Design Factors for Bituminous Concrete

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ABSTRACT

DESIGN FACTORS FOR BITUMINOUS CONCRETE

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The main purpose of this research was to look for practical, quantitative factors which would describe the behavior of different aggregates and gradings used in bituminous mixes.

Eight aggregates were selected having a wide representation of properties (slag, porous sandstone, limestone, mine rock, smooth beach pebbles, natural gravel, dolomite and crushed gravel). The work was divided into two main phases:

1. Aggregate factors were defined and measured for one sieve-size fractions.

2. The developed parameters were expanded to describe and test the behavior of graded bituminous mixtures.

In the first phase the packing volume concept, as developed by Tons *et al.*[1] for one-volume particles, was extended. Two factors, mainly (a) the packing volume of a particle and (b) the geometric irregularity[2] (particle shape, angularity, and roughness combined) were found to be the unifying parameters for

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[1] AAPT Proceedings, 1970, page 24.

[2] Called rugosity by Tons, Goetz, and Anderson.

Abstract continued:

all aggregates tested. The one-volume particles were represented by easily obtainable one-size sieve fractions. The packing volume of the aggregates was measured using a newly developed pouring test. The geometric irregularity (rugosity) of uncoated aggregates was characterized by specific rugosity (S_{rv}) in terms of a volume ratio calculated from the pouring test data. For asphalt coated particles the amount of stationary asphalt inside the aggregate voids and surface crevices was measured and expressed as asphalt lost by rugosity (B_{rv}). The remaining active asphalt was designated as flow asphalt (W_{fv}).

In the second phase, the one-size aggregate parameters were used to develop procedures for characterizing graded (multi-size) aggregate and asphalt mixtures. The amount of finer particles which interact and get lost in the surface crevices of the larger particles was measured and designated as fines lost by rugosity (F_r). The important components making up a compacted bituminous mix were identified as follows:

1. Aggregate particles lost in the surface crevices of the larger fractions (total fines lost by rugosity).
2. Active aggregate particles (not lost, floating in the matrix).
3. Asphalt filling the micro and macro voids in the aggregate surface (asphalt lost by rugosity).

Abstract continued:

4. Flow or active asphalt between the active aggregate particles.
5. Air voids.

Laboratory tests using one grading and one asphalt with the 8 widely different aggregates were performed including Marshall measurements. The optimum conditions for the eight compacted mixes were achieved at similar flow asphalt contents regardless of aggregate type. Thus a new, unified, quantitative approach to a bituminous mix design has been initiated.

In addition to the number of new mix parameters, conventional ones were also measured both for the aggregates and the mix. Comparisons and relationships are shown and analyzed to explain the differences and similarities between the existing and new parameters for bituminous concrete mixes.

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I

INTRODUCTION

Description of the Problem

The present methods used for designing bituminous concrete mixes are based on trial-and-error testing in the laboratory and on field correlation studies. Since such tests and observations involve measurements on specimens in bulk, it is difficult to see and discuss mix behavior with certainty when various types and sizes of aggregates and different bitumens are used. In other words, there is a lack of proper quantitative factors which would tie together the properties of the components making up the bituminous concrete (bitumen and aggregate particles) with the behavior of the compacted mixture in a specimen and on the road.

One of the main stumbling blocks towards a unified approach of designing bituminous mixtures has been the great variety of irregular aggregate particles found in various geographic locations. Since aggregates occupy by far the largest volume of the mix, they have a profound influence on its behavior. Therefore, the most important objective of this research was to find quantitative (physical) factors or parameters which can characterize the properties of particles (aggregates) from different sources and of different sizes and gradings in such a way that the bulk behavior (in pavement) can be made more predictable. Since the aim of this work was to develop an approach which applies to a wide range of aggregates, it is often called a unified approach in this report.

Purpose and Scope of this Investigation

The purpose of this investigation was:

(a) To develop physical factors for a unified characterization of dry aggregate particles of different types and sizes.

(b) To relate these parameters with factors which would reflect the asphalt requirement for bituminous concrete mixtures.

(c) To develop simple and practical techniques for measuring the aggregate parameters.

(d) To compare the developed parameters with aggregate factors presently used in bituminous mixture technology.

(e) To develop a practical procedure for estimating the optimum asphalt content in compacted bituminous mixtures.

With regard to (a) and (b), the unified aggregate factors were based on the recently developed packing volume concept (2, 3).[1] This concept (which will be described later in detail) led to a development of aggregate parameters which serve to characterize rock particles individually, as well as in bulk. The main intention was to come up with factors which will be both quantitative and practical.

As for (c), several testing methods were tried for measuring single parameters. The final test methods were chosen based on reliability, simplicity, rapidity, repeatability and reproducibility. A practical test for measuring packing volume of aggregate was developed.

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[1] (2, 3) numbers in parentheses refer to the list of references in the Bibliography.

In connection with (d), a comparison of the new aggregate factors with the conventional ones underscored the advantages of the suggested new approach.

Concerning (e), a preliminary procedure for estimating the optimum asphalt content for compacted bituminous mixtures was suggested. This procedure is based uniquely on the new aggregate factors discussed above.

In general, the entire investigation involved literature review, theoretical considerations, statistical design of laboratory experiments and analysis of test results, and computer programming. The experimental work involved investigation of eight different types of aggregates which represent a wide range of aggregates used in bituminous mixtures. For each type of aggregate six different sizes were tested. These sizes were combined when graded mixtures were investigated.

A total of more than a thousand measurements were made to obtain the experimental data.

II

THEORETICAL AND EXPERIMENTAL CRITERIA FOR ADOPTING AGGREGATE FACTORS FOR ONE-SIZE AGGREGATE FRACTIONS

Theoretical Considerations

As indicated in the literature review, two major factors largely characterize the properties of aggregate particles and their influence on the performance of the compacted bituminous mixture: (a) particle volume and (b) particle geometry (shape, angularity, and surface texture). An attempt has been made to assign quantitative values to these basic properties, but the wide range of irregularity of aggregate particles has made it difficult to measure and implement them in design of bituminous mixtures.

Therefore, the first concern and emphasis was to find aggregate factors which:

(a) Can be defined quantitatively (physically).

(b) Can be based on a concept which unifies the major properties of particle and at the same time reflects the behavior of particles in bulk with or without the asphalt binder.

(c) Can be measured by simple, practical and reliable tests.

(d) Can have predictable relationships.

(e) Can show significant advantages when compared to conventional factors presently used.

Since volume and geometric properties are two basic properties of aggregate particles, a definition of particle volume which would reflect the bulk behavior and which would also serve as a basis for a definition of the geometry is desirable.

Volume of Particles

It was shown by Tons et al. (2, 3) that the volume which a rock particle occupies in a mass of monovolume one-size particles largely determines the density and the voids in bulk, and therefore this volume is important in the resistance of these particles to various forces. Since the particles usually touch one another at the peaks of the surface roughness, the volume which a particle occupies in a mass of other particle encompasses not only the volume of the solids and voids of the particle, but also the volume of the macro dips and valleys of the particle surface (see Figure 3).

This volume was designated as packing volume of a particle and the packing volume concept was stated as follows:

> Different types of monovolume (V_p) aggregates will be compacted to the same bulk volume (V_{b1}) when they possess identical total packing volumes (ΣV_p) under identical compaction procedures.

That is, when ΣV_p is constant, any type of monovolume particles will be compacted to the same volume in bulk under identical compaction energy input (provided the particles are not crushed or broken during compaction).

If V_p is constant, the following equation can be written (4):

$$V_p = \frac{\Sigma W_1}{G_{p1}} = \frac{\Sigma W_2}{G_{p2}} = \ldots. = \frac{\Sigma W_i}{G_{pi}} = \ldots. = \text{constant}, \qquad (1)$$

and thus

$$\Sigma W_1 : \Sigma W_2 : \ldots : \Sigma W_i : \ldots = G_{pi} : G_{p2} : \ldots : G_{pi} : \ldots , \qquad (2)$$

where

ΣW_i = the weight of all particles of the i-th monovolume (one-size) fraction which occupy the same volume in bulk

G_{pi} = the packing specific gravity of the i-th monovolume fraction (dry-weight divided by packing volume).

The packing volume can also be measured by fitting to the particle an ellipsoid as a geometric shape. In this case the long, medium and short dimensions (ℓ, m, s, respectively) can be used to calculate V_p by $V_p = \pi \ell ms/6$ (2).

It is also possible to approximate the packing volume membrane by immersing the aggregate particle in asphalt and scraping the excess asphalt down to the peaks of the rock surface (2, 3).

Equation (1) leads to a practical way for direct evaluation of the packing specific gravity of monovolume particles. If one takes two types of monovolume particles, one standard with known and another with an unknown packing specific gravity, and pours them into the same size container by identical procedures, then the packing specific gravity of the unknown material can be defined by the ratio of the weights of the particles which occupy the same bulk volume (4), that is:

$$G_{px} = \frac{\Sigma W_x}{\Sigma W_s} G_{ps} , \qquad (3)$$

where

G_{px}, G_{ps} = packing specific gravities of the unknown and the standard fractions, respectively

$\Sigma W_x, \Sigma W_s$ = weights of the unknown and standard fractions which occupy the same bulk volumes.

If the packing specific gravity of the particles has been determined, the packing volume of a particle can be evaluated when the particle weight (average) of the one-size fraction is known. This relationship was used all through this study to measure the packing volumes of different rock types and sizes.

Geometric Properties of Particles

The packing volume can be visualized as volume under an imaginary membrane enveloping the particle solids, voids and surface hills and valleys. (See Figure 4.) The geometric factors such as shape, angularity and surface roughness are all united under one parameter called rugosity or surface voids of the particle. This unified geometric property was defined by Ishai and Tons (4) as the specific rugosity (S_{rv}):

$$S_{rv} = 100 \frac{V_{sr}}{V_p} , \tag{4}$$

where

S_{rv} = specific rugosity, percent of packing volume

V_{sr} = volume of all the surface roughness voids down to the membrane of apparent specific gravity (see Figure 5)

V_p = packing volume of the particle.

Practically, S_{rv} can be defined by the packing specific gravity (G_p) and by the apparent specific gravity of the particle (G_{ap}):[1]

$$S_{rv} = 100 \frac{G_{ap} - G_p}{G_{ap}} . \tag{5}$$

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[1] Used for practical convenience

Since both apparent and packing specific gravity can be obtained by simple tests, this equation will be used for calculating the rugosity of monovolume (one-size) particles.

Other Related Factors

So far both the volume (in terms of a packing volume V_p and packing specific gravity G_p) and the geometric factors in terms of a specific rugosity S_{rv} have been defined. These two will now be used to expand into the area of one-size aggregate mixes. To achieve this, additional definitions and equations will be developed.

Packing Porosity: In a way, the imaginary membrane makes all particles smooth and somewhat similar in appearance. The work by Tons et al. (2, 3) showed that by using the packing volume as a basis a given number N of monovolume particles placed or compacted in a specified bulk volume (container) will have identical packing porosities (air spaces between the particles) regardless of the type of aggregate (gravel, slag, limestone, etc.), or

$$P_p = \frac{V_{bl} - \sum V_p}{V_{bl}} = \text{constant} , \qquad (6)$$

where

P_p = packing porosity (interparticle voids) of monovolume (one-size) aggregates

V_{bl} = volume of the calibrated container

$\sum V_p$ = total packing volume of monovolume particles.

Rugosity and Flow Asphalt: If one-size aggregate is mixed with asphalt (or tar) part of the asphalt will fill the surface voids and irregularities of the particle while the other part will remain in the interparticle voids. The packing volume membrane again serves to define the two parts of asphalt (2, 3):

(a) The rugosity asphalt (asphalt lost in the undermembrane voids).

(b) The flow asphalt (binding or effective asphalt, see Figure 5).

A knowledge of the rugosity asphalt is essential since it determines the amount of the flow asphalt (for a given asphalt content), which was found to be one of the major factors that affect the flow (strength-deformation relationship) characteristics of the compacted mixture (3).

The amount of the rugosity asphalt can be defined in two ways:

(a) A simple way to express the amount of asphalt lost is using the term asphalt lost by rugosity (B_{rw}):

$$B_{rw} = 100 \frac{W_{rw}}{W_{ag}} , \tag{7}$$

where

B_{rw} = asphalt lost by rugosity (under the packing volume membrane), <u>percent by weight of aggregate</u>

W_{rw} = the weight of rugosity asphalt

W_{ag} = the dry weight of the aggregate particles.

The amount of asphalt lost by rugosity can be practically determined from the specific properties of the asphalt, the aggregates, and the mixture; namely: the specific gravity of the asphalt (G_b), the packing specific gravity of the aggregates (G_p), the asphalt content (w), and the maximum specific gravity of the mixture (G_{mm}):

$$B_{rw} = \frac{100}{100-w}\left(w - 100\,\frac{G_b}{G_{mm}}\right) + 100\,\frac{G_b}{G_p}\,. \tag{8}$$

The asphalt content (w) is expressed here as a percentage of the total mixture by weight. The derivation of Equation (8) is given in Appendix B.

(b) A more general way to express asphalt lost by rugosity is on volume basis:

$$B_{rv} = 100\,\frac{V_{br}}{V_p} = \frac{G_p}{G_b}\,B_{rw}\,, \tag{9}$$

where

B_{rv} = asphalt lost by rugosity, percent of packing volume

V_{br} = volume of rugosity asphalt

V_p = packing volume of the particles

G_p = packing specific gravity of the particles

G_b = specific gravity of the asphalt.

Multiplying Equation (8) by the ratio G_p/G_b, the practical form for B_{rv} is obtained:

$$B_{rv} = 100 - \frac{100}{100-w}\left(\frac{100}{G_{mm}} - \frac{w}{G_b}\right) G_p\,, \tag{10}$$

but since

$$G_{ef} = \frac{100 - w}{\frac{100}{G_{mm}} - \frac{w}{G_b}}\,, \tag{11}$$

then

$$B_{rv} = 100\left(1 - \frac{G_p}{G_{ef}}\right), \tag{12}$$

where

G_{ef} = effective specific gravity of the aggregate particles

G_{mm} = maximum specific gravity of the one-size mix.

Specific Rugosity and Asphalt Lost by Rugosity: It must be pointed out that there is a similarity between the specific rugosity (S_{rv}) as measured on dry, uncoated aggregates and the asphalt lost by rugosity (B_{rv}). They both give a measure for the surface roughness and voids of the aggregate particle. Usually $B_{rv} < S_{rv}$, since it is expected that the imaginary apparent volume membrane (see Figure 5) used in S_{rv} equation usually represents the limits of asphalt absorption inside the surface voids (rugosity). The ratio of B_{rv} to S_{rv} can be used to characterize the degree of asphalt penetration into the surface roughness and pores, thus:

$$S_b = 100 \frac{B_{rv}}{S_{rv}}, \tag{13}$$

where

S_b = percent asphalt saturation inside the surface voids (assuming water saturation after 24 hours of immersion as 100 percent).

Since the difference between the effective and apparent volumes of aggregate particles is within the small (micro) surface voids[1] and since the larger (macro) void volumes[2] usually govern the variability of the rugosity terms, it is expected (where differences in solid specific gravities are not great) that S_{rv} and B_{rv} will have mutual linear relationship for a wide range of aggregates.

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[1] Surface voids between the bulk and apparent volume membrane of the particles (see Figure 5).

[2] Surface voids between the bulk and packing volume membranes (see Figure 5).

Thus, for a given type of asphalt, this approximate relationship should permit the estimation of the amount of asphalt lost by rugosity (B_{rv} or B_{rw}) on the basis of the specific rugosity (S_{rv}) alone. This has a practical value in mix design.

Equations for Macro and Micro Surface Voids: The total rugosity voids as expressed by the specific rugosity (S_{rv}) can be quantitatively partitioned into the micro and macro surface voids, and can be expressed by volumetric equations (see Figure 5):

$$S_{ma} = 100 \frac{G_{ag} - G_p}{G_{ag}} , \tag{14}$$

and

$$S_{mi} = 100 \, G_p \frac{G_{ap} - G_{ag}}{G_{ag} - G_{ap}} , \tag{15}$$

where

S_{ma} = percent macro surface voids (volume basis)

S_{mi} = percent micro surface voids (volume basis)

G_{ag} = bulk specific gravity

G_{ap} = apparent specific gravity

G_p = packing specific gravity

S_{rv} = $S_{ma} + S_{mi}$.

Experimental Work

The main goals of the experimental work were (1) to measure the various factors discussed for one-size aggregates of greatly varied origin with and without asphalt; (2) to analyze their effectiveness; and (3) to build a base for applying them to two-size and multi-size mixes.

Statistical Experimental Design

This part of the research was designed with the following experimental and statistical considerations:

(1) Because of the large number of experimental treatments, and because of the nature of test procedures, the design had to be simple and practical to provide efficient laboratory operation.

(2) The basic design structure had to provide maximum information about the effect of the main factors.

Two main factors were considered in this research phase:

(1) Aggregate type - with eight different aggregates (levels), see list on page 14, and also Figures 8 and 9.

