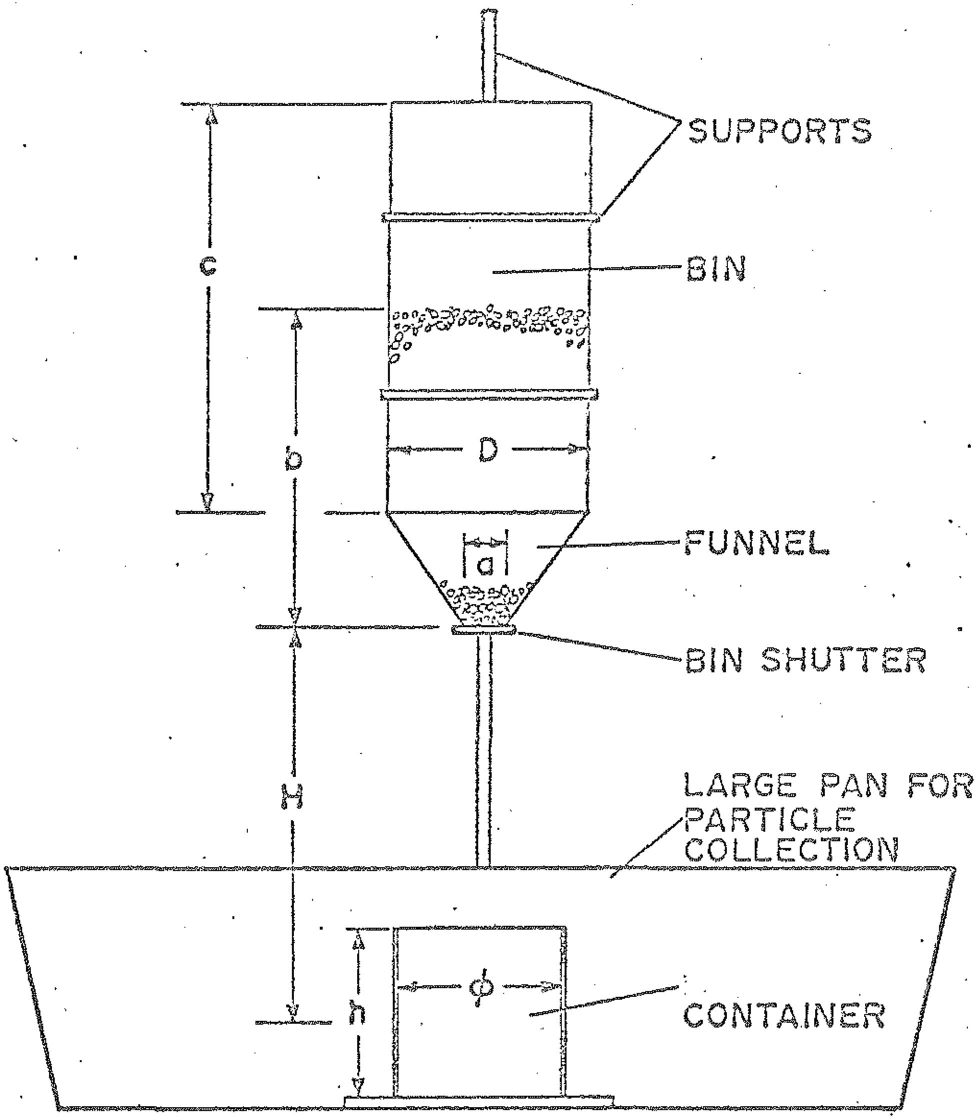
* G_{px} = packing specific gravity of the aggregate tested,

G_{ps} = packing specific gravity of the glass beads,

ΣW_s = weight of the glass beads which filled the container,

ΣW_x = weight of the aggregates which filled the container,

Q = packing specific gravity factor.



D = BIN DIAMETER
a = FUNNEL ORIFICE DIAMETER
c = BIN HEIGHT
b = AGGREGATE HEAD
H = POURING HEIGHT
ϕ = CONTAINER DIAMETER
h = CONTAINER HEIGHT

Figure 22 Schematic description of the pouring device setup.

TABLE 6

BULK AND PACKING VOLUME PARAMETERS FOR 1/2 IN.-5/8 IN. FRACTIONS
(eight selected aggregates)

	Bulk Volume Parameters					Packing Volume Parameters									
Aggregate Type	Average Particle Weight, gr (W)	Bulk Specific Gravity (G_{ag})	Apparent Specific Gravity (G_{ap})	Percent Water Absorption (A_w)	Percent Aephalt Lost by Absorption (B_{ag})	Packing Volume, cm^3 (V_p)	Equivalent Sphere Diameter, cm (d)	Packing Specific Gravity (G_p)	Percent Specific Rugosity (S_{rv})	Geometric Irregularity Number (I_g)	Percent Asphalt Lost by Rugosity (B_{rw})	Percent Asphalt Lost by Rugosity (B_{rv})	Percent Asphalt Saturation (S_b)	Percent Macro Surface Voids (S_{ma})	Percent Micro Surface Voids (S_{mi})
NG/A	4.548	2.628	2.748	1.67	0.47	1.825	1.516	2.492	9.33	0.9067	2.59	6.33	67.79	5.18	4.15
NG/B	4.666	2.603	2.725	1.71	0.27	1.855	1.524	2.516	7.65	0.9235	1.63	4.02	52.48	3.34	4.29
DL/A	5.053	2.805	2.829	0.30	0.05	2.009	1.566	2.515	11.09	0.8891	4.25	10.47	94.41	10.34	0.75
DL/B	4.848	2.800	2.829	0.37	0.37	1.922	1.543	2.522	10.87	0.8913	4.39	10.85	99.85	9.93	0.94
SS/A	3.819	2.182	2.566	6.85	2.46	1.777	1.503	2.149	16.24	0.8376	3.18	6.69	41.18	1.51	14.73
SS/B	3.868	2.177	2.570	7.03	2.44	1.807	1.511	2.140	16.74	0.8325	3.25	6.82	40.77	1.70	15.04
CG/A	4.519	2.688	2.751	0.85	0.55	1.860	1.526	2.430	11.67	0.8833	4.58	10.91	93.47	9.60	2.07
CG/B	4.503	2.695	2.753	0.78	0.47	1.844	1.522	2.442	11.28	0.8872	4.39	10.50	93.09	9.39	1.89
SL/A	3.687	2.232	2.468	4.28	3.75	1.935	1.546	1.905	22.81	0.7719	11.60	21.66	94.96	14.65	8.16
SL/B	3.599	2.227	2.467	4.37	3.64	1.880	1.534	1.906	22.74	0.7726	11.35	21.22	93.31	14.41	8.33
MR/A	5.088	2.837	2.933	1.16	0.09	2.023	1.569	2.515	14.26	0.8574	4.70	11.58	81.19	11.35	2.91
MR/B	4.831	2.840	2.929	1.07	0.02	1.929	1.545	2.504	14.51	0.8549	5.02	12.32	84.93	11.83	2.68
LS/A	4.599	2.641	2.695	0.76	0.55	1.951	1.550	2.358	12.50	0.8750	5.19	12.00	95.95	10.72	1.78
LS/B	4.619	2.647	2.698	0.72	0.17	1.950	1.550	2.369	12.21	0.8779	4.70	10.91	89.34	10.50	1.71
BP/A	5.169	2.652	2.688	0.51	0.47	1.969	1.555	2.625	2.35	0.9765	0.86	2.22	94.48	1.02	1.33
BP/B	5.193	2.661	2.701	0.55	0.18	1.973	1.556	2.632	2.55	0.9745	0.60	1.55	60.75	1.09	1.46
Average	4.538	2.582	2.709	2.06	1.01	1.907	1.538	2.376	12.43	0.8757	4.52	10.00	79.87	7.91	4.51

TABLE 7

BULK AND PACKING VOLUME PARAMETERS FOR #3-#4 FRACTIONS
(eight selected aggregates)