(2) Fraction size - with six levels (1/2 in.-5/8 in., #3-#4, #8-#10, #20-#30, #60-#80, #200-#270).

For each experimental treatment (type-size combination) two replicates were made.

Based on the experimental and statistical considerations given above, a two-factor nested (hierarchal) design (80) was chosen. The main group factor was the size of the fraction. The subgroup (nested) factor was aggregate type. The replicates were nested within the treatments, thus, nested within size and type. The design is illustrated in Figure 6.

The statistical model which described the experiment was as follows:

$$y_{ijk} = \mu + \alpha_i + \beta_{ij} + \varepsilon_{ijk}\,, \qquad (16)$$

where

y_{ijk} = the k-th response of type j within size i (the dependent variable).

μ = an overall mean value common to each treatment and replicate

α_i = an effect due to size i

β_{ij} = an effect due to material j within size i

ε_{ijk} = an effect due to replicate k within material j within size i (experimental error).

Since the levels within each factor were not chosen randomly to represent the entire population, the factors were considered to provide fixed effects.

This specific model provides the basic information about main effects (size and type). For each dependent variable (measured or calculated parameter), data have been analyzed by means of analysis of variance. Tables of ANOVA, cell means, and cell deviation were obtained by computer with the UCLA Biomedical Computer Program - BMD8V (see reference 81).

Chosing Materials

In order to include aggregate types which will represent a wide range of geometric irregularity as well as different specific gravities the following aggregates were chosen (see also Figures 8 and 9).

(1) BP - Lake Superior Beach Pebbles and sand.

(2) NG - Natural Pit-Run Gravel from McAvory Pit 76-22.

(3) LS - Crushed Limestone from Inland L & S Co., Pit 75-5.

(4) DL - Crushed Dolomite from Drummond Dolomite Co., Pit 17-66.

(5) MR - Crushed Mine Rock from Pit 66-76.

(6) CG - Crushed Gravel from American Aggregate Co., Pit 47-3.

(7) SL - Slag from Gary, Indiana.

(8) SS - Sandstone from Grindstone City.

The asphalt used was asphalt cement 120-150 penetration grade, see Table 1.

Laboratory Work

Aggregate Preparation: Batches of the eight types of aggregate were supplied by Michigan Department of State Highways. In order to obtain particles from each chosen size, some of the aggregates were crushed in the laboratory.

After crushing, the aggregates were sieved by vibratory sieve shaker (23 in. x 15 in.) to form nine fractions from each material. The sieves used were 3/4 in., 3/8 in., #4, #8, #16, #30, #50, #100, and #200. The fractions were stored in closed canvas bags.

Modifying Test Procedures: For measuring the packing specific gravity (G_p) of one-size aggregates, a simple pouring test was developed and reported by Ishai and Tons (4). It worked well for natural gravel aggregates but had to be revised to achieve uniform pouring rate for the great variety of aggregates used in this investigation.

In order to investigate the influence of pouring rate on the packing of particles, a series of measurements employing different orifice sizes were performed with the pouring device for each aggregate (and size) and also for the glass beads of the appropriate size (used as standard). This testing permitted the fitting of a single orifice diameter for each aggregate size. These orifice diameters were used later to obtain the final testing data. The modified pouring test is described in Appendix D. An example of the influence of pouring time on the packing of #8-#10 particles is shown in Figure 7.

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[1] Pouring rate - amount of packing volume of particles poured in a unit time.

As described in reference (4), the comparison between the values of water and asphalt absorption indicated that during the measurement of the maximum specific gravity of the mixtures by the solvent immersion test, the solvent dissolved the asphalt which coated the particles and probably penetrated inside the voids which were impermeable to asphalt. This distorted the physical definition of the rugosity terms. It was, therefore, decided to compare various methods for the measurement of the maximum specific gravity. These methods were as follows:

(1) Water Saturation Test, ASTM D 2041, based on Rice's Method (33), (9), (13).

(2) The Michigan Solvent Immersion Test (10, 15).

(3) Methanol (Methyl Alcohol) Saturation Test (see Appendix E).

All tests were performed with Michigan immersion flasks.

In order to check the amount of air bubbles trapped between coated particles, and to eliminate any other factors which might influence test results, the three procedures were compared by using three one-size glass beads mixed with asphalt.[1] For determining the influence of solvent penetration into the micro surface voids on the maximum specific gravity, the solvent and methanol tests were further compared by using one-size mixtures with different types of aggregates (beach pebbles, limestone, slag, and sandstone). Test results are summarized in Tables 2 and 3. Based on these results, it was decided to adopt the methanol test for obtaining the final testing data.

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[1] The diameters of the glass beads were 16mm, 6mm, and 3mm.

Measuring Packing and Bulk Volume Parameters: Tests were performed by blocking the size factor and randomly choosing types of aggregate within the blocks (as specified by the nested design). For each 48 treatments, two replicates were run to form a total of 96 experimental units.

Similar to previous research (4), the following tests and operations were performed:

(1) Subsieving to obtain one-size fractions.

(2) Washing and drying.

(3) Measuring mean particle weight.

(4) Measuring particle dimensions for shape analysis.

(5) Measuring packing specific gravity by the pouring test (Appendix D).

(6) Measuring bulk specific gravity and water absorption.

(7) Mixing with asphalt and measuring maximum specific gravity.

(8) Evaluating asphalt content by extraction.

The above work was performed as follows:

The subsieving was performed both by manual and sieve shaker. An attempt was made to follow the same procedure for all types and sizes using 8-inch diameter sieves.

The one-size fractions were washed for 10 minutes under hot water on a sieve, then dried in the oven overnight (120 C).

The mean particle weight was measured by counting 1000 particles (chosen randomly by quartering) and weighing them on an analytical balance.

Particle dimensions (long, medium, and short) were measured for random samples of about 50 particles from 1/2 in. - 5/8 in.

and #3-#4 fractions. Measurements were performed by a caliper. The packing specific gravity was measured by the modified pouring device (see Appendix D). Six sizes of uniform glass beads were used as reference materials. Each size was chosen to fit closely the specific sizes of the one-size aggregate fractions.

The bulk specific gravities and water absorption of the aggregates were measured according to ASTM standards. Fractions 1/2 in. - 5/8 in. and #3-#4 were tested according to C 127; fraction #20-#30 according to C 128. Fraction #8-#10 was surface dried according to C 127, but the volumetric measurements were done according to C 128.

The maximum specific gravity test was performed on mixtures with one-size fractions. Then mixtures were prepared by using 120-150 penetration asphalt--mixed at 300 F, mixing time 2 minutes. Because of the uniform nature of the particles, the mixtures were remixed every 5 minutes during cooling to avoid the settling of the asphalt at the bottom of the bowl. This operation was stopped when uniform stable coating was observed.

The maximum specific gravities of the mixtures were measured according to the Michigan immersion procedure, but with the use of Methanol (Methyl Alcohol) as the volumetric liquid. A partial vacuum (20 cm of mercury) was applied for three minutes when mixtures with #20-#30 aggregates and finer were tested. The methanol was reused about five times. Before each use, the methanol was filtered, and a sample was taken to determine its specific gravity. The procedure is described in detail in Appendix E.

The asphalt content for each mixture was determined by hot extraction.

The above testing procedures were used for direct determination of six aggregate parameters:

(a) The average particle weight (W).

(b) Bulk specific gravity (G_{ag}).

(c) Water absorption (A_w).

(d) Packing specific gravity (G_p).

(e) Maximum specific gravity of mixtures (G_{mm}).

(f) Asphalt content (w).

These parameters were used for calculating the rugosity terms.

The specific rugosity (S_{rv}) was calculated using Equation (5), and the asphalt lost by rugosity (B_{rw} and B_{rv}) were calculated by using Equations (8) and (12).

Conventional parameters, such as bulk specific gravity, were measured primarily for purpose of comparison. Also, using bulk specific gravity (G_b), maximum specific gravity of the one-size mix (G_{mm}) and the asphalt content w (percent by weight) the asphalt lost by absorption (B_{ag}) was determined:

$$B_{ag} = \frac{100}{100-w} \left(w - 100 \frac{G_b}{G_{mm}} \right) + 100 \frac{G_b}{G_{ag}} \qquad (17)$$

<u>Additional Standard Tests:</u> Samples from each type of aggregate were tested for resistance to abrasion by the Los Angeles machine. Grading B and D were tested according to ASTM C 131 (see Reference 6) and the results are summarized in Table 14.

The absolute specific gravity of each aggregate was determined by using ASTM C 188 test (37) on material passing sieve #270 with results summarized in Table 15.

Aggregates from #20-#30 fraction were tested for bearing strength by using the Florida bearing test (82). Data on bearing strength are summarized in Table 16 and Figure 14.

Results and Discussion

Modification of Testing Methods

As reported by Ishai and Tons (4), the particle pouring test was adopted as a basic method for direct evaluation of the packing specific gravity (G_p) of one-size gravel and sand particles from Michigan. Using Equations (5) and (8) the rugosity terms S_{rv} and B_{rw} (or B_{rv}) could be calculated using the pouring test data.

One of the important requirements in the pouring test is that the compaction energy must be kept constant for all aggregates of a given one-size fraction. This means that the height of particle drop and the rate of pouring (in units of packing volume) had to be kept constant to achieve a similar packing for a given one-size fraction.

There were no problems with the gravel and sand as reported by Ishai and Tons (4). However, the present research involved particles of greatly different geometric properties (slag, limestone, smooth gravel, etc.) and therefore certain refinements in the pouring test were necessary.

It was found that at a given orifice opening, different types of one-size rocks used in this investigation showed different flow (pouring) rates. This difference was found to be statistically significant for all sizes tested. Thus, in order to maintain the unified characteristics of the pouring test procedure, it was decided to investigate and solve this problem. For each experimental unit within the basic experimental design, aggregate particle and glass beads were poured through different orifice sizes. As shown in Figure 7, it was found that the pouring rate had a definite influence on the pouring test response (ΣW). That is the density of the particle packing increased with a decrease in the pouring rate (when particles are poured slowly), probably because particles had more time to locate denser positions when there was less mutual interference. Figure 7 shows that the increase in density was more significant at high pouring rates (particles are poured quickly), while at low pouring rates the curves tend to level and reach a flat section. At this stage the pouring rate had a small influence on the packing of particles, probably because the particles approached the efficient packing arrangement under the given compaction conditions (size of container, size of particles, pouring height, etc.).

For practical use of the pouring method, a unified (standard) orifice diameter was desired for each size of aggregate. For the determination of the unified diameter for each particle size the variation of the packing density with pouring rate must be considered as well as the variation of pouring rates with different types of aggregates through a given orifice diameter. Therefore, for each size of particle a unified orifice was chosen based on the following considerations:

(1) The orifice had to be small enough to produce a low rate of pouring so that test responses would fall within the flat range of the curves, for eliminating the influence of different pouring rates for different materials.

(2) The orifice had to be large enough to produce a continuous rate of pouring without any bridging of particles at the funnel opening.

Based on these criteria six different orifice openings were chosen for the six fraction sizes. These openings were used to determine the final testing data. For further details about the pouring device and procedure, see Appendix D.

As described in the previous chapter, the use of the solvent immersion test for measuring the maximum specific gravity of mixtures produced close values for water and asphalt absorption. It was assumed that these results may be influenced by the solvent which dissolved the asphalt that coated the particles and penetrated into the pores which were impermeable to asphalt.

A series of maximum specific gravity evaluations on various mixtures using ASTM D 2041 test, based on Rice's method (9, 13), introduced the difficulty of expelling air bubbles which were trapped between the coated particles (although a partial vacuum was applied and a wetting agent was added to the water). Thus, it was decided to find another liquid which, on one hand would not dissolve the asphalt, and on the other hand would be characterized by a better wetting property. Different types of liquids were checked and it was found that alcohols had good wetting properties. Methanol was finally chosen for the experiments mainly because of economic considerations and availability.

For checking the wetting properties of the methanol (capability of expelling air bubbles) a series of tests were performed on mixtures with three sizes of uniform glass beads. Glass beads were chosen because no asphalt absorption can take place, and thus, any variability in the maximum specific gravity of identical mixtures tested by different methods will be due to the amount of trapped air bubbles.

Test results for identical mixtures, which were tested by the three methods previously described are shown in Table 2. It is evident that by dissolving all the asphalt which coated the particles, the beads became loose, and all the air bubbles could be expelled easily. Thus, if the maximum specific gravities obtained by the ASTM D 2041 and the methanol tests are compared with those obtained by the solvent immersion test, an indication about the amount of trapped air bubbles can be obtained. Test results indicate that the maximum specific gravities as obtained by the methanol test deviate from the solvent test only slightly for all sizes of glass beads (less than 0.43%). On the other hand, the deviations of the ASTM test results from the solvent test results increased with decreasing particle size (up to 2.67% for 6 mm glass beads). It is expected that these deviations will increase when smaller particles will be involved, because of the high surface tension of bubbles inside the capillary voids. It must be noted here that no vacuum was applied in the methanol test.

Since the solvent and methanol tests tend to produce similar results for non-absorptive particles, it was possible to check the amount of solvent penetration into the aggregate during the solvent test. Identical mixtures with two sizes of four types of aggregates (beach pebbles, limestone, slag, and sandstone) were tested in the solvent and methanol tests. As shown in Table 3, the maximum specific gravities which were determined by the two methods deviated considerably (up to 7.61% for the absorptive sandstone). This would verify, of course, the expected high amount of solvent penetration using the solvent immersion test with porous aggregates.

Furthermore, the methanol test was found to be simple, economical, and produced repeatable results. For these reasons it was decided to use the methanol test in the investigation. It was found later that in about 150 tests, the variations between replicates were always less than 0.015 units of specific gravity. The vacuum application was also found to be unnecessary for one-size mixes since a vacuum of 35 cm of mercury, which was applied to finer fractions, caused an increase of only 0.008 units of specific gravity.

General Physical Trends

Based on the statistical analysis [as shown in Table 17 a) and b)], it was found that the effects of the main factors (type and size of aggregates) are significant for all bulk and packing volume parameters (G_{ag}, G_{ap}, A_w, B_{ag}, G_p, S_{rv}, B_{rw}, B_{rv}, S_b, S_{ma}, and S_{mi}, which are summarized in Tables 4 through 9). That is, these parameters, as measured by the specific techniques, are considerably different due to type and size of the particles.

The specific statistical model used cannot provide any information about type-size interactions, but because of the high repeatability of replicates and the nature of the testing procedures a fully crossed (factorial) design of main factors may lead to similar variability of testing data. Therefore, an inference about interactions could be drawn by analyzing the same data according to an 8 x 6 factorial experiment with nested replicates. This analysis was performed and it was found that for all ten dependent variables, the interactions between size and type of aggregates are significant. The existence of these interactions is very well shown (for a typical parameter - S_{rv}) in Figure 10.

Based on the above findings, the following average physical trends are significant for all types and sizes (see Tables 4 through 10).

(1) The amount of asphalt lost by rugosity (B_{rw} and B_{rv}), the geometric irregularity (specific rugosity - S_{rv}), and the relative volume of the macro surface voids (S_{ma}) tend to decrease with particle size (see also Figure 10).

(2) The packing specific gravity (G_p) tends to increase with particle size.

(3) On the other hand, the bulk and apparent specific gravities (G_{ag} and G_{ap}) tend to decrease with particle size, but within a narrower range.

(4) No similarly consistent trends have been observed for asphalt lost by absorption (B_{ag}) (and also for water absorption). The average value here tends to increase with particle size for the sand fractions (finer than #8) but decrease with particle size for the coarse aggregate fractions (1/2 in.-5/8 in., and #3-#4).

(5) Based on the rugosity terms, the sandstone and the slag possess the highest geometric irregularity, while the beach pebbles and the natural gravel possess the lowest. Other aggregates fall between as shown in Table 10.

Bulk and Packing Volume Parameters

The main objective of the laboratory work in this stage was to verify the theoretical relationships and assumptions which were described at the beginning of this chapter. That is, to show that the packing volume parameters could also characterize and unify the geometric properties, and asphalt requirements, of one-size particles from aggregates which possess different solid specific gravities.

Table 13 and Figures 10 through 14 represent relationships between packing and other parameters.

Table 13 summarizes the range of correlation coefficients between different parameters, as determined for each size separately.

As predicted, the weight-volume relationships between the packing specific gravity (G_p) and the rugosity terms (S_{rv} and B_{rw}) were characterized by low correlation coefficients for some of the fractions of aggregates which possessed different solid specific gravity.

It was also predicted that since B_{rw} is defined on a weight basis, the relationship between B_{rw} and S_{rv} will also deviate from its linearity when aggregate with different specific gravity are involved. Although this relationship is characterized by high linear correlation coefficients (as indicated in Table 13), Figure 12 shows that a nonlinear relationship would better fit test data for all types and sizes combined.