		Bulk Volume Parameters				Packing Volume Parameters									
Aggregate Type	Average Particle Weight, 10^{-1} gr (W)	Bulk Specific Gravity (B_{ag})	Apparent Specific Gravity (G_{ap})	Percent Water Absorption (A_w)	Percent Asphalt Lost by Absorption (B_{ag})	Packing Volume, 10^{-1} cm^3 (V_p)	Equivalent Sphere Diameter, 10^{-1} cm (d)	Packing Specific Gravity (G_p)	Percent Specific Rugosity (S_{rv})	Geometric Irregularity Number (I_g)	Percent Asphalt Lost by Rugosity (B_{rw})	Percent Asphalt Lost by Rugosity (B_{rv})	Percent Asphalt Saturation (S_b)	Percent Macro Surface Voids (S_{ma})	Percent Micro Surface Voids (S_{mi})
NG/A	2.667	2.553	2.737	2.63	1.27	1.158	6.048	2.304	15.81	0.8419	5.59	12.62	79.78	9.75	6.06
NG/B	2.601	2.568	2.741	2.46	0.99	1.122	5.984	2.318	15.44	0.8456	5.27	11.98	77.60	9.74	5.70
DL/A	2.896	2.800	2.837	0.46	0.43	1.253	6.209	2.311	18.54	0.8146	8.13	18.43	99.41	17.46	1.08
DL/B	3.035	2.797	2.838	0.51	0.48	1.314	6.308	2.310	18.59	0.8141	8.17	18.49	99.46	17.41	1.18
SS/A	2.202	2.178	2.632	7.92	4.66	1.131	6.000	1.948	25.99	0.7401	10.19	19.46	74.86	10.56	15.43
SS/B	2.272	2.174	2.628	7.95	4.45	1.165	6.060	1.950	25.81	0.7419	9.84	18.82	72.90	10.30	15.51
CG/A	2.498	2.668	2.749	1.10	0.57	1.166	6.060	2.143	22.03	0.7797	9.94	20.88	94.76	19.68	2.35
CG/B	2.378	2.673	2.750	1.04	0.57	1.109	5.961	2.145	21.99	0.7801	9.96	20.95	95.28	19.75	2.24
SL/A	2.334	2.392	2.649	4.05	3.40	1.265	6.229	1.845	30.35	0.6965	16.05	29.02	95.63	22.87	7.48
SL/B	2.399	2.386	2.654	4.23	3.57	1.305	6.293	1.838	30.73	0.6927	16.32	29.40	95.66	22.97	7.76
MR/A	2.958	2.826	2.923	1.17	0.53	1.237	6.181	2.392	18.17	0.8183	7.08	16.61	91.43	15.36	2.81
MR/B	3.048	2.819	2.929	1.34	1.03	1.274	6.243	2.392	18.35	0.8165	7.49	17.56	95.71	15.15	3.20
LS/A	2.423	2.636	2.701	0.91	0.75	1.137	6.010	2.131	21.10	0.7890	9.92	20.73	98.24	19.16	1.94
LS/B	2.442	2.637	2.701	0.90	0.77	1.147	6.028	2.129	21.19	0.7881	10.00	20.88	98.54	19.26	1.93
BP/A	2.960	2.719	2.762	0.57	0.14	1.114	5.971	2.656	3.84	0.9616	1.03	2.68	69.83	2.32	1.52
BP/B	2.868	2.716	2.755	0.51	0.09	1.081	5.910	2.653	3.69	0.9631	0.98	2.55	69.05	2.32	1.37
Average	2.624	2.546	2.749	2.36	1.48	1.186	6.156	2.166	19.48	0.8052	8.50	17.56	88.01	14.63	4.85

TABLE 8

BULK AND PACKING VOLUME PARAMETERS FOR #8-#10 FRACTIONS
(eight selected aggregates)