Theoretically, it was suggested to eliminate the differences in solid specific gravities by using parameters which are defined volumetrically. Therefore, as expected, linear relationships with high correlation coefficients exist between the volumetric rugosity terms S_{rv} and B_{rv}[1] for all sizes separately (see Table 13). As shown in Figure 13, a linear relationship can also be assigned to data for all types and sizes combined (quantitatively, $r = 0.980$, $F = 2223$). This combined relationship for all aggregate tested can be described by the following equation:

$$B_{rv} = 1.009\, S_{rv} - 1.60 \,. \tag{18}$$

This unique relationship permits a fast and reliable estimate of the amount of asphalt lost by rugosity on the basis of S_{rv}.

Attention must be given to two pairs of points in Figure 13 which deviate considerably from the others. These points represent test data for coarse sandstone particles (1/2 in.-5/8 in., and #3-#4).

Based on a theoretical concept which was adopted here, the coarse sandstone is a very special material, since its geometric irregularity is not a property of the surface of the particle alone but a property of the total solid structure. The coarse sandstone particle was a combination of very fine sand particles cemented together to form a capillary porous medium. Thus, when it is immersed in water, the water penetrates through the capillaries and usually saturates the particle. For this reason, the capillaries within the particle are measured as the micro surface voids. This is why the macro surface voids (S_{ma}) are equal, or even sometimes smaller, than the micro surface voids (S_{mi}) for the coarse fractions (see Tables 4 and 5).

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[1] B_{rv} is defined by Equation (33).

When coarse sandstone particles are mixed with asphalt, the asphalt will penetrate only below the surface (up to about 1/8 in. penetration (83)) while leaving the smaller inside voids unfilled. This will be reflected in a very low asphalt saturation inside the surface voids (S_b) (about 41% for 1/2 in.-5/8 in. particles, see Table 4. Since most of the other types of aggregates are characterized by a much higher asphalt saturation (usually about 80%), the points which reflect the relationships between the total geometric irregularity (as expressed by S_{rv}) and the volume of the rugosity asphalt (as expressed by B_{rv}) for the sandstone, are expected to deviate from those of other aggregates. This deviation will diminish with the decreasing size of sandstone particle sizes, since in rock pieces smaller than 1/8 in., the asphalt can penetrate the inner capillaries.

Thus, if the specific sandstone observations are excluded from the above data a better correlation is achieved within each size ($0.983 > r > 0.999$), and for all sizes and types combined ($r = 0.995$, $F = 7652$). The combined relationship (excluding the sandstone) can be described in the following equation:

$$B_{rv} = 1.012\ S_{rv} - 1.33\ . \qquad (19)$$

It must be pointed out, however, that in spite of the deviation for sandstone, the basic procedure is still valid. The only limitation is that the asphalt requirement, as expressed by B_{rv}, could not be predicted for the sandstone on the basis of S_{rv} alone (with the aid of Figure 13) but it will also need an experimental evaluation of B_{rv}. It is anticipated that a similar deviation will be obtained for other types of lightweight and porous aggregates; therefore, Figure 13 for asphalt prediction purposes must be used with care and judgment. If in doubt, both S_{rv} and B_{rv} should be measured.

Based on Table 13 and Figure 14, the linear correlations between water absorption (A_w) and asphalt absorption (B_{ag}), obtained in the first stage of this investigation (4), are still maintained when aggregates of different solid specific gravities are involved. This trend might be expected since both parameters are based on weight ratio, and the specific gravity of water and asphalt is almost identical. Therefore, in this case, the difference in the specific gravity of solids does not change the linear relationship which is governed here only by the geometric characteristic of the particles.

In Figure 14 regression lines were constructed for the materials used showing relationship between A_w and B_{ag}. Although a good linear correlation was found ($r = 0.920$ for all materials, $r = 0.933$ if sandstone is excluded) it is apparent that the curves have little practical value for predicting asphalt absorption (B_{ag}) from water absorption A_w.

The geometric irregularity of one-size particles (S_{rv}) was also correlated with the Florida bearing values for sand. Although this test is empirical, it is thought to provide a relative indication of stability of particles in bulk. As expressed in Table 16 and Figure 15 a linear correlation ($r = 0.975$) was obtained between S_{rv} and the Florida bearing value for all aggregates (excluding the sandstone) within the fraction tested.

Aggregate Types and Sizes

The main effects within the experimental model, and the significant interactions of types and sizes, permit the sensitive rating of different types of aggregates. Besides the rating which has been made on the basis of the average values of parameters, it is also possible to compare on the basis of the variability of a certain parameter with size. Figure 13 represents a typical relationship between rugosity term (S_{rv}) and the size (V_p). The varying behavior of a given material with size, and the existence of interactions can be very well noted in the Figure.

Summary for One-Size Aggregates

The following important aggregate and mix factors have been measured in this laboratory study for a wide range of one-size aggregates and mixes:

(1) Particle packing volume, V_p.

(2) Packing specific gravity, G_p.

(3) Specific rugosity of aggregates, S_{rv}.

(4) Asphalt lost by rugosity, B_{rw}, B_{rv}.

These parameters have been useful for characterizing each of the aggregates and helpful for explaining bulk behavior of one-size fractions. The next step is to look into 2-size and multi-size plain aggregates and mixes with asphalt.

III

TWO-SIZE AGGREGATE SYSTEM

Theoretical Considerations

In the previous chapters, physical parameters were defined to characterize the behavior of individual one-size particles, as well as the properties of one-size aggregate packings. The next step was to see what happens when two sizes of aggregates are mixed together.

The packing volume definition is based on a concept which unifies the porosity of packings formed by different types of one-size aggregate particles. That is, within a constant volume container, and under identical compaction procedures, different types and sizes of uniform particles will possess identical packing porosity (P_p), and therefore, will also have identical total packing volume (ΣV_p). This concept has been formulated by Equation (6).

Consider now the same container full with one-size, large, smooth particles. If there is added to this container a certain amount of one-size fine particles with diameter ratios (related to the large particle) smaller than the so-called critical ratio of entrance (79), these fine particles will filter between the large ones and will fill the inter-particle voids of the coarse ones, and thus, without changing the bulk volume (volume of the container) the total packing volume of the particles (ΣV_p) will increase, while the amount of packing porosity (V_p) will decrease. It can be seen now that the unified concept of constant volumes (constant bulk volume, constant ΣV_p, and constant P_p) which is expressed by Equation (6) is no longer valid for systems of multi-size fractions. However, when ideally smooth particles are involved, the model is still additive. That is, under no dilation of coarse particles, the increase of the total packing volume of the system is equal to the decrease of the volume of inter-particle voids (packing porosity). Thus, if the packing volume of the individual fractions is known, the total packing porosity of the system can be calculated. The above conditions are similar to the model described by Furnas (78).

When the size ratio of the fine and coarse fractions (smooth surfaces) is greater than the ratio of occupation (79), a dilation will occur in the coarse particle structure and the introduction of the fine fraction will increase the bulk volume. However, the model is still additive, since, under constant packing volume of the particles, any additional increase in bulk volume will be equal to an increase in the volume of inter-particle voids (packing porosity).

The additivity and simplicity of the above models is distorted when irregular and rough aggregate fractions are involved. In this case, fine particles can penetrate under the imaginary packing volume membrane of coarse particles. These fine particles are then said to be lost inside the macro surface voids of the coarse particles. This interaction between coarse and fine particles is the reason for the distortion of the additivity, since, by adding fine particles to the packed system of the coarse aggregate fraction, the increase in total packing volume is not equal to the decrease of the packing porosity because of a loss of packing volume of the fine particles inside the macro surface voids of the coarse fraction.

The non-additivity of packing volumes caused by the interaction between coarse and fine particles can be seen better by considering aggregate-asphalt mixtures. When different sizes of aggregates are involved, the total amount of the rugosity asphalt will not be the sum of the rugosity asphalts of each fraction since, similar to the asphalt, fine particles are lost inside the macro surface voids of coarser particles. Thus, the amount of rugosity asphalt of the coarser particles is reduced by the same volume of fine particles which are trapped with the asphalt under their packing volume membrane. This decrease of rugosity asphalt can be easily verified. As shown in Table 10, the calculated average asphalt lost by rugosity (B_{rw}) of six sizes of limestone and crushed gravel are 9.79 and 10.87 (per cent by weight of aggregates), respectively. The same mixtures may require only 6% total asphalt content under practical construction conditions. This reduction in asphalt content is said to be due to the fine particles which occupy part of the volume of the macro surface voids of coarser particles which were filled with asphalt when only one-size fractions were involved.

A microscopic inspection of the macro surface voids of coarse particles, with relation to the sizes of finer fraction, was performed on different types of aggregates. It was found that fine particles can be partially or completely lost in the macro surface voids of coarse particles if the ratio of their equivalent sphere diameter is greater than 2.5, or if the ratio of their packing volume is greater than 16. By comparing these numbers with the data reported by Lees (79), it can be said that each coarse fraction of irregular aggregates can interact with finer particles which possess size ratio less than the critical ratio of occupation under dense packing conditions of the coarse particles. Thus, particles from #3-#4 fraction and finer can be lost partially or completely in the macro surface voids of 1/2 to 5/8 inch particles, or particles from #60-#80 and finer, in the macro surface voids of #20-#30 particles, etc.

Since no previous theory or experimental data are available on this specific subject,[1] theoretical definitions and experimental approach had to be adopted for the quantitative formulation and evaluation of the interaction between coarse and fine fractions.

It was decided to designate the interaction effect between coarse and fine particles as fines lost by rugosity (F_r), and,

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[1] The need for reduction of rugosity asphalt due to the introduction of fine particles within the surface roughness of coarser ones was mentioned by N.W. McLeod in a discussion to a paper by Tons *et al.* (3).

F_r was defined as the ratio of the packing volume of the fine particles involved; that is:

$$F_r = \frac{V_p \text{ fines}}{V_p \text{ coarse}} \qquad (20)$$

Further, it was assumed that since no fine particles were able to penetrate into the micro surface voids, it can be concluded that:

$$F_r < \frac{S_{ma}}{100} < \frac{S_{rv}}{100}, \qquad (21)$$

where

S_{ma} = percent macro surface voids

S_{rv} = percent specific rugosity.

Three major factors were assumed to influence the fines lost by rugosity (F_r) of a certain fraction:

(1) The geometric irregularity of the large and small particles.

(2) The total asphalt content of the two-size mixture.

(3) The amount of potential fine particles[1] within the mixture.

The first factor was fixed for a certain type and size of aggregate. The other two factors varied with the size of the aggregates and the asphalt content of the mixture. For easier handling, it

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[1] Fine particles which possess size ratio less than the critical ratio of occupation of the given coarse fraction under dense packing condition.

was decided to combine the last two factors by introducing the term fines concentration (C_{fv}), which will be defined as follows:

$$C_{fv} = \frac{V_{pf}}{V_{be}} , \tag{22}$$

where

V_{pf} = packing volume of potential fine particles in the mixture

V_{be} = volume of effective asphalt[1] of coarse fraction in the mixture.

Therefore, the amount of fines lost by rugosity (F_r) within a given fraction is a function of the geometry of that fraction, and also a function of the fines concentration (C_{fv}).

A quantitative evaluation of the fines lost by rugosity was attempted. It was assumed that the concentration of fine one-size particles within the macro surface voids of one-size coarser particles is equal to the total concentration of fine particles in the mixture as expressed by C_{fv}. Therefore:

$$C_{fv} = \frac{V_{pf}}{V_{be}} = \frac{V_{fr}}{V_{bm}} , \tag{23}$$

where

V_{fr} = volume of fine particles within the macro surface voids in units of packing volume

V_{bm} = volume of asphalt within the macro surface voids.

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[1] Since it was assumed that no fine particles will penetrate the micro surface voids of coarser particles, the effective asphalt will be the total amount of asphalt minus the amount of asphalt lost by absorption inside the micro surface voids of the coarse fraction.

In such case, for a given coarse fraction, the volume of asphalt lost by absorption plus the volume of the asphalt and fine particle mix within the macro surface voids is equal to the total volume of asphalt lost by rugosity (as measured for the one-size coarse fraction). Thus, the knowledge of asphalt lost by rugosity (B_{rw}), the asphalt by absorption (B_{ag}), and the fines concentration (C_{fv}) is sufficient for a quantitative evaluation of the fines lost by rugosity (F_r) in the coarse fraction, as can be seen in the following equations (for derivation see Appendix C):

$$F_r = \frac{G_{pc} \; (B_{rw} - B_{ag})}{100 \;\; G_b \; (1 + \frac{1}{C_{fv}})} \; , \qquad (24)$$

or in the volumetric form:

$$F_{rv} = \frac{S_{ma}}{100 \; (1 + \frac{1}{C_{fv}})} \; , \qquad (25)$$

where:

G_{pc} = packing specific gravity of the coarse fraction

G_b = specific gravity of the asphalt

S_{ma} = percent macro surface voids.

Equations (24) and (25) can be used for quantitative evaluation of the fines lost by rugosity in a given two-size mixture. These equations will be practical only if Equation (23) (which represents the basic hypothesis) is found to be true. Thus, by knowing the concentration of potential fine particles for a given coarse fraction within the mixture, the quantity of fine particles which are lost inside the macro surface voids of this fraction could be determined.

The physical parameters of two one-size fractions can be used to evaluate physical parameters of multi-size systems. The extension of this theory to a general graded bituminous mixture will be discussed in the next chapter.

Experimental Approach

General Considerations

In order to be able to use Equations (24) and (25) for quantitative evaluation of the fines lost by rugosity of a given fraction; and in order to be able to implement the above theoretical approach for a graded bituminous mixture, the hypothesis had to be verified experimentally. It was, therefore, desired to show that, for a given coarse fraction mixed with given fine particles (one-size) and asphalt, the concentration of fine particles within the macro surface voids is equal to the known fine particles concentration in the mixture. It was also desired to show that this equality is independent of the type of coarse and fine fractions, and the amount of the fines concentration (C_{fv}).

In the experimental part, a given coarse fraction was mixed with potential fine particles and asphalt using a given amount of fines concentration within the mixture. The concentration within the macro surface voids of the coarser fraction was then measured and compared with the known concentration in the mixture.

Statistical Experimental Design

Three major factors were considered for the experiment.

(1) Aggregate type - with three levels (NG, CG, SL).

(2) Size and combination of the fine fractions - with three levels (#20-#30, #20-#30 combined with #60-#80, and #60-#80).

(3) Fines concentration within the mixture (C_{fv}) - with three levels (0.5, 1.0, 1.5).

For each experimental treatment only one test was performed. In order to provide information about main effect and interactions, a 3 x 3 x 3 factorial experiment was chosen. The statistical model which describes the experiment is as follows:

$$y_{ijk} = \mu + \alpha_i + \beta_j + \gamma_k + (\alpha\beta)_{ij} + (\alpha\gamma)_{ik} + (\beta\gamma)_{jk} + (\alpha\beta\gamma)_{ijk} + \\ + \varepsilon_{ijk}, \qquad (26)$$

where

y_{ijk} = the response of the combination of the i-th aggregate, j-th size of fines, and k-th concentration of fines

μ = an overall mean value common to each treatment

α_i = an effect due to aggregate i

β_j = an effect due to the j-th size of the fine fraction

γ_k = an effect due to the k-th level of fines concentration

ε = experimental error.

All other terms represent the second and third order interactions within the model.

Since only one replicate was performed in each treatment, the experimental error can only be estimated by high order interactions. Thus, the significance of main effects and second order interactions was determined on the basis of this third order interaction. For each dependent variable, data were checked by analysis of variance. Tables for ANOVA, cell means, and cell variations were obtained by using UCLA Biomedical program - BMD 8V (See Reference 81).

Laboratory Work

Three types of aggregates were involved in the investigation: natural gravel (NG), crushed gravel (CG), and slag (SL). The aggregates were chosen to represent low, high and medium levels of geometric irregularity. For each aggregate, fraction 1/2 inch - 5/8 inch represented the coarse fraction, while fractions #20-#30 and #60-#80 represented the potential fine particles. Three levels of fines concentration (C_{fv}) were chosen for investigation: 0.5, 1.0 and 1.5.

The following conditions were kept constant in preparing each sample within the twenty-seven treatments:

(1) The weight of the coarse aggregate fraction was 300 grams.

(2) The amount of asphalt added was calculated to be equal to the amount of asphalt lost by rugosity (B_{rv}) of both fine and coarse particles, plus additional asphalt which was needed to exceed B_{rv} of the coarse fraction by 10 percent (volume basis) to insure good coating.

The exact amount of fine particles and asphalt needed for each treatment combination were calculated on the basis of the one-size parameters of the fractions involved and the specific value of C_{fv}.

Twenty-seven blends of dry coarse and fine fractions were prepared and stored in paper bags. A random number which reflected the order of operation was assigned to each bag. The following testing procedure was identical for each treatment:

(1) Placing the blend in a stainless steel bowl and heating to 300 F.

(2) Mixing the blend for two minutes with the proper amount of hot asphalt.

(3) Remixing while cooling to avoid draining of the asphalt.

(4) At about 150 to 200F, scraping the excess asphalt and fine particle mix from the coarse particles (down to the approximated packing volume membrane).

(5) Placing the scraped particles into a hot extractor basket and weighing them.

(6) After extraction, weighing the basket with dry aggregates to obtain the amount of asphalt.

(7) Separating coarse and fine particles and weighing them.

(8) Calculating the actual fines concentration within the macro surface voids of the coarse fraction.

Results and Discussion

Table 18 summarizes the actual fines concentration (C_{fv}) as measured for each treatment in the experiment. In the same table, three additional dependent variables are presented: The difference between the measured C_{fv} (which represent the actual fine particle concentration within the macro surface voids) and the concentration of fine particles within the mixture (as prepared) are given in terms of concentration units and percentage. Equation (25) was used to calculate the amount of fines lost by rugosity (F_r) for each treatment. Values of F_r are also given in the table.

Tables 19 through 21 represent the ANOVA for each independent variable in Table 18. The ANOVA is based on the statistical model used for the experimental design.

The basic hypothesis assumes equal fines concentration within the macro surface voids of a given fraction and the fines concentration in the mixture, and thus allows a physical estimate of the fines lost by rugosity of any given fraction in the mixture. Under this hypothesis, under the specific experimental design, and based on the previous theoretical considerations, the following constraints were predicted prior to testing:

(1) Since materials were combined to have given values of C_{fv}, and since the amounts of fine particles and asphalt

for these concentrations were calculated on the basis of aggregate type and sizes (volume and geometric properties), the measured fines concentration (C_{fv}) within the macro surface voids of the given fraction must be a function of the fines concentration in the mixture and independent of the type of aggregates involved and the size of the fine particles.

(2) Since the three factors of the experiment are assumed independent, they should not interact.

(3) Under the basic hypothesis, the experiment must show no significant difference between the measured C_{fv} and the concentration of fine particles in the mixture.

(4) Following Equation (25), the calculated fines-lost by rugosity (F_r) of the given fraction (based on the measured C_{fv}) must vary with the type of aggregate (expressed by S_{ma}) and C_{fv} in the mixture.

(5) Since the volume of the fine particles is already accounted for in C_{fv}, the calculated F_r by Equation (25) must be independent of the size of fine particles.

(6) Under prediction (5), an interaction between the type and concentration factors must exist for F_r.

The statistical analysis shown in ANOVA Tables 19 through 21A verified all the above predictions.

Table 19 indicates the significant influence of the concentration factor in the measured C_{fv}, and the insignificance of all other factors and interactions (predictions 1, 2).

Tables 20 and 21 indicate that the difference between the fines concentration within the macro surface voids and the fines concentration in the mixture is insignificant for all factors and interactions (prediction 3).

Table 21A indicates the significant influence of the type and concentration factors on the calculated fines-lost by rugosity. This table also shows the significance of the type-concentration interaction and the insignificance of all other factors and interactions (predictions 4 through 6).

It can be seen that the basic physical hypothesis has been verified by the experimental data. Therefore, the quantity of fines-lost by rugosity (F_r) can be physically estimated for any given fraction in the bituminous mixture.

IV

MODEL FOR A UNIFIED DESIGN OF ACTUAL GRADED BITUMINOUS MIXTURES

Theoretical Considerations

One of the basic problems in designing graded bituminous mixtures is the proper estimation of the asphalt content needed for optimum service condition. As described previously, this estimation is possible only using empirical indices or trial-and-error testing methods. Therefore, the final part of this investigation is aimed at the development of models which can be used as a basis for a unified mixture design procedure regardless of the type of aggregates used. These models will represent the implementation of the one-size aggregate parameters for actual graded bituminous mixtures.

The granular system of a continuous graded bituminous mixture can be partitioned into finite numbers of one-size aggregate fractions. Each of the large size fractions can interact with finer fractions within the system.

At this stage, the interaction effect between coarse and fine particles has been defined theoretically, and evaluated quantitatively for a two-size system. Thus, the quantity of the fines-lost by rugosity (F_r) of the given one-size fraction in the mixture, can be determined on the basis of the one-size aggregate parameters of the fractions involved, and the fines concentration factor (C_{fv}) within the mixture.

The actual volume of rugosity asphalt for each individual aggregate fraction (V_{rv}) can be expressed by the following equation:

$$V_{rv} = V_{br} - V_{fr} , \tag{27}$$

where

V_{br} = volume of rugosity asphalt as measured for the one-size fraction

V_{fr} = volume of the fine particles lost inside the macro surface voids of the given fraction (in units of packing volume).

When all the fractions of the graded mixture have been combined, a successive loss of fines particles will occur. That is, particles from a given fraction, which already possess finer particles in their macro-surface voids, can be lost in the macro voids of still coarser fractions.

Under these conditions the total actual volume of the rugosity asphalt (V_{rt}) in a graded mixture can be expressed as follows:

$$V_{rt} = \sum_{i=1}^{n} (V_{rvi} - V_{fri}) , \tag{28}$$

where i represents the i-th one-size fraction in the mixture and n the number of fractions in the mixture. The terms V_{rv} and V_{fr} are defined for Equation (27).

The actual amount of rugosity asphalt in the mixture is considered as stationary, that is, the part of the total asphalt content which is lost inside the surface voids of the particles, and does not participate in the flow (strength-deformation characteristics) of the mixture. On the other hand, the flow asphalt, namely, the part of the total asphalt content outside the packing volume membrane of active particles,[1] is assumed to govern the flow characteristics of the mixture.

For a given total asphalt content of the mixture, and with the knowledge of the actual volume of rugosity asphalt, the flow asphalt content of the mixture can be determined by the following equation (see derivation in Appendix C):

$$w_{fv} = \frac{w_{bt} - \sum_{i=1}^{n} Y_i (\frac{B_{rvi}}{100} - F_{ri})}{1 - F_{rt}} , \tag{29}$$

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[1] Particles which have not been lost in the surface voids of other particles.

where:

w_{fr} = flow asphalt content is percent of packing volume of active particles in the mixture.

w_{bt} = total asphalt content in percent of total packing volume of aggregate in the mixture.

Y_i = percent by volume of the i-th fraction in the mixture (packing volume basis).

B_{rvi} = percent asphalt lost by rugosity (volume basis).

F_{ri} = fines lost by rugosity of the i-th fraction.

F_{rt} = total fines lost by rugosity in the mixture.

n = number of one-size fraction in the mixture.

Most of the terms in Equation (29) are defined uniquely: the asphalt lost by rugosity (B_{rvi}) and Y_i are based on the properties of the individual one-size fractions in the mixture. The total asphalt content (w_{bt}) is a property of the combined fractions and can be determined by relating the volume of the total asphalt to the sum of the packing volumes of the fractions.

On the other hand, the determination of F_{ri} and F_{rt}, using Equations (24) or (25), requires additional considerations in order to fit a proper model for the specific gradation of the granular system within the mixture. These considerations are as follows:

In the previous chapter, it was assumed that fine particles can be lost in the macro surface voids of a given coarser fraction if the ratio of their equivalent sphere diameter is greater than 2.5. Consider now a graded granular system of n one-size fractions. The coarser fraction will be designated as the 1-st fraction, while the finer as the n-th fraction. Each fraction possesses an average equivalent sphere diameter (d_1, d_2, . . . , d_n). If for a given i and j ($i < j < n$) fraction, j is the coarser fraction which satisfies the inequality $d_j \leq 0.4\ d_i$, then all the fractions j, j + 1, . . . , n - 1, n are said to be potential fine particles for fraction i. That is, these fractions can be lost in the macro surface voids of fraction i or coarser fractions.

Thus, for a given gradation, and a given set of one-size fractions, the terms of Equation (22) can be expanded to define the fines concentration of a given i-th fraction within the mixture (C_{fvi}) as follows:

$$V_{pfi} = \sum_{k=j}^{n} V_{pk}\ , \tag{30}$$

and

$$V_{bei} = V_{bt} - \sum_{\ell=1}^{i} V_{ag\ell}\ , \tag{31}$$

therefore, on the basis of Equation (23) one can get

$$C_{fvi} = \frac{\sum_{k=j}^{n} V_{pk}}{V_{bt} - \sum_{\ell=1}^{i} V_{ag\ell}}\ , \tag{32}$$

where

C_{fvi} = the fines concentration of a given i-th fraction within the mixture

V_{pk} = the packing volume of the k-th potential fine fraction

V_{bt} = total volume of asphalt in the mixture

$V_{ag\ell}$ = volume of the asphalt lost by absorption of the ℓ-th coarse fraction

V_{pfi} = volume of potential fines can be lost in the macro surface voids of the i-th fraction

V_{bei} = volume of effective asphalt of the i-th fraction

n = number of one-size fractions in the mixture.

Equation (32) can be applied to any graded bituminous mixture, provided that for any given fraction i in the mixture the potential fine fractions are defined uniquely. Two specific examples will be given for additional emphasis.

Consider first a graded mixture in which the ratios of equivalent sphere diameter of any successive fractions is two. That is, $d_1 : d_2 : d_3 : \ldots d_n = 1 : 2 : 4 : \ldots 2^{n-1}$. In this situation the potential fine fractions for a given i-th (coarse) fraction are the (i + 2) fraction and all finer fractions. Therefore, based on Equation (32), the fines concentration (C_{fvi}) for the i-th fraction in the mixture will be determined as follows:

$$C_{fvi} = \frac{\sum_{k=i+2}^{n} V_{pk}}{V_{bt} - \sum_{\ell=1}^{i} V_{ag\ell}} \qquad (33)$$

A graphical illustration of this model, which describes the successive loss of fines particles, is given in Figure 16.

The second specific example will be a mixture which is combined of the six actual one-size fractions used in this investigation, namely: 1/2 in.-5/8 in., #3-#4, #8-#10, #20-#30, #60-#80, #200-#270. In this case the ratios of equivalent sphere diameters of successive fractions are always greater than 2.5 (see Tables 4 through 9). Any combination of these fractions will form a gap graded mixture. In this situation the potential fine fractions of the i-th fraction are the (i + 1) fraction and all finer fractions. Thus, for example, C_{fv} for the third fraction in the mixture (#8-#10) is as follows:

$$C_{fv3} = \frac{\sum_{k=4}^{6} V_{pk}}{V_{bt} - \sum_{\ell=1}^{3} V_{ag\ell}} \quad . \qquad (34)$$

By defining the fines concentration C_{fvi}, the fines-lost by rugosity of a given fraction (F_{ri}) can be determined with the aid of Equation (44). (See Appendix B.)

$$F_{ri} = \frac{S_{mai}}{100(1 + \frac{1}{C_{fvi}})} , \qquad (35)$$

where

S_{mai} = the amount of macro surface voids in the i-th fraction.

Thus, all the terms of Equation (29) are defined uniquely for a quantitative determination of the flow asphalt content (w_{fv}) of the mixture.

Three more volumetric parameters will be used to describe the void characteristics of a compacted bituminous mixture. They are the conventional - percent VMA, the new parameter - percent packing-VMA (VMA_p), and the independent parameter - percent air voids (U). These parameters can be defined in the following equations (see also Figure 17):

$$U = 100 \frac{\frac{100 + w}{G_{mx}} - \left(\frac{100}{G_{at}} + \frac{w_{ew}}{G_b}\right)}{\frac{100 + w}{G_{mx}}} , \tag{36}$$

$$VMA = 100 \frac{\frac{100 + w}{G_{mx}} - \frac{100}{G_{at}}}{\frac{100 + w}{G_{mx}}} , \tag{37}$$

$$VMA_p = 100 \frac{\frac{100 + w}{G_{mx}} - \frac{100}{G_{pt}}(1 - F_{rt})}{\frac{100 + w}{G_{mx}}} , \tag{38}$$

where

w = total asphalt content of mix (by percent of total aggregate weight)

w_{ew} = conventional effective asphalt content (by percent of total aggregate weight)

G_{mx} = specific gravity of the compacted mixture

G_{at} = average bulk specific gravity of aggregates in the mixture

G_b = specific gravity of asphalt

G_{pt} = average packing specific gravity of aggregates in mixture

F_{rt} = total fines lost by rugosity in the mixture.

To summarize, the following parameters are assumed to characterize the physical properties of a compacted, graded bituminous mix:

(1) The specific gravity of the mixture (G_{mx}).

(2) The amount of air voids in the mixture (U).

(3) The packing-VMA (VMA_p).

(4) The total fines lost by rugosity (F_{rt}).

(5) The flow asphalt content (w_{fv}).

Two additional parameters will be discussed which may characterize the mechanical behavior of bituminous mix:

(6) The strength (stability).

(7) The deformation (flow).

For a given material, and under a given gradation (fraction proportions), the total fines-lost by rugosity (F_{rt}) and the flow asphalt content (w_{fv}) are a function of the total asphalt content only as shown by Equations (29) through (35), while the air voids (U) and the packing-VMA (VMA_p) will vary also with the specific gravity of the mixture (G_{mx}) as indicated by Equations (36) and (38). A systematic illustration of the above relationship, as obtained for the actual eight types of aggregate, is presented in Tables 22 through 29 (Mixture Design Tables). The value of these tables for a unified mixture design will be emphasized later in this chapter.

The mechanical behavior of the mixture, namely, strength-deformation characteristics, is influenced by an unknown combination of the above physical properties, and by the characteristics of the specific strength test used.

An attempt will be made here to relate the physical properties to the mechanical behavior of the mixture by using the flow asphalt content (w_{fv}) as the basic parameter which should unify optimum asphalt content conditions based on strength, specific gravity (unit weight) and air voids for mixtures with different types of aggregates.

Predictions Prior to Testing

Prior to laboratory experiments the following trends were predicted:

Under a unified quantity of flow asphalt (w_{fv}), bituminous mixtures with a given gradation but with different types of aggregate should have similar optimum strength points (optimum asphalt content as indicated by maximum strength). Under these optimum conditions, graded mixtures with different types of aggregate are assumed to have different strengths due to different geometric characteristics[1] which affect the structure of the mixture.

These predictions can be justified as follows:

It was shown by Tons et al. (3) that the mechanical behavior (resistance to flow) of mixtures using different types of monovolume (one-size) aggregates can be made equal by filling the surface voids of the particles with rugosity asphalt and by introducing a constant amount of flow asphalt. Quantitatively, for a given contact point between particles, this was explained by the following simplified equations:

$$P = k_1 \frac{r^4}{h^2} \quad \text{for compression and tension cases} \tag{39}$$

$$S = k_2 \frac{r^2}{h} \quad \text{for shear case,} \tag{40}$$

where

P = resistance to deformation in tension and compression, force between two rocks

S = resistance to deformation in shear, force between two rocks

r = radius of the cylindrical asphalt plug between two rocks (particles)

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[1] This difference is expected to be primarily due to the differences in the amount of fine particles lost in the surface voids of the coarse particles.

h = initial average height of the cylindrical asphalt plug

k = a factor related to the viscosity of the asphalt and time.

For multi-size (graded) bituminous mixes using different aggregates with one gradation and identical flow asphalt contents, there will be difference in the average thickness of asphalt (h) between the particles. Mixes containing large quantity of macro surface voids in the coarse fractions will have a greater amount of the finer particles from the mix lost in these voids than in the case with mixes containing smooth particles. Such mixes (with smooth coarse particles) will have most of their fines floating between the larger particles and may cause dilation and higher (h) values as compared to the mixes with high geometric irregularity (particle roughness). For a given amount of asphalt between two particles, the increase in (h) is usually accompanied by decrease in r and thus a noticeable reduction in resistance to load (stability).

Equations (39) and (40) also suggest an explanation for optimum asphalt content in bituminous mixes. At low asphalt content (dry mix) both r and h are small, and the stability is low. At high asphalt content (fat mixes) both r and h are large and the ratios are similar to the dry case. At optimum the h is small while r is getting to be large.

Experimental Work -- Graded Mixtures

Preliminary Considerations and Preparations

The following preparations for testing of the mixtures were performed:

(1) In order to check the validity of the theoretical considerations and practical predictions for a wide range of aggregate types, it was decided to include all eight types of aggregate which have been tested before.[1]

(2) One gradation was chosen for all types of aggregates. This gradation was similar to that of wearing courses used by MSHD, and was determined by averaging the results of sixty graded field samples from various state highway projects (see Table 30).

Based on the above gradation the proportions of the six one-size fractions[2] were calculated. By combining the above fractions, a gap-graded system was produced since not all the sizes are represented. Nevertheless, as it was shown by Lees (79), there is little or no difference between the aggregate porosity that can be achieved with a well designed gap grading and the

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[1] See list in Chapter II, p. 14.

[2] 1/2in.-5/8in., #3-#4, #8-#10, #20-#30, #60-#80, #200-#270.

porosity of a well designed continuous grading. Since all the above fractions possess successive size ratios which are always less than the critical ratios of occupation, it can be assumed that the performance of the gap-graded mixtures will be similar to those of continuous graded mixtures.

(3) The given aggregate proportions together with the parameters of the one-size fractions, and the parameters of the mixture for a given type of aggregate, were used to calculate the expected properties of the compacted mixture for different asphalt contents and different specific gravities of the mixture. The results are presented for each type of aggregate in a computerized mixture design table. Portions of the tables are presented in Tables 22 through 29. These tables provided the main tool for predicting optimum asphalt contents for each type of aggregate.