		Bulk Volume Parameters				Packing Volume Parameters										
Aggregate Type	Average Particle Weight, 10^{-2} gr (W)	Bulk Specific Gravity (G_{ag})	Apparent Specific Gravity (G_{ap})	Percent Water Absorption (A_w)	Percent Asphalt Lost by Absorption (B_{ag})	Packing Volume, 10^{-3} cm^3 (V_p)	Equivalent Sphere Diameter, 10^{-1} cm (d)	Packing Specific Gravity (G_p)	Percent Specific Rugosity (S_{rv})	Geometric Irregularity Number (I_g)	Percent Asphalt Lost by Rugosity (B_{rw})	Percent Asphalt Lost by Rugosity (B_{rv})	Percent Asphalt Saturation (S_b)	Percent Macro Surface Voids (S_{ma})	Percent Micro Surface Voids (S_{mi})
NG/A	1.803	2.556	2.727	2.46	1.19	7.861	2.467	2.294	15.89	0.8411	5.75	12.92	81.31	10.25	5.64
NG/B	1.791	2.566	2.746	2.55	1.00	7.816	2.462	2.291	16.56	0.8344	5.78	12.97	78.33	10.72	5.84
DL/A	1.857	2.788	2.840	0.65	0.37	8.010	2.482	2.318	18.37	0.8163	7.79	17.70	96.31	16.86	1.51
DL/B	1.889	2.790	2.836	0.58	0.32	8.133	2.495	2.323	18.08	0.8192	7.67	17.47	96.62	16.74	1.34
SS/A	1.490	2.178	2.697	8.83	6.63	8.264	2.508	1.803	33.14	0.6686	16.37	28.93	87.31	17.22	15.92
SS/B	1.513	2.182	2.688	8.62	6.47	8.403	2.522	1.801	32.99	0.6701	16.36	28.88	87.54	17.46	15.53
CG/A	1.824	2.675	2.771	1.29	0.65	8.840	2.565	2.063	25.54	0.7446	11.97	24.20	94.75	22.88	2.66
CG/B	1.780	2.680	2.761	1.10	0.32	8.638	2.546	2.060	25.40	0.7460	11.78	23.78	93.64	23.13	2.27
SL/A	1.624	2.595	2.845	3.39	2.77	8.480	2.530	1.915	32.69	0.6731	16.73	31.41	96.07	26.20	6.49
SL/B	1.597	2.594	2.846	3.41	2.71	8.340	2.516	1.915	32.71	0.6729	16.65	31.25	95.55	26.18	6.53
MR/A	1.884	2.793	2.915	1.50	0.52	8.316	2.514	2.265	22.30	0.7770	9.04	20.07	90.01	18.90	3.40
MR/B	1.828	2.793	2.915	1.50	0.46	8.076	2.489	2.263	22.36	0.7764	9.01	19.99	89.39	18.98	3.38
LS/A	1.688	2.631	2.702	1.00	0.45	7.671	2.447	2.201	18.54	0.8146	8.02	17.31	93.38	16.34	2.20
LS/B	1.712	2.630	2.702	1.01	0.60	7.773	2.458	2.202	18.50	0.8150	8.14	17.57	94.98	16.27	2.23
BP/A	2.105	2.703	2.757	0.73	- .27	8.401	2.522	2.506	9.12	0.9088	2.69	6.62	72.58	7.29	1.83
BP/B	2.075	2.690	2.744	0.73	0.03	8.286	2.511	2.504	8.74	0.9126	2.84	6.98	79.83	6.91	1.83
Average	1.779	2.615	2.781	2.46	1.53	8.200	2.502	2.170	21.93	0.7807	9.79	19.88	89.23	17.02	4.91

TABLE 9

BULK AND PACKING VOLUME PARAMETERS FOR #20-#30 FRACTIONS
(eight selected aggregates)