(4) The new concept for optimum asphalt prediction was compared with a practical method of mixture design. It was decided to use the Marshall method to evaluate the optimum asphalt content and other mixture properties.

As described before, the Marshall method can be considered as a popular empirical method used for obtaining the mechanical behavior of bituminous mixtures. Nevertheless, in most cases this method has been found to provide reliable mixture design along with satisfactory service conditions. This method, as improved by the U.S. Corps of Engineers, can be considered the most useful method for bituminous mixture design. The Marshall test procedures have been also standardized by the ASTM under D1559.

It is evident that a correlation between the suggested concept for mixture design and prediction and the Marshall method may indicate the practicality of the new concept for a more rational design of actual bituminous mixtures.

Laboratory Work

Two major factors were involved in the basic experiment:

(a) Aggregate type, with eight types of aggregate (levels), see list on p. 14.

(b) Asphalt content, with five to seven levels at intervals of 0.5% (percent by weight of the mixture).

For each treatment combination (aggregate type-asphalt content combination) two replicates were tested.

The laboratory work was performed by blocking the aggregate type factor. Thus a series of Marshall tests were performed on each type of aggregate at a time.

The following procedure was used for determining the optimum asphalt content for the 8 different mixes:

(1) From field experience the approximate optimum total asphalt content was known for one of the mixes.

(2) From the above given optimum total asphalt content, the optimum flow asphalt contents and the total asphalt contents were predicted for each of the 8 mixes using a computer printed design table.

(3) The predicted optimum total asphalt contents were checked by laboratory tests using the Marshall procedure.

The laboratory procedures were as follows:

The aggregates and the 120-150 penetration asphalt were heated to 300 F. Two replicates for each asphalt content were mixed in the same batch by a mechanical mixer for one and one-half minutes. After mixing, the batch was separated into two samples and the samples were stored in sealed cans. After reheating the sample for one hour they were compacted, two replicates at a time, by mechanical Marshall compactor, applying 40 blows[1] on each side of the specimen. The rest of the testing procedure was identical to the standard Marshall procedure (1).

The exact amount of asphalt content for each sample was determined by the aid of the Mixture Design Tables on the basis of actual asphalt contents and specific gravity of the compacted mixtures.

The data of these tests are summarized in Figures 18 through 25.

Results and Discussion

Figure 26 and Table 31 summarize the mixture properties at optimum stability conditions. It is evident that the optimum asphalt content, and the conventional effective asphalt content (w_{ev} - as expressed volumetrically) vary considerably for different types of aggregates. On the other hand, the variations of the flow

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[1] This is equivalent to 50 blows applied manually.

asphalt content (w_{fv}) are very small.[1] It can also be shown that mixes with different types of aggregates have different values of maximum stability.

By performing regression analyses on the above data, it was found that there is no correlation between the flow asphalt content (w_{fv}) and maximum stabilities of different types of aggregates. The analysis of variance of the regression (see Table 32) indicates the acceptance of the hypothesis that the relationship between these two parameters is a straight line parallel to the maximum stability axis. This line intersects w_{fv} axis at the average value of 6.30%. If this average value of the flow asphalt content is used to predict the optimum asphalt contents[2] of different aggregates, it can be seen from Table 31 that the deviations between the predicted and the actual optimum asphalt contents are never greater than 0.35%.

By similar regression analysis it was found that linear correlation, with high correlation coefficient ($r = 0.906$), exists between the conventional effective asphalt content (w_{ev}) and the

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[1] As shown in Figure 22 two optimum asphalt contents of maximum stability were obtained for the slag. However, based on visual evaluation of samples, and the relationships between air voids, maximum specific gravity of the mixture, and maximum stability point, it was decided to choose the optimum asphalt content of the slag as 8.75% (percent by weight of the mixture). Moreover, the Marshall samples were dried, reheated, remixed, recompacted, and tested again. A single definite optimum asphalt content due to maximum stability was found around 8.3%.

[2] This prediction is done by the aid of the mixture design tables (Tables 22 through 29).

maximum stability for mixtures with different types of aggregates (see Figure 26). This relationship is expected since, for constant flow asphalt (w_{fv}), the variations in effective asphalt content are due to the different amounts of stationary asphalt (rugosity asphalt) needed to fill the macro surface voids of different types of aggregates. Since the amount of rugosity asphalt was related directly to the geometric irregularity of the particles,[1] it can be concluded that the relationship between the effective asphalt content and the maximum stability at optimum, reflects the expected influence of the geometry factor on the stability of bituminous mixtures. To verify this, the weighted average of macro surface voids (S_{ma}) was calculated for each type of aggregate. The regression analysis between S_{ma} and maximum stability at optimum also indicated linear correlation with high correlation coefficient ($r = 0.870$).

The relationships between the effective asphalt content and maximum stability indicated also the variability of the conventional effective asphalt content (w_{ev}) with different types of aggregate. If, by the same method as before, the average value of w_{ev} (14.68%) is used to predict the optimum asphalt contents, a deviation between the predicted and actual optimum asphalt content as high as 1.65% could be found (see Table 33).

It can be concluded that the flow asphalt content (w_{fv}), as defined in this work, see Equation (29), can be used as a unified physical parameter to predict the optimum asphalt contents for

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[1] See Figure 13.

maximum strength conditions. This behavior was expected prior to testing and explained earlier in this chapter.

Furthermore, the flow asphalt content was found to provide a unified parameter also for the combined optimum condition based on stability, specific gravity, and air voids. Table 33 shows that w_{fv} also varies only slightly and therefore is independent of the type of aggregate. Quantitatively, the average value of w_{fv} for the combined optimum is very close to the average value of w_{fv} for optimum stability (6.42% and 6.30%, respectively). The prediction of the combined optimum asphalt content also produces small variations which are at most 0.55%.

This trend was also expected since optimum stabilities usually tend to be related to optimum densities (1) and thus to constant values of air voids.

The theoretical model, which was used to explain the predicted variability of maximum strength values with the different types of aggregates, is seen to be verified by the experimental results.

Table 34 summarizes the various mixture properties at optimum stability conditions. Based on these data, the following results are observed.

(1) Good linear correlation exists between maximum stability values and the total fines lost by rugosity (F_{rt}) ($r = 0.833$).

(2) Mixtures with high stability usually possess low values of packing-VMA, while mixtures with low stabilities--high values of VMA_p.

(3) Opposite trends occur when comparing the conventional VMA with maximum stabilities; namely, VMA increases with the increase of maximum stability.

These results provide a consistent verification for the model which was used to describe the strength variability. A low packing VMA indicates high volumetric density and particles which are closer to one another. Thus, higher strength is expected, see Equation (40). On the other hand, when more fine particles are likely to be located in the contact points region among the coarser ones, the granular system tends to dilate. This dilation produces asphalt plugs with lower ratio r/h, see Equations (39) and (40), and thus lower stabilities. This condition is indicated, of course, by the high packing-VMA in aggregates which possess lower geometric irregularity and then, a lower quantity of fines-lost by rugosity.

The conventional VMA fails to explain the strength variability. In fact, it indicates contradictory trends, since the stability increases when the VMA is higher.

Figures 18 through 25 also indicate definite minimum values of packing-VMA. The minimum values usually occur in the region of maximum stability and maximum specific gravity of a given mixture. It is therefore recommended to use the minimum packing VMA conditions as additional design criteria for optimum asphalt content of a mixture.

CONCLUSIONS

The following major conclusions are based on theoretical considerations and laboratory work with 8 widely different aggregates, including one-size and graded mixes with one asphalt:

(1) The packing volume concept provided a good theoretical basis for defining quantitative and measurable aggregate factors which characterize important aggregate properties for individual particles and in bulk. A practical test (pouring test) was developed which measures the packing specific gravity (G_p) of any aggregate fraction.

(2) The geometric irregularity of aggregate pieces (shape, angularity, and surface texture combined) was expressed by specific rugosity (S_{rv}) which was also measured by the pouring test. This specific rugosity was further subdivided into micro (S_{mi}) and macro (S_{ma}) rugosity ($S_{rv} = S_{ma} + S_{mi}$).

(3) The interaction between the coarse and fine particles in a graded bituminous concrete mix was determined and the amount of the small particles falling into and getting lost in the crevices of the larger aggregate pieces could be expressed quantitatively through a factor called fines-lost by rugosity (F_r).

(4) The amount of asphalt lost into the surface crevices (macro and micro voids) was also measured and designated as (B_{rw}).

(5) The portion of asphalt which was not lost in the aggregate pores but was freely spaced between aggregate pieces was measured as flow asphalt (w_{fv}). For a given gradation and asphalt, the optimum flow asphalt constant was found to be similar for any mix, regardless of aggregate source (slag, natural gravel, etc.). This permitted a development of practical mix design tables which can be applied for prediction of optimum asphalt contents for various mixes (using various other parameters developed in this study).

Practical Applications

Several practical applications can be drawn from the results of this investigation:

(1) Physical volumetric parameters were developed to characterize aggregate factors in bituminous mixtures. These parameters can provide better understanding of the properties and behavior of the compacted bituminous mixture, and thus may replace some of the less descriptive terms which are now being used to correlate aggregate properties and mixture performance. This applies mainly to the specific rugosity (S_{rv}), which expresses the combined geometric properties of aggregate particles. This parameter may overcome the difficulties, and the lack of unity, which characterize the conventional definitions of the geometric factors.

(2) A practical test, called the pouring test was developed to evaluate aggregate parameters (see Appendix D).

(3) The accuracy in measurement of the maximum specific gravity of bituminous mixtures was improved by using methanol as the liquid (see Appendix E).

(4) The major practical result of this investigation is a unified concept in bituminous mixture design. A general procedure for bituminous mixture design is outlined in Appendix F.

Recommendation for Further Research

The theoretical concepts which were developed in this work should be applicable for a wide range of aggregate types and gradations used in bituminous mixture technology. Additional research will be needed to use these concepts to find if there are exceptions and broaden the theoretical base:

(1) Since only one gradation and one type of asphalt were tested, additional work should be aimed to apply the aggregate factors to different types of asphalt and different gradations.

(2) It is also recommended to verify the suggested concept with more mechanical (strength) testing and thus to provide more information about the relationships between the suggested aggregate factors and the mechanical behavior of the compacted mixture.

(3) Research could be concentrated to provide quantitative theory which will unify (or will be used to predict) the strength for different types of aggregate under optimum conditions with minimum number of tests.

(4) Research could also be oriented to relate the suggested aggregate factors to other mixture properties, such as, fatigue, dynamic behavior, durability, flexibility and stiffness, cracking, etc.

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TABLES

TABLE 1

PROPERTIES OF ASPHALT USED

STATE OF MICHIGAN
DEPARTMENT OF STATE HIGHWAYS
TESTING AND RESEARCH DIVISION
TESTING LABORATORY DIVISION
UNIVERSITY OF MICHIGAN
ANN ARBOR

REPORT OF TEST

Project General
Laboratory No. 72B-124 thru 126
Date January 24, 1972

Report on sample of ASPHALT CEMENT
Date sampled January 18, 1972 Date received January 18, 1972
Source of material Leonard Refineries, Incorporated, Alma, Michigan
Sampled from Producer's storage Quantity represented Not stated
Submitted by C.J. Stoike, Testing Laboratory Section
Intended use Bituminous mixtures Specification 120-150, 1970 Std Specs

TEST RESULTS

Laboratory Number 72B-	124	125	126	Average
Specific Gravity @ 25/25 C		1.020		
Penetration @ 25 C, 100 g, 5 sec, dmm	141	140	140	140
Penetration @ 46.1 C, 50 g, 5 sec, dmm				
Penetration @ 0 C, 200 g, 1 min, dmm				
Flash Point, Cleveland Open Cup, C		280		
Softening Point, Ring and Ball, C				
Ductility @ 25 C, 5 cm/min, cm		100+		
Ductility @ 15.6C, 5 cm/min, cm				
Solubility in CCl_4, per cent by weight		99.78		
Oliensis Spot Test		Neg.		
THIN FILM OVEN TEST 1/8 inch, 163 C, 5 hr				
Loss on Heating, per cent by weight		0.12		
Penetration of Residue, per cent of original		61		
Ductility of Residue @ 25 C, 5 cm/min, cm		100+		
STANDARD LOSS ON HEATING @ 163 C, 5 hr, 50 g				
Loss on Heating, per cent by weight				
Penetration of Residue, per cent of original				
Bitumen, per cent by weight				
Viscosity, ~~Saybolt Furol @ 275 F, sec~~ Kinematic, 135 C, cs		263		
HEAT STABILITY TEST @ 500 F, 2 hr				
Penetration of Residue @ 25 C, 100 g, 5 sec, dmm				
Viscosity of Residue, Saybolt Furol @ 275 F, sec				
Seal No.				

TABLE 2

MAXIMUM SPECIFIC GRAVITY OF GLASS BEAD MIXTURES AS TESTED IN THREE METHODS

Size of Glass Beads	Solvent Immersion		Methanol Test				ASTM D 2041			
	Measured Max Sp Gr	Average	Measured Max Sp Gr	Average	Difference* in Unit of Sp Gr	Difference* in Percent	Measured Max Sp Gr	Average	Difference* in Unit of Sp Gr	Difference* in Percent
16 mm	2.414		2.410				2.405			
	2.409	2.412	2.410	2.410	-0.002	-0.08	2.401	2.403	-0.009	-0.37
6 mm	2.107		2.092				2.075			
	2.103	2.105	2.099	2.096	-0.009	-0.43	2.076	2.076	-0.029	-1.38
3 mm	2.056		2.056				2.008			
	2.061	2.059	2.048	2.052	-0.007	-0.34	2.000	2.004	-0.055	-2.67

*Differences are based on the Solvent Immersion Values.

TABLE 3

MAXIMUM SPECIFIC GRAVITY OF AGGREGATE MIXTURE AS COMPARED BY THE SOLVENT AND METHANOL TESTS

Aggregate Type	Size of Aggregates	Solvent Immersion		Methanol Test			
		Measured Max Sp Gr	Average	Measured Max Sp Gr	Average	Difference* in Unit of Sp Gr	Difference* in Percent
Beach pebbles	3/8 in.-#3	2.499		2.493			
		2.482	2.491	2.501	2.497	+0.006	+0.24
	#4-#8	2.409		2.381			
		2.400	2.405	2.383	2.382	-0.023	-0.96
Limestone	3/8 in.-#3	2.468		2.437			
		2.462	2.465	2.438	2.438	-0.027	-1.09
	#4-#8	2.391		2.350			
		2.384	2.388	2.356	2.353	-0.035	-1.46
Slag	3/8 in.-#3	2.301		2.227			
		2.298	2.300	2.231	2.229	-0.071	-3.08
	#4-#8	2.264		2.220			
		2.249	2.257	2.197	2.199	-0.058	-2.59
Sandstone	3/8 in.-#3	2.264		2.087			
		2.255	2.260	2.088	2.088	-0.172	-7.61
	#4-#8	2.170		2.057			
		2.174	2.172	2.066	2.062	-0.110	-5.06

*Differences are based on the Solvent Immersion Values.

TABLE 4

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 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	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	0.8326	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 5

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 6

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 7

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 8

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 9

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

TABLE 10

AVERAGE PARAMETER VALUES FOR EACH TYPE OF AGGREGATE OVER ALL SIZES

	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 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	2.588	2.714	1.80	0.92	2.317	14.65	0.8535	5.68	12.55	83.67	10.48	4.17
DL	2.804	2.843	0.48	0.38	2.274	19.99	0.8001	9.01	19.73	98.46	18.91	1.09
SS	2.329	2.658	5.52	3.76	1.891	28.83	0.7117	14.01	25.18	83.04	18.34	10.49
CG	2.689	2.762	0.99	0.59	2.125	23.05	0.7695	10.87	22.19	95.91	20.96	2.09
SL	2.581	2.810	3.25	2.73	2.013	28.25	0.7175	13.82	27.12	95.95	21.81	6.44
MR	2.808	2.929	1.47	0.86	2.240	23.50	0.7650	10.31	22.07	92.83	20.24	3.25
LS	2.635	2.710	1.05	0.63	2.138	21.08	0.7892	9.79	20.16	95.33	18.86	2.23
BP	2.691	2.720	0.40	0.13	2.568	5.58	0.9442	1.93	4.80	84.46	4.56	1.13
Total Average	2.641	2.768	1.87	1.25	2.196	20.62	0.7938	9.43	19.23	91.20	16.77	3.86

TABLE 11

PARTICLE DIMENSIONS FOR 1/2 IN.-5/8 IN. FRACTIONS

Aggregate Type	ℓ, cm	m, cm	s, cm	m/ℓ	s/ℓ	s/m	Equivalent Sphere Diameter, cm (d)	Sphericity (ψ)
NG/A	2.065	1.500	0.988	0.726	0.478	0.659	1.452	0.703
NG/B	2.020	1.512	1.041	0.749	0.515	0.688	1.470	0.728
DL/A	2.050	1.504	0.846	0.734	0.413	0.563	1.377	0.672
DL/B	2.145	1.495	0.845	0.697	0.394	0.565	1.394	0.650
SS/A	1.997	1.556	1.097	0.779	0.549	0.705	1.505	0.754
SS/B	2.045	1.542	1.098	0.754	0.537	0.712	1.513	0.740
CG/A	2.106	1.460	0.870	0.693	0.413	0.596	1.388	0.659
CG/B	2.151	1.480	0.840	0.688	0.391	0.568	1.388	0.645
SL/A	2.154	1.605	1.180	0.745	0.548	0.735	1.598	0.742
SL/B	2.080	1.536	1.202	0.738	0.578	0.783	1.566	0.753
MR/A	1.968	1.473	0.832	0.748	0.423	0.565	1.356	0.689
MR/B	2.118	1.485	0.834	0.701	0.394	0.562	1.379	0.651
LS/A	2.345	1.636	0.914	0.698	0.390	0.559	1.520	0.648
LS/B	2.301	1.623	1.011	0.705	0.439	0.623	1.556	0.676
BP/A	2.230	1.694	0.869	0.760	0.390	0.513	1.486	0.666
BP/B	2.294	1.697	0.891	0.740	0.388	0.525	1.516	0.661
Average	2.129	1.550	0.960	0.728	0.453	0.620	1.467	0.690

TABLE 12

PARTICLE DIMENSIONS FOR #4-#3 FRACTIONS

Aggregate Type	ℓ, cm	m, cm	s, cm	m/ℓ	s/ℓ	s/m	Equivalent Sphere Diameter, cm (d)	Sphericity (ψ)
NG/A	0.838	0.595	0.350	0.710	0.418	0.588	0.559	0.667
NG/B	0.765	0.594	0.368	0.776	0.481	0.620	0.551	0.720
DL/A	0.848	0.597	0.330	0.704	0.389	0.553	0.551	0.650
DL/B	0.903	0.599	0.318	0.663	0.352	0.531	0.556	0.616
SS/A	0.792	0.576	0.394	0.727	0.497	0.684	0.564	0.712
SS/B	0.722	0.565	0.386	0.783	0.535	0.683	0.539	0.747
CG/A	0.898	0.573	0.283	0.638	0.315	0.494	0.526	0.586
CG/B	0.877	0.576	0.283	0.657	0.323	0.491	0.523	0.596
SL/A	0.830	0.574	0.394	0.692	0.475	0.686	0.572	0.689
SL/B	0.716	0.553	0.404	0.772	0.564	0.731	0.543	0.758
MR/A	0.739	0.566	0.385	0.766	0.521	0.680	0.544	0.736
MR/B	0.848	0.554	0.374	0.653	0.441	0.675	0.560	0.660
LS/A	0.819	0.589	0.293	0.719	0.358	0.497	0.521	0.636
LS/B	0.966	0.581	0.308	0.601	0.319	0.530	0.557	0.577
BP/A	0.781	0.620	0.357	0.794	0.457	0.576	0.557	0.713
BP/B	0.790	0.636	0.346	0.805	0.438	0.544	0.558	0.706
Average	0.821	0.584	0.348	0.716	0.430	0.598	0.549	0.673

TABLE 13

LINEAR CORRELATION COEFFICIENTS BETWEEN OR WITHIN BULK AND PACKING VOLUME PARAMETERS (Including Sandstone)

Bulk Specific Gravity	Apparent Specific Gravity	Water Absorption	Asphalt Lost by Absorption	Packing Specific Gravity	Specific Rugosity	Asphalt Lost by Rugosity (weight)	Asphalt Lost by Rugosity (volume)	Macro Surface Voids	Micro Surface Voids
-0.172 to -0.947									
-0.288 to -0.935		0.827 to 0.990							
0.262 to 0.857	-0.101 to 0.811								
				-0.525 to -0.967					
		0.297 to 0.817	0.612 to 0.806	-0.660 to -0.985	0.873 to 0.993				
				-0.491 to -0.957	0.858 to 0.999				
								0.128 to 0.500	

TABLE 14

LOS ANGELES ABRASION VALUES

Aggregate Type	Percent Wear	
	Grading B	Grading D
MR/A	14.2	15.6
MR/B	13.6	15.5
BP/A	17.3	13.4
BP/B	17.8	14.3
CG/A	21.3	23.1
CG/B	20.7	23.0
NG/A	22.5	24.9
NG/B	24.0	24.3
DL/A	23.7	25.1
DL/B	25.2	24.8
LS/A	31.5	23.3
LS/B	31.8	23.1
SL/A	45.6	32.3
SL/B	46.0	32.3
SS/A	53.8	45.8
SS/B	52.9	45.8

TABLE 15

SPECIFIC GRAVITY OF FILLERS - #270

Aggregate Type	Absolute Specific Gravity
NG/A	2.683
NG/B	2.683
LS/A	2.715
LS/B	2.709
BP/A	2.723
BP/B	2.723
SS/A	2.736
SS/B	2.736
CG/A	2.778
CG/B	2.778
MR/A	2.844
MR/B	2.844
DL/A	2.850
DL/B	2.850
SL/A	2.895
SL/B	2.895

TABLE 16

FLORIDA BEARING VALUES FOR #20-#30 FRACTIONS

Aggregate Type	Florida Bearing Value*
OTTAWA S	2.06
BP	2.95
SS	3.31
NG	3.35
DL	6.66
LS	6.83
MR	7.83
SL	7.94
CG	8.30

*Each number is an average of five tests.

TABLE 17

STATISTICAL ANALYSIS OF ONE-SIZE AGGREGATE PARAMETERS

a) TYPICAL ANOVA TABLE FOR DEPENDENT VARIABLES IN THE EXPERIMENT

Dependent Variable - S_{rv}

Source of Variation	DF	Sum of Squares	Mean Square	F Ratio	F Statistic
Mean	1	40810.28	40810.28		
S (Size)	5	1548.83	309.77	4190	$F_{0.95,5,48} = 2.41$
T (S) (Type)	42	5582.76	132.92	1800	$F_{0.95,42,48} = 1.58$
R (ST) (Reps)	48	3.54	0.0738		

b) A SUMMARY OF F RATIOS FOR DEPENDENT VARIABLES (PARAMETERS) IN THE EXPERIMENT

Dependent Variable	F for Size ($F_{0.95,5,48} = 2.41$)	F for Type ($F_{0.95,42,48} = 1.58$)
G_{ag}	770	1071
G_{ap}	429	611
A_w	144	254
B_{ag}	405	128
G_p	4200	3060
S_{rv}	4190	1800
B_{rw}	3910	1411
B_{rv}	2970	927
S_b	44	12
S_{ma}	4710	1046
S_{mi}	342	1067

TABLE 18

EXPERIMENT FOR EVALUATING FINES LOST BY RUGOSITY
(for aggregates NG,CG and SL)
(DATA SUMMARY)

C_{fv}	Size of Fine Fractions	Type of Aggregate		
		Natural Gravel	Crushed Gravel	Slag
0.5	#20-#30	0.485	0.522	0.515
		-0.015	0.022	0.015
		-3.00	4.40	3.00
		0.0139	0.0326	0.0494
	#20-#30 #60-#80	0.440	0.467	0.540
		-0.060	-0.033	0.040
		-12.00	-6.60	8.00
		0.0130	0.0302	0.0510
	#60-#80	0.495	0.515	0.537
		-0.005	0.015	0.037
		-1.00	3.00	7.40
		0.0141	0.0323	0.0508
1.0	#20-#30	1.020	1.039	1.025
		0.020	0.039	0.025
		2.00	3.90	2.50
		0.0215	0.0484	0.0736
	#20-#30 #60-#80	0.951	1.002	1.072
		-0.049	0.002	0.072
		-4.90	0.20	7.20
		0.0208	0.476	0.0752
	#60-#80	1.045	1.022	1.017
		0.045	0.022	0.017
		4.50	2.20	1.70
		0.0218	4.80	0.0733
1.5	#20-#30	1.552	1.512	1.531
		0.052	0.012	0.031
		3.47	0.80	2.07
		0.0259	0.0572	0.0879
	#20-#30 #60-#80	1.588	1.534	1.532
		0.088	0.034	0.032
		5.93	2.26	2.13
		0.0261	0.0575	0.0879
	#60-#80	1.505	1.574	1.544
		0.005	0.074	0.044
		0.34	4.94	2.94
		0.0256	0.0581	0.0867

For Each Cell:

← Measured C_{fv}
← C_{fv} Differences
← Differences in Percent
← F_r

TABLE 19

ANOVA TABLE FOR THE MEASURED FINES CONCENTRATION (C_{fv})

Source of Variation	DF	Sum of Squares	Mean Square	F Ratio	$F_{0.95,\nu_1,\nu_2}$
Mean	1	28.175	28.175		
C (C_{fv})	2	4.863	2.432	1890	4.46
S (Size of Fines)	2	0.000919	0.000460	0.36	4.46
T (Type	2	0.002998	0.001499	1.17	4.46
CS	4	0.002241	0.000560	0.44	3.84
CT	4	0.003784	0.000946	0.74	3.84
ST	4	0.003166	0.000791	0.62	3.84
CST	8	0.010294	0.001287		

TABLE 20

ANOVA TABLE FOR THE FINES CONCENTRATION DIFFERENCES

Source of Variation	DF	Sum of Squares	Mean Square	F Ratio	$F_{0.95,\nu_1,\nu_2}$
Mean	1	0.012502	0.012502		
C (C_{fv})	2	0.007041	0.003520	2.74	4.46
S (Size of Fines)	2	0.000919	0.000460	0.36	4.46
T (Type)	2	0.002998	0.001499	1.16	4.46
CS	4	0.002441	0.000560	0.44	3.84
CT	4	0.003784	0.000946	0.74	3.84
ST	4	0.003166	0.000791	0.62	3.84
CST	8	0.010294	0.001287		

TABLE 21

ANOVA TABLE FOR THE PERCENT FINES CONCENTRATION DIFFERENCES

Source of Variation	DF	Sum of Squares	Mean Square	F Ratio	$F_{0.95,\nu_1,\nu_2}$
Mean	1	83.143	83.143		
C (C_{fv})	2	28.162	14.081	1.13	4.46
S (Size of Fines)	2	33.336	16.668	1.33	4.46
T (Type)	2	96.222	48.111	3.84	4.46
CS	4	49.265	12.316	0.98	3.84
CT	4	118.225	29.556	2.46	3.84
ST	4	69.483	17.371	1.39	3.84
CST	8	100.112	12.514		

TABLE 21A

ANOVA TABLE FOR THE FINES LOST BY RUGOSITY (F_r)*

Source of Variation	DF	Sum of Squares	Mean Square	F Ratio	$F_{0.95,\nu_1,\nu_2}$
Mean	1	560.479	560.479		
C (C_{fv})	2	28.941	14.471	3290	4.46
S (Size of Fines)	2	0.001076	0.000538	0.12	4.46
T (Type)	2	113.915	56.957	12970	4.46
CS	4	0.016510	0.004127	0.94	3.84
CT	4	4.795	1.199	190	3.84
ST	4	0.047470	0.011867	1.92	3.84
CST	8	0.035138	0.004392		

*Sum of squares were calculated by expressing F_r in percent.

TABLE 22

MIXTURE DESIGN TABLE FOR NATURAL GRAVEL
(eight aggregate series)

AGGREGATE TYPE - NG
NUMBER OF FRACTIONS N= 6
X(1),......X(N)=20.0,28.0,15.0,19.5,12.5, 5.0 (FRACTIONS PROPORTION - WEIGHT BASIS)

PERC. ASPH. CONT. MIX BASIS	PERC. ASPH. CONT. AGG. BASIS	PERC. TOTAL ASPH. ABS.	EFF. ASPH. VOL. BASIS	PERC. BUG. ASPH. WT. BASIS	PERC. BUG. ASPH. VOL. BASIS	FLOW ASPH. WT. BASIS	FLOW ASPH. VOL. BASIS	TOTAL FINES LOST BY BUG.	PERC. ACTIV PACK. VOL.	SPEC. GRAV. OF MIX	PERC. AIR VOIDS	PERC. CONV. VMA	PERC. PACK. VMA
w	w	B_{ag}	w_{ev}			w_{fw}	w_{fv}	F_{rt}	V_{pa}	G_{mx}	U	VMA	VMA_p
3.00	3.09	0.95	5.44	2.11	4.65	0.99	2.43	.0645	93.55				
										2.100	16.88	21.17	18.85
										2.150	14.90	19.29	16.92
										2.200	12.92	17.42	14.99
										2.250	10.95	15.54	13.06
										2.300	8.97	13.66	11.12
										2.350	6.99	11.78	9.19
										2.400	5.01	9.91	7.26
										2.450	3.03	8.03	5.33
										2.500	1.05	6.15	3.40
										2.550	-0.93	4.28	1.46
										2.600	-2.91	2.40	-0.47
3.50	3.63	0.95	6.79	2.21	5.08	1.42	3.49	.0623	93.77				
										2.100	16.25	21.58	19.07
										2.150	14.26	19.71	17.15
										2.200	12.26	17.84	15.22
										2.250	10.27	15.97	13.29
										2.300	8.27	14.11	11.37
										2.350	6.28	12.24	9.44
										2.400	4.29	10.37	7.51
										2.450	2.29	8.50	5.59
										2.500	0.30	6.64	3.66
										2.550	-1.70	4.77	1.73
										2.600	-3.69	2.90	-0.19
4.00	4.17	0.95	8.16	2.29	5.28	1.87	4.59	.0602	93.98				
										2.100	15.62	21.98	19.32
										2.150	13.61	20.12	17.40
										2.200	11.60	18.27	15.48
										2.250	9.59	16.41	13.55
										2.300	7.58	14.55	11.63
										2.350	5.57	12.69	9.71
										2.400	3.56	10.84	7.79
										2.450	1.55	8.98	5.87
										2.500	-0.46	7.12	3.95
										2.550	-2.46	5.26	2.03
										2.600	-4.47	3.41	0.11
4.50	4.71	0.95	9.54	2.38	5.47	2.34	5.71	.0583	94.17				
										2.100	14.98	22.39	19.58
										2.150	12.96	20.54	17.66
										2.200	10.94	18.69	15.75
										2.250	8.91	16.84	13.83
										2.300	6.89	15.00	11.92
										2.350	4.86	13.15	10.00
										2.400	2.84	11.30	8.09
										2.450	0.82	9.45	6.17
										2.500	-1.21	7.61	4.26
										2.550	-3.23	5.76	2.34
										2.600	-5.26	3.91	0.43
5.00	5.26	0.95	10.94	2.45	5.65	2.81	6.66	.0566	94.34				
										2.100	14.35	22.79	19.85
										2.150	12.31	20.96	17.94
										2.200	10.27	19.12	16.03
										2.250	8.23	17.28	14.12
										2.300	6.19	15.44	12.21
										2.350	4.16	13.60	10.31
										2.400	2.12	11.77	8.40
										2.450	0.08	9.93	6.49
										2.500	-1.96	8.09	4.58
										2.550	-4.00	6.25	2.67
										2.600	-6.04	4.41	0.76
5.50	5.82	0.95	12.35	2.52	5.81	3.30	8.03	.0549	94.51				
										2.100	13.72	23.20	20.13
										2.150	11.66	21.37	18.23
										2.200	9.61	19.54	16.33
										2.250	7.56	17.72	14.43
										2.300	5.50	15.89	12.53
										2.350	3.45	14.06	10.62
										2.400	1.39	12.23	8.72
										2.450	-0.66	10.40	6.82
										2.500	-2.72	8.57	4.92
										2.550	-4.77	6.74	3.02
										2.600	-6.82	4.92	1.12
6.00	6.38	0.95	13.77	2.59	5.96	3.79	9.23	.0534	94.66				
										2.100	13.09	23.61	20.43
										2.150	11.02	21.79	18.53
										2.200	8.95	19.97	16.64
										2.250	6.88	18.15	14.74
										2.300	4.81	16.33	12.85
										2.350	2.74	14.51	10.95
										2.400	0.67	12.69	9.06
										2.450	-1.40	10.88	7.16
										2.500	-3.47	9.06	5.27
										2.550	-5.54	7.24	3.38
										2.600	-7.61	5.42	1.48

TABLE 23

MIXTURE DESIGN TABLE FOR DOLOMITE
(eight aggregate series)

AGGREGATE TYPE - DL
NUMBER OF FRACTIONS N= 6
X(1),......X(N)=20.0,28.0,15.0,19.5,12.5, 5.0 (FRACTIONS PROPORTION - WEIGHT BASIS)