		Bulk Volume Parameters				Packing Volume Parameters									
Aggregate Type	Average Particle Weight, 10^{-4} gr (W)	Bulk Specific Gravity (G_{ag})	Apparent Specific Gravity (G_{ap})	Percent Water Absorption (A_w)	Percent Asphalt Lost by Absorption (B_{ag})	Packing Volume, 10^{-4} cm^3 (V_p)	Equivalent Sphere Diameter, 10^{-2} cm (d)	Packing Specific Gravity (G_p)	Percent Specific Rugosity (S_{rv})	Geometric Irregularity Number (I_g)	Percent Asphalt Lost by Rugosity (B_{rw})	Percent Asphalt Lost by Rugosity (B_{rv})	Percent Asphalt Saturation (S_b)	Percent Macro Surface Voids (S_{ma})	Percent Micro Surface Voids (S_{mi})
NG/A	6.279	2.585	2.711	1.79	1.29	2.633	7.952	2.385	12.02	0.8798	4.60	10.75	89.44	7.74	4.28
NG/B	6.225	2.576	2.692	1.68	1.53	2.623	7.943	2.373	11.86	0.8814	4.91	11.43	96.39	7.88	3.98
DL/A	6.328	2.786	2.842	0.70	0.72	2.878	8.191	2.199	22.62	0.7738	10.49	22.62	100.00	21.07	1.55
DL/B	6.346	2.785	2.846	0.77	0.78	2.887	8.200	2.198	22.77	0.7723	10.56	22.76	99.95	21.08	1.69
SS/A	4.889	2.349	2.629	4.54	4.61	2.864	8.178	1.707	35.08	0.6492	20.94	35.05	99.90	27.33	7.75
SS/B	4.962	2.296	2.661	5.98	5.88	2.905	8.217	1.708	35.82	0.6418	21.17	35.45	98.96	25.61	10.21
CG/A	6.002	2.675	2.771	1.29	0.88	2.894	8.206	2.074	25.14	0.7486	11.93	24.25	96.44	22.47	2.67
CG/B	5.959	2.675	2.769	1.27	0.86	2.869	8.183	2.077	24.98	0.7502	11.84	24.11	96.49	22.36	2.62
SL/A	5.945	2.725	2.920	2.45	2.09	2.786	8.103	2.134	26.91	0.7309	12.45	26.05	96.82	21.69	5.22
SL/B	6.064	2.728	2.912	2.31	1.75	2.859	8.174	2.121	27.16	0.7284	12.45	25.88	95.28	22.25	4.91
MR/A	6.142	2.775	2.908	1.65	1.05	2.870	8.184	2.140	26.42	0.7358	11.96	25.09	94.95	22.88	3.54
MR/B	6.443	2.774	2.908	1.66	1.32	3.007	8.312	2.143	26.32	0.7368	12.15	25.52	96.98	22.75	3.57
LS/A	5.940	2.627	2.708	1.14	0.70	2.755	8.073	2.156	20.38	0.7962	9.18	19.40	95.19	17.93	2.45
LS/B	5.883	2.627	2.708	1.14	0.50	2.730	8.049	2.155	20.42	0.7958	9.00	19.03	93.17	17.97	2.45
BP/A	6.691	2.661	2.686	0.35	0.12	2.605	7.924	2.568	4.40	0.9560	1.51	3.80	86.43	3.49	0.91
BP/B	6.602	2.661	2.684	0.33	0.17	2.572	7.890	2.567	4.37	0.9563	1.58	3.97	90.80	3.53	0.84
Average	6.044	2.644	2.772	1.82	1.52	2.796	8.111	2.169	21.67	0.7833	10.42	20.95	95.45	18.00	3.66

TABLE 10

BULK AND PACKING VOLUME PARAMETERS FOR #60-#80 FRACTIONS
(eight selected aggregates)

		Bulk Volume Parameters				Packing Volume Parameters									
Aggregate Type	Average Particle Weight, 10^{-5} gr (W)	Bulk Specific Gravity (B_{ag})	Apparent Specific Gravity (G_{ap})	Percent Water Absorption (A_w)	Percent Asphalt Lost by Absorption (B_{ag})	Packing Volume, 10^{-6} cm^3 (V_p)	Equivalent Sphere Diameter, 10^{-2} cm (d)	Packing Specific Gravity (G_p)	Percent Specific Rugosity (S_{rv})	Geometric Irregularity Number (I_g)	Percent Asphalt Lost by Rugosity (B_{rw})	Percent Asphalt Lost by Rugosity (B_{rv})	Percent Asphalt Saturation (S_b)	Percent Macro Surface Voids (S_{ma})	Percent Micro Surface Voids (S_{mi})
NG/A	1.546	2.612	2.665	0.76	0.51	6.576	2.324	2.351	11.77	0.8823	4.85	11.18	94.96	9.99	1.78
NG/B	1.596	2.615	2.660	0.65	0.56	6.809	2.352	2.344	11.90	0.8810	5.07	11.66	98.01	10.36	1.54
DL/A	1.512	2.807	2.845	0.48	0.40	7.221	2.398	2.094	26.40	0.7360	12.77	26.21	99.29	25.40	1.00
DL/B	1.330	2.808	2.844	0.45	0.47	6.345	2.297	2.096	26.30	0.7370	12.81	26.31	100.00	25.36	0.94
SS/A	1.166	2.531	2.703	2.51	2.46	6.351	2.298	1.836	32.07	0.6793	17.71	31.89	99.42	27.46	4.61
SS/B	1.152	2.534	2.697	2.38	2.23	6.275	2.288	1.836	31.92	0.6808	17.53	31.56	98.87	27.55	4.37
CG/A	1.386	2.682	2.757	1.01	0.88	6.916	2.364	2.004	27.30	0.7270	13.75	27.00	98.91	25.28	2.02
CG/B	1.504	2.682	2.759	1.04	0.84	7.468	2.425	2.014	26.99	0.7301	13.46	26.57	98.43	24.91	2.08
SL/A	1.680	2.751	2.955	2.51	2.24	7.629	2.443	2.202	25.49	0.7451	11.48	24.79	97.28	19.96	5.53
SL/B	1.872	2.753	2.953	2.46	2.14	8.540	2.536	2.192	25.77	0.7423	11.62	24.97	96.91	20.38	5.39
MR/A	1.574	2.821	2.950	1.55	1.13	7.575	2.437	2.078	29.56	0.7044	14.06	28.65	96.93	26.34	3.22
MR/B	1.598	2.819	2.952	1.60	1.23	7.701	2.450	2.075	29.71	0.7029	14.21	28.90	97.26	26.39	3.32
LS/A	1.344	2.617	2.726	1.52	1.07	6.754	2.345	1.990	26.99	0.7301	13.35	26.06	96.54	23.96	3.03
LS/B	1.382	2.619	2.724	1.47	1.05	6.945	2.367	1.990	26.94	0.7306	13.36	26.06	96.73	24.02	2.92
BP/A	2.006	2.707	2.714	0.10	-.04	7.941	2.475	2.526	6.94	0.9306	2.66	6.58	94.86	6.69	0.25
BP/B	2.016	2.706	2.715	0.13	0.15	7.984	2.480	2.525	7.00	0.9300	2.85	7.06	100.00	6.69	0.31
Average	1.542	2.692	2.789	1.29	1.09	7.189	2.392	2.136	23.31	0.7669	11.35	22.84	97.78	20.68	2.64