PERC. ASPH. CONT. MIX BASIS	PERC. ASPH. CONT. AGG. BASIS	PERC. TOTAL ASPH. ABS.	EFF. ASPH. VOL. BASIS	PERC. RUG. ASPH. WT. BASIS	PERC. RUG. ASPH. VOL. BASIS	FLOW ASPH. WT. BASIS	FLOW ASPH. VOL. BASIS	TOTAL FINES LOST BY RUG.	PERC. ACTIV PACK. VOL.	SPEC. GRAV. OF MIX	PERC. AIR VOIDS	PERC. CONV. VMA	PERC. PACK. VMA
w	w	B_{ag}	w_{ev}			w_{fw}	w_{fv}	F_{rt}	V_{pa}	G_{mx}	U	VMA	VMA_p
4.50	4.71	0.43	11.76	3.26	7.33	1.45	3.69	.1173	88.27				
										2.100	19.93	28.35	22.78
										2.150	18.02	26.64	20.94
										2.200	16.11	24.94	19.10
										2.250	14.21	23.23	17.26
										2.300	12.30	21.53	15.42
										2.350	10.39	19.82	13.59
										2.400	8.49	18.11	11.75
										2.450	6.58	16.41	9.91
										2.500	4.67	14.70	8.07
										2.550	2.77	13.00	6.23
										2.600	0.86	11.29	4.39
5.00	5.26	0.43	13.27	3.42	7.69	1.84	4.67	.1137	88.63				
										2.100	19.27	28.73	22.87
										2.150	17.35	27.03	21.03
										2.200	15.42	25.33	19.20
										2.250	13.50	23.63	17.36
										2.300	11.58	21.94	15.53
										2.350	9.66	20.24	13.69
										2.400	7.73	18.54	11.85
										2.450	5.81	16.85	10.02
										2.500	3.89	15.15	8.18
										2.550	1.97	13.45	6.34
										2.600	0.05	11.76	4.51
5.50	5.82	0.43	14.80	3.57	8.02	2.25	5.69	.1104	88.96				
										2.100	18.61	29.10	22.99
										2.150	16.67	27.41	21.15
										2.200	14.73	25.72	19.32
										2.250	12.80	24.04	17.49
										2.300	10.86	22.35	15.65
										2.350	8.92	20.66	13.82
										2.400	6.98	18.97	11.99
										2.450	5.04	17.28	10.15
										2.500	3.11	15.60	8.32
										2.550	1.17	13.91	6.49
										2.600	-0.77	12.22	4.65
6.00	6.38	0.43	16.34	3.71	8.33	2.68	6.74	.1073	89.27				
										2.100	17.95	29.48	23.13
										2.150	16.00	27.80	21.30
										2.200	14.04	26.12	19.47
										2.250	12.09	24.44	17.64
										2.300	10.14	22.76	15.81
										2.350	8.18	21.08	13.98
										2.400	6.23	19.40	12.15
										2.450	4.28	17.72	10.32
										2.500	2.32	16.04	8.49
										2.550	0.37	14.36	6.66
										2.600	-1.59	12.68	4.83
6.50	6.95	0.43	17.90	3.84	8.62	3.11	7.81	.1043	89.57				
										2.100	17.29	29.85	23.29
										2.150	15.32	28.18	21.46
										2.200	13.35	26.51	19.63
										2.250	11.38	24.84	17.81
										2.300	9.41	23.17	15.98
										2.350	7.45	21.50	14.15
										2.400	5.48	19.83	12.33
										2.450	3.51	18.16	10.50
										2.500	1.54	16.49	8.67
										2.550	-0.43	14.82	6.85
										2.600	-2.40	13.15	5.02
7.00	7.53	0.43	19.48	3.96	8.90	3.57	8.92	.1016	89.84				
										2.100	16.63	30.23	23.46
										2.150	14.65	28.56	21.64
										2.200	12.66	26.90	19.82
										2.250	10.68	25.24	18.00
										2.300	8.69	23.58	16.17
										2.350	6.71	21.92	14.35
										2.400	4.72	20.26	12.53
										2.450	2.74	18.60	10.71
										2.500	0.75	16.94	8.88
										2.550	-1.23	15.27	7.06
										2.600	-3.22	13.61	5.24
7.50	8.11	0.43	21.08	4.08	9.16	4.03	10.06	.0990	90.10				
										2.100	15.97	30.60	23.65
										2.150	13.97	28.95	21.84
										2.200	11.97	27.30	20.02
										2.250	9.97	25.64	18.20
										2.300	7.97	23.99	16.38
										2.350	5.97	22.34	14.56
										2.400	3.97	20.69	12.75
										2.450	1.97	19.03	10.93
										2.500	-0.03	17.38	9.11
										2.550	-2.03	15.73	7.29
										2.600	-4.03	14.08	5.48

TABLE 24

MIXTURE DESIGN TABLE FOR SANDSTONE
(eight aggregate series)

AGGREGATE TYPE - SS
NUMBER OF FRACTIONS N= 6
X(1),.....X(N)=20.0,28.0,15.0,19.5,12.5, 5.0 (FRACTIONS PROPORTION - WEIGHT BASIS)

PERC. ASPH. CONT. MIX BASIS	PERC. ASPH. CONT. AGG. BASIS	PERC. TOTAL ASPH. ABS.	EFF. ASPH. VOL. BASIS	PERC. RUG. ASPH. WT. BASIS	PERC. RUG. ASPH. VOL. BASIS	FLOW ASPH. WT. BASIS	FLOW ASPH. VOL. BASIS	TOTAL FINES LOST BY RUG.	PERC. ACTIV PACK. VOL.	SPEC. GRAV. OF MIX	PERC. AIR VOIDS	PERC. CONV. VMA	PERC. PACK. VMA
w	w	B_{ag}	w_{ev}			w_{fw}	w_{fv}	F_{rt}	V_{pa}	G_{mx}	U	VMA	VMA_p
9.00	9.89	4.14	12.77	8.09	14.98	1.81	3.69	.0912	90.88				
										2.100	4.78	15.56	8.18
										2.150	2.52	13.55	5.99
										2.200	0.25	11.54	3.80
										2.250	-2.02	9.53	1.62
										2.300	-4.29	7.52	-0.57
										2.350	-6.55	5.51	-2.76
										2.400	-8.82	3.50	-4.94
										2.450	-11.09	1.49	-7.13
										2.500	-13.35	-0.52	-9.31
										2.550	-15.62	-2.53	-11.50
										2.600	-17.89	-4.54	-13.69
9.50	10.50	4.14	14.11	8.23	15.26	2.26	4.61	.0884	91.16				
										2.100	4.17	16.03	8.39
										2.150	1.89	14.03	6.21
										2.200	-0.39	12.03	4.03
										2.250	-2.67	10.03	1.85
										2.300	-4.95	8.03	-0.33
										2.350	-7.23	6.03	-2.51
										2.400	-9.51	4.03	-4.69
										2.450	-11.80	2.03	-6.87
										2.500	-14.08	0.03	-9.05
										2.550	-16.36	-1.97	-11.24
										2.600	-18.64	-3.97	-13.42
10.00	11.11	4.14	15.47	8.38	15.53	2.73	5.55	.0857	91.43				
										2.100	3.57	16.49	8.63
										2.150	1.27	14.50	6.46
										2.200	-1.03	12.51	4.28
										2.250	-3.32	10.52	2.11
										2.300	-5.62	8.54	-0.07
										2.350	-7.91	6.55	-2.24
										2.400	-10.21	4.56	-4.42
										2.450	-12.51	2.57	-6.59
										2.500	-14.80	0.58	-8.77
										2.550	-17.10	-1.41	-10.94
										2.600	-19.39	-3.39	-13.12
10.50	11.73	4.14	16.85	8.51	15.78	3.22	6.51	.0832	91.68				
										2.100	2.96	16.95	8.89
										2.150	0.65	14.98	6.72
										2.200	-1.66	13.00	4.56
										2.250	-3.97	11.02	2.39
										2.300	-6.28	9.04	0.22
										2.350	-8.59	7.07	-1.95
										2.400	-10.90	5.09	-4.12
										2.450	-13.21	3.11	-6.29
										2.500	-15.53	1.14	-8.46
										2.550	-17.84	-0.84	-10.63
										2.600	-20.15	-2.82	-12.80
11.00	12.36	4.14	18.24	8.64	16.01	3.72	7.51	.0809	91.91				
										2.100	2.35	17.42	9.17
										2.150	0.03	15.45	7.01
										2.200	-2.30	13.49	4.85
										2.250	-4.62	11.52	2.68
										2.300	-6.95	9.55	0.52
										2.350	-9.27	7.59	-1.64
										2.400	-11.60	5.62	-3.80
										2.450	-13.92	3.65	-5.97
										2.500	-16.25	1.69	-8.13
										2.550	-18.57	-0.28	-10.29
										2.600	-20.90	-2.24	-12.46
11.50	12.90	4.14	19.65	8.75	16.24	4.24	8.53	.0787	92.13				
										2.100	1.74	17.88	9.46
										2.150	-0.60	15.93	7.31
										2.200	-2.94	13.97	5.15
										2.250	-5.28	12.02	3.00
										2.300	-7.62	10.06	0.84
										2.350	-9.95	8.11	-1.32
										2.400	-12.29	6.15	-3.47
										2.450	-14.63	4.20	-5.63
										2.500	-16.97	2.24	-7.78
										2.550	-19.31	0.29	-9.94
										2.600	-21.65	-1.67	-12.09
12.00	13.64	4.14	21.08	8.87	16.45	4.77	9.57	.0766	92.34				
										2.100	1.13	18.35	9.77
										2.150	-1.22	16.40	7.62
										2.200	-3.57	14.46	5.47
										2.250	-5.93	12.51	3.32
										2.300	-8.28	10.57	1.18
										2.350	-10.63	8.62	-0.97
										2.400	-12.99	6.68	-3.12
										2.450	-15.34	4.74	-5.27
										2.500	-17.70	2.79	-7.42
										2.550	-20.05	0.85	-9.57
										2.600	-22.40	-1.10	-11.71

TABLE 25

MIXTURE DESIGN TABLE FOR CRUSHED GRAVEL
(eight aggregate series)

AGGREGATE TYPE - CG
NUMBER OF FRACTIONS N= 6
X(1),.....X(N)=20.0,28.0,15.0,19.5,12.5, 5.0 (FRACTIONS PROPORTION - WEIGHT BASIS)

PERC. ASPH. CONT. MIX BASIS	PERC. ASPH. CONT. AGG. BASIS	PERC. TOTAL ASPH. ABS.	EFF. ASPH. VOL. BASIS	PERC. RUG. ASPH. WT. BASIS	PERC. RUG. ASPH. VOL. BASIS	FLOW ASPH. WT. BASIS	FLOW ASPH. VOL. BASIS	TOTAL FINES LOST BY RUG.	PERC. ACTIV PACK. VOL.	SPEC. GRAV. OF MIX	PERC. AIR VOIDS	PERC. CONV. VMA	PERC. PACK. VMA
W	W	B_{ag}	V_{ev}			W_{fw}	V_{fv}	F_{rt}	V_{pa}	G_{mx}	U	VMA	VMA_p
5.00	5.26	0.62	12.21	3.93	8.30	1.34	3.24	.1302	86.98				
										2.100	16.52	25.60	19.13
										2.150	14.53	23.83	17.20
										2.200	12.54	22.06	15.28
										2.250	10.55	20.29	13.35
										2.300	8.57	18.52	11.43
										2.350	6.58	16.75	9.50
										2.400	4.59	14.97	7.57
										2.450	2.60	13.20	5.65
										2.500	0.61	11.43	3.72
										2.550	-1.37	9.66	1.80
										2.600	-3.36	7.89	-0.13
5.50	5.82	0.62	13.68	4.10	8.67	1.72	4.15	.1265	87.35				
										2.100	15.87	25.99	19.21
										2.150	13.87	24.23	17.29
										2.200	11.87	22.47	15.37
										2.250	9.86	20.71	13.44
										2.300	7.86	18.95	11.52
										2.350	5.86	17.18	9.60
										2.400	3.85	15.42	7.67
										2.450	1.85	13.66	5.75
										2.500	-0.15	11.90	3.83
										2.550	-2.15	10.14	1.90
										2.600	-4.16	8.37	-0.02
6.00	6.38	0.62	15.16	4.27	9.01	2.12	5.10	.1231	87.69				
										2.100	15.23	26.39	19.33
										2.150	13.21	24.63	17.41
										2.200	11.19	22.88	15.49
										2.250	9.17	21.13	13.56
										2.300	7.15	19.37	11.64
										2.350	5.14	17.62	9.72
										2.400	3.12	15.87	7.80
										2.450	1.10	14.12	5.88
										2.500	-0.92	12.36	3.96
										2.550	-2.94	10.61	2.04
										2.600	-4.96	8.86	0.12
6.50	6.95	0.62	16.65	4.42	9.33	2.53	6.08	.1198	88.02				
										2.100	14.58	26.78	19.46
										2.150	12.55	25.03	17.54
										2.200	10.52	23.29	15.63
										2.250	8.48	21.55	13.71
										2.300	6.45	19.80	11.79
										2.350	4.42	18.06	9.87
										2.400	2.38	16.32	7.96
										2.450	0.35	14.57	6.04
										2.500	-1.69	12.83	4.12
										2.550	-3.72	11.09	2.20
										2.600	-5.75	9.34	0.29
7.00	7.53	0.62	18.16	4.56	9.64	2.96	7.09	.1168	88.32				
										2.100	13.94	27.17	19.61
										2.150	11.89	25.43	17.70
										2.200	9.84	23.70	15.79
										2.250	7.79	21.97	13.87
										2.300	5.74	20.23	11.96
										2.350	3.69	18.50	10.04
										2.400	1.65	16.76	8.13
										2.450	-0.40	15.03	6.22
										2.500	-2.45	13.30	4.30
										2.550	-4.50	11.56	2.39
										2.600	6.55	9.83	0.48
7.50	8.11	0.62	19.69	4.70	9.93	3.41	8.12	.1139	88.61				
										2.100	13.30	27.56	19.79
										2.150	11.23	25.84	17.88
										2.200	9.17	24.11	15.97
										2.250	7.10	22.39	14.06
										2.300	5.04	20.66	12.15
										2.350	2.97	18.94	10.24
										2.400	0.91	17.21	8.33
										2.450	-1.16	15.49	6.42
										2.500	-3.22	13.76	4.51
										2.550	-5.28	12.04	2.60
										2.600	-7.35	10.31	0.69
8.00	8.70	0.62	21.24	4.83	10.20	3.86	9.19	.1111	88.89				
										2.100	12.65	27.95	19.97
										2.150	10.57	26.24	18.07
										2.200	8.49	24.52	16.16
										2.250	6.41	22.81	14.26
										2.300	4.33	21.09	12.35
										2.350	2.25	19.37	10.44
										2.400	0.17	17.66	8.54
										2.450	-1.91	15.94	6.63
										2.500	-3.99	14.23	4.73
										2.550	-6.07	12.51	2.82
										2.600	-8.15	10.80	0.92

TABLE 26

MIXTURE DESIGN TABLE FOR SLAG
(eight aggregate series)

AGGREGATE TYPE - SL
NUMBER OF FRACTIONS N= 6
X(1),.....X(N)=20.0,28.0,15.0,19.5,12.5, 9.0 (FRACTIONS PROPORTION - WEIGHT BASIS)