TABLE 11

BULK AND PACKING VOLUME PARAMETERS FOR #200-#270 FRACTIONS
(eight selected aggregates)

	Bulk Volume Parameters				Packing Volume Parameters									
Aggregate Type	Bulk Specific Gravity (G_{ag})	Apparent Specific Gravity (G_{ap})	Percent Water Absorption (A_w)	Percent Asphalt Lost by Absorption (B_{ag})	Packing Volume, cm^3 (V_p)	Equivalent Sphere Diameter, cm (d)	Packing Specific Gravity (G_p)	Percent Specific Rugosity (S_{rv})	Geometric Irregularity Number (I_g)	Percent Asphalt Lost by Rugosity (B_{rw})	Percent Asphalt Lost by Rugosity (B_{rv})	Percent Asphalt Saturation (S_b)	Percent Macro Surface Voids (S_{ma})	Percent Micro Surface Voids (S_{mi})
NG/A	2.605	2.710	1.49	0.82	Estimated $V_p = 1.8 \times 10^{-7}$ cm^3	Estimated $d = 7.0 \times 10^{-3}$cm	2.073	23.51	0.7649	10.86	22.08	93.93	20.42	3.09
NG/B	2.585	2.711	1.80	1.12			2.058	24.09	0.7591	11.22	22.64	94.00	20.39	3.70
DL/A	2.842	2.864	0.27	0.06			2.196	23.32	0.7668	10.62	22.86	98.04	22.73	0.59
DL/B	2.843	2.862	0.23	0.05			2.205	22.96	0.7704	10.43	22.54	98.20	22.44	0.52
SS/A	2.578	2.725	2.09	1.51			1.892	30.57	0.6943	15.86	29.42	96.22	26.61	3.96
SS/B	2.593	2.698	1.50	1.29			1.898	29.64	0.7036	15.69	29.20	98.49	26.80	2.84
CG/A	2.736	2.774	0.50	0.24			2.022	27.11	0.7289	13.41	26.58	98.03	26.10	1.01
CG/B	2.734	2.778	0.58	0.27			2.023	27.18	0.7282	13.38	26.54	97.66	26.01	1.17
SL/A	2.784	3.027	2.88	2.49			2.087	31.05	0.6895	14.73	30.13	97.04	25.04	6.01
SL/B	2.806	3.028	2.62	2.20			2.101	30.62	0.6938	14.40	29.66	96.86	25.12	5.50
MR/A	2.801	2.944	1.73	1.39			2.057	30.12	0.6988	14.56	29.37	97.50	26.56	3.56
MR/B	2.803	2.941	1.68	1.36			2.061	29.93	0.7007	14.47	29.23	97.66	26.47	3.46
LS/A	2.655	2.731	1.05	0.49			1.990	27.14	0.7286	13.33	26.01	95.84	25.05	2.09
LS/B	2.656	2.729	1.01	0.48			1.990	27.09	0.7291	13.33	26.01	96.02	25.08	2.01
Average	2.715	2.809	1.23	0.87			2.107	24.89	0.7511	11.99	24.12	96.89	22.39	2.82