PERC. ASPH. CONT. MIX BASIS	PERC. ASPH. CONT. AGG. BASIS	PERC. TOTAL ASPH. ABS.	EFF. ASPH. VOL. BASIS	PERC. RUG. ASPH. WT. BASIS	PERC. RUG. ASPH. VOL. BASIS	FLOW ASPH. WT. BASIS	FLOW ASPH. VOL. BASIS	TOTAL FINES LOST BY RUG.	PERC. ACTIV PACK. VOL.	SPEC. GRAV. OF MIX	PERC. AIR VOIDS	PERC. CONV. VMA	PERC. PACK. VMA
W	W	B_{ag}	V_{ev}			V_{fw}	V_{fv}	F_{rt}	V_{pa}	G_{mx}	U	VMA	VMA_p
7.00	7.53	2.95	11.24	6.44	12.45	1.08	2.44	.1445	85.55				
										2.100	13.21	21.98	15.28
										2.150	11.14	20.12	13.26
										2.200	9.07	18.26	11.24
										2.250	7.01	16.40	9.23
										2.300	4.94	14.54	7.21
										2.350	2.87	12.69	5.19
										2.400	0.81	10.83	3.17
										2.450	-1.26	8.97	1.16
										2.500	-3.33	7.11	-0.86
										2.550	-5.39	5.26	-2.88
										2.600	-7.46	3.40	-4.89
7.50	8.11	2.95	12.67	6.64	12.81	1.47	3.31	.1408	85.92				
										2.100	12.57	22.40	15.37
										2.150	10.48	20.55	13.35
										2.200	8.40	18.70	11.34
										2.250	6.32	16.85	9.32
										2.300	4.24	15.00	7.31
										2.350	2.16	13.16	5.29
										2.400	0.07	11.31	3.28
										2.450	-2.01	9.46	1.26
										2.500	-4.09	7.61	-0.75
										2.550	-6.17	5.77	-2.77
										2.600	-8.25	3.92	-4.78
8.00	8.70	2.95	14.11	6.82	13.16	1.88	4.21	.1373	86.27				
										2.100	11.92	22.81	15.49
										2.150	9.83	20.98	13.47
										2.200	7.73	19.14	11.46
										2.250	5.63	17.30	9.45
										2.300	3.54	15.46	7.44
										2.350	1.44	13.63	5.42
										2.400	-0.66	11.79	3.41
										2.450	-2.75	9.95	1.40
										2.500	-4.85	8.11	-0.61
										2.550	-6.95	6.28	-2.62
										2.600	-9.05	4.44	-4.64
8.50	9.29	2.95	15.57	6.99	13.49	2.30	5.14	.1340	86.60				
										2.100	11.28	23.23	15.62
										2.150	9.17	21.41	13.61
										2.200	7.06	19.58	11.61
										2.250	4.95	17.75	9.60
										2.300	2.84	15.92	7.59
										2.350	0.72	14.10	5.58
										2.400	-1.39	12.27	3.57
										2.450	-3.50	10.44	1.56
										2.500	-5.61	8.61	-0.45
										2.550	-7.73	6.78	-2.46
										2.600	-9.84	4.96	-4.47
9.00	9.89	2.95	17.04	7.15	13.81	2.74	6.09	.1309	86.91				
										2.100	10.64	23.65	15.78
										2.150	8.52	21.84	13.78
										2.200	6.39	20.02	11.77
										2.250	4.26	18.20	9.76
										2.300	2.13	16.38	7.76
										2.350	0.01	14.56	5.75
										2.400	-2.12	12.75	3.75
										2.450	-4.25	10.93	1.74
										2.500	-6.38	9.11	-0.26
										2.550	-8.50	7.29	-2.27
										2.600	-10.63	5.48	-4.27
9.50	10.50	2.95	18.53	7.30	14.10	3.19	7.07	.1279	87.21				
										2.100	10.00	24.07	15.96
										2.150	7.86	22.27	13.95
										2.200	5.72	20.46	11.95
										2.250	3.58	18.65	9.95
										2.300	1.43	16.84	7.95
										2.350	-0.71	15.03	5.95
										2.400	-2.85	13.23	3.95
										2.450	-4.99	11.42	1.95
										2.500	-7.14	9.61	-0.05
										2.550	-9.28	7.80	-2.05
										2.600	-11.42	6.00	-4.05
10.00	11.11	2.95	20.04	7.45	14.39	3.66	8.08	.1250	87.49				
										2.100	9.36	24.49	16.15
										2.150	7.21	22.69	14.15
										2.200	5.05	20.90	12.15
										2.250	2.89	19.10	10.16
										2.300	0.73	17.30	8.16
										2.350	-1.43	15.50	6.16
										2.400	-3.58	13.71	4.17
										2.450	-5.74	11.91	2.17
										2.500	-7.90	10.11	0.17
										2.550	-10.06	8.31	-1.82
										2.600	-12.22	6.51	-3.82

TABLE 27

MIXTURE DESIGN TABLE FOR MINE ROCK
(eight aggregate series)

AGGREGATE TYPE - MR
NUMBER OF FRACTIONS N= 6
X(1),.....X(N)=20.0,28.0,15.0,19.5,12.5, 5.0 (FRACTIONS PROPORTION - WEIGHT BASIS)

PERC. ASPH. CONT. MIX BASIS	PERC. ASPH. CONT. AGG. BASIS	PERC. TOTAL ASPH. ABS.	EFF. ASPH. VOL. BASIS	PERC. RUG. ASPH. WT. BASIS	PERC. RUG. ASPH. VOL. BASIS	FLOW ASPH. WT. BASIS	FLOW ASPH. VOL. BASIS	TOTAL FINES LOST BY RUG.	PERC. ACTIV PACK. VOL.	SPEC. GRAV. OF MIX	PERC. AIR VOIDS	PERC. CONV. VMA	PERC. PACK. VMA
w	w	B_{eg}	w_{ev}			w_{fw}	w_{fv}	F_{rt}	V_{pa}	G_{mx}	U	VMA	VMA_p
4.50	4.71	0.77	10.86	3.74	8.37	0.97	2.46	.1220	87.80				
										2.100	20.90	28.65	22.80
										2.150	19.02	26.95	20.96
										2.200	17.13	25.25	19.13
										2.250	15.25	23.55	17.29
										2.300	13.37	21.85	15.45
										2.350	11.48	20.15	13.61
										2.400	9.60	18.46	11.77
										2.450	7.72	16.76	9.93
										2.500	5.83	15.06	8.10
										2.550	3.95	13.36	6.26
										2.600	2.07	11.66	4.42
5.00	5.26	0.77	12.38	3.92	8.76	1.35	3.41	.1181	88.19				
										2.100	20.23	29.02	22.87
										2.150	18.34	27.33	21.03
										2.200	16.44	25.64	19.20
										2.250	14.54	23.95	17.36
										2.300	12.64	22.26	15.52
										2.350	10.74	20.57	13.69
										2.400	8.84	18.88	11.85
										2.450	6.94	17.19	10.01
										2.500	5.04	15.50	8.18
										2.550	3.14	13.81	6.34
										2.600	1.24	12.12	4.50
5.50	5.82	0.77	13.91	4.08	9.11	1.74	4.40	.1146	88.54				
										2.100	19.57	29.40	22.96
										2.150	17.66	27.71	21.13
										2.200	15.74	26.03	19.30
										2.250	13.83	24.35	17.46
										2.300	11.91	22.67	15.63
										2.350	10.00	20.99	13.79
										2.400	8.08	19.31	11.96
										2.450	6.17	17.63	10.13
										2.500	4.25	15.95	8.29
										2.550	2.34	14.27	6.46
										2.600	0.42	12.59	4.62
6.00	6.38	0.77	15.47	4.22	9.45	2.16	5.43	.1112	88.86				
										2.100	18.91	29.77	23.08
										2.150	16.98	28.10	21.25
										2.200	15.05	26.42	19.42
										2.250	13.12	24.75	17.59
										2.300	11.18	23.08	15.76
										2.350	9.25	21.41	13.93
										2.400	7.32	19.74	12.10
										2.450	5.39	18.06	10.27
										2.500	3.46	16.39	8.43
										2.550	1.53	14.72	6.60
										2.600	-0.40	13.05	4.77
6.50	6.95	0.77	17.03	4.36	9.76	2.59	6.49	.1081	89.19				
										2.100	18.24	30.14	23.23
										2.150	16.30	28.48	21.40
										2.200	14.35	26.82	19.57
										2.250	12.40	25.15	17.74
										2.300	10.46	23.49	15.91
										2.350	8.51	21.83	14.09
										2.400	6.56	20.16	12.26
										2.450	4.62	18.50	10.43
										2.500	2.67	16.84	8.60
										2.550	0.72	15.17	6.77
										2.600	-1.22	13.51	4.95
7.00	7.53	0.77	18.62	4.49	10.05	3.03	7.58	.1052	89.48				
										2.100	17.58	30.52	23.39
										2.150	15.62	28.86	21.56
										2.200	13.66	27.21	19.74
										2.250	11.69	25.55	17.91
										2.300	9.73	23.90	16.09
										2.350	7.77	22.24	14.27
										2.400	5.81	20.59	12.44
										2.450	3.84	18.94	10.62
										2.500	1.88	17.28	8.79
										2.550	-0.08	15.63	6.97
										2.600	-2.04	13.97	5.14
7.50	8.11	0.77	20.22	4.62	10.32	3.49	8.69	.1024	89.76				
										2.100	16.92	30.89	23.56
										2.150	14.94	29.24	21.74
										2.200	12.96	27.60	19.92
										2.250	10.98	25.95	18.10
										2.300	9.00	24.31	16.28
										2.350	7.03	22.66	14.46
										2.400	5.05	21.02	12.64
										2.450	3.07	19.37	10.82
										2.500	1.09	17.73	9.00
										2.550	-0.89	16.08	7.18
										2.600	-2.87	14.44	5.36

TABLE 28

MIXTURE DESIGN TABLE FOR LIMESTONE (eight aggregate series)

AGGREGATE TYPE - LS
NUMBER OF FRACTIONS N= 6
X(1),......X(N)=20.0,28.0,15.0,19.5,12.5, 5.0 (FRACTIONS PROPORTION - WEIGHT BASIS)

PERC. ASPH. CONT. MIX BASIS	PERC. ASPH. CONT. AGG. BASIS	PERC. TOTAL ASPH. ABS.	EFF. ASPH. VOL. BASIS	PERC. RUG. ASPH. WT. BASIS	PERC. RUG. ASPH. VOL. BASIS	FLOW ASPH. WT. BASIS	FLOW ASPH. VOL. BASIS	TOTAL FINES LOST BY RUG.	PERC. ACTIV PACK. VOL.	SPEC. GRAV. OF MIX	PERC. AIR VOIDS	PERC. CONV. VMA	PERC. PACK. VMA
W	W	B_{ag}	W_{ev}			W_{fw}	W_{fv}	F_{rt}	V_{pa}	G_{mx}	U	VMA	VMA_p
5.00	5.26	0.64	11.94	3.62	7.60	1.64	3.93	.1161	88.39				
										2.100	15.22	24.26	18.43
										2.150	13.20	22.46	16.48
										2.200	11.18	20.66	14.54
										2.250	9.16	18.85	12.60
										2.300	7.14	17.05	10.66
										2.350	5.12	15.25	8.71
										2.400	3.11	13.44	6.77
										2.450	1.09	11.64	4.83
										2.500	-0.93	9.84	2.89
										2.550	-2.95	8.03	0.95
										2.600	-4.97	6.23	-1.00
5.50	5.82	0.64	13.38	3.77	8.00	2.05	4.89	.1129	88.71				
										2.100	14.58	24.66	18.56
										2.150	12.55	22.87	16.62
										2.200	10.51	21.07	14.68
										2.250	8.48	19.28	12.74
										2.300	6.44	17.49	10.80
										2.350	4.41	15.69	8.87
										2.400	2.38	13.90	6.93
										2.450	0.34	12.10	4.99
										2.500	-1.69	10.31	3.05
										2.550	-3.72	8.52	1.11
										2.600	-5.76	6.72	-0.83
6.00	6.38	0.64	14.84	3.92	8.30	2.47	5.87	.1099	89.01				
										2.100	13.94	25.06	18.72
										2.150	11.89	23.28	16.78
										2.200	9.84	21.49	14.85
										2.250	7.80	19.71	12.91
										2.300	5.75	17.92	10.98
										2.350	3.70	16.14	9.04
										2.400	1.65	14.35	7.10
										2.450	-0.40	12.57	5.17
										2.500	-2.45	10.79	3.23
										2.550	-4.50	9.00	1.30
										2.600	-6.55	7.22	-0.64
6.50	6.95	0.64	16.30	4.05	8.58	2.90	6.89	.1071	89.29				
										2.100	13.30	25.46	18.89
										2.150	11.24	23.68	16.96
										2.200	9.18	21.91	15.03
										2.250	7.11	20.13	13.10
										2.300	5.05	18.36	11.17
										2.350	2.98	16.58	9.24
										2.400	0.92	14.81	7.31
										2.450	-1.14	13.03	5.37
										2.500	-3.21	11.26	3.44
										2.550	-5.27	9.49	1.51
										2.600	-7.34	7.71	-0.42
7.00	7.53	0.64	17.79	4.18	8.65	3.35	7.93	.1044	89.56				
										2.100	12.67	25.86	19.08
										2.150	10.59	24.09	17.16
										2.200	8.51	22.33	15.23
										2.250	6.43	20.56	13.30
										2.300	4.35	18.80	11.38
										2.350	2.27	17.03	9.45
										2.400	0.19	15.27	7.52
										2.450	-1.89	13.50	5.60
										2.500	-3.97	11.73	3.67
										2.550	-6.05	9.97	1.75
										2.600	-8.13	8.20	-0.18
7.50	8.11	0.64	19.29	4.30	9.10	3.81	9.00	.1018	89.82				
										2.100	12.03	26.26	19.29
										2.150	9.94	24.50	17.37
										2.200	7.84	22.74	15.45
										2.250	5.75	20.99	13.53
										2.300	3.65	19.23	11.61
										2.350	1.56	17.48	9.68
										2.400	-0.54	15.72	7.76
										2.450	-2.63	13.96	5.84
										2.500	-4.73	12.21	3.92
										2.550	-6.82	10.45	2.00
										2.600	-8.92	8.70	0.08
8.00	8.70	0.64	20.81	4.41	9.34	4.29	10.09	.0994	90.06				
										2.100	11.39	26.65	19.51
										2.150	9.28	24.91	17.60
										2.200	7.17	23.16	15.68
										2.250	5.06	21.42	13.76
										2.300	2.95	19.67	11.85
										2.350	0.84	17.92	9.93
										2.400	-1.27	16.18	8.01
										2.450	-3.38	14.43	6.10
										2.500	-5.48	12.68	4.18
										2.550	-7.59	10.94	2.27
										2.600	-9.70	9.19	0.35

TABLE 29

MIXTURE DESIGN TABLE FOR BEACH PEBBLES
(eight aggregate series)

AGGREGATE TYPE - BP
NUMBER OF FRACTIONS N= 6
X(1),.....X(N)=20.0,28.0,15.0,19.5,12.5, 5.0 (FRACTIONS PROPORTION - WEIGHT BASIS)

PERC. ASPH. CONT. MIX BASIS	PERC. ASPH. CONT. AGG. BASIS	PERC. TOTAL ASPH. ABS.	EFF. ASPH. VOL. BASIS	PERC. BUG. ASPH. WT. BASIS	PERC. BUG. ASPH. VOL. BASIS	FLOW ASPH. WT. BASIS	FLOW ASPH. VOL. BASIS	TOTAL FINES LOST BY BUG.	PERC. ACTIV PACK. VOL.	SPEC. GRAV. OF MIX	PERC. AIR VOIDS	PERC. CONV. VMA	PERC. PACK. VMA
w	w	B_{ag}	w_{ev}			w_{fw}	w_{fv}	F_{rt}	V_{pa}	G_{mx}	U	VMA	VMA_p
2.50	2.56	0.14	6.40	1.03	2.61	1.53	3.96	.0235	97.65				
										2.100	19.05	23.92	22.13
										2.150	17.12	22.11	20.27
										2.200	15.20	20.30	18.42
										2.250	13.27	18.49	16.57
										2.300	11.34	16.68	14.71
										2.350	9.42	14.87	12.86
										2.400	7.49	13.05	11.00
										2.450	5.56	11.24	9.15
										2.500	3.63	9.43	7.29
										2.550	1.71	7.62	5.44
										2.600	-0.22	5.81	3.59
3.00	3.09	0.14	7.80	1.07	2.70	2.02	5.23	.0225	97.75				
										2.100	18.41	24.31	22.45
										2.150	16.47	22.51	20.60
										2.200	14.53	20.71	18.76
										2.250	12.58	18.91	16.91
										2.300	10.64	17.10	15.06
										2.350	8.70	15.30	13.22
										2.400	6.76	13.50	11.37
										2.450	4.81	11.70	9.52
										2.500	2.87	9.90	7.68
										2.550	0.93	8.09	5.83
										2.600	-1.01	6.29	3.99
3.50	3.63	0.14	9.21	1.11	2.79	2.52	6.51	.0216	97.84				
										2.100	17.77	24.70	22.78
										2.150	15.81	22.91	20.94
										2.200	13.85	21.12	19.10
										2.250	11.90	19.32	17.26
										2.300	9.94	17.53	15.43
										2.350	7.98	15.74	13.59
										2.400	6.02	13.95	11.75
										2.450	4.07	12.15	9.91
										2.500	2.11	10.36	8.07
										2.550	0.15	8.57	6.23
										2.600	-1.81	6.78	4.40
4.00	4.17	0.14	10.63	1.14	2.87	3.03	7.82	.0208	97.92				
										2.100	17.13	25.09	23.12
										2.150	15.16	23.31	21.29
										2.200	13.18	21.53	19.46
										2.250	11.21	19.74	17.63
										2.300	9.24	17.96	15.80
										2.350	7.26	16.18	13.97
										2.400	5.29	14.39	12.14
										2.450	3.32	12.61	10.31
										2.500	1.35	10.83	8.47
										2.550	-0.63	9.04	6.64
										2.600	-2.60	7.26	4.81
4.50	4.71	0.14	12.07	1.17	2.94	3.55	9.14	.0201	97.99				
										2.100	16.49	25.48	23.46
										2.150	14.50	23.71	21.64
										2.200	12.51	21.93	19.82
										2.250	10.52	20.16	18.00
										2.300	8.54	18.39	16.17
										2.350	6.55	16.61	14.35
										2.400	4.56	14.84	12.53
										2.450	2.57	13.06	10.71
										2.500	0.58	11.29	8.88
										2.550	-1.41	9.52	7.06
										2.600	-3.39	7.74	5.24
5.00	5.26	0.14	13.52	1.19	3.01	4.07	10.49	.0195	98.05				
										2.100	15.85	25.87	23.81
										2.150	13.84	24.11	22.00
										2.200	11.84	22.34	20.18
										2.250	9.84	20.58	18.37
										2.300	7.83	18.81	16.56
										2.350	5.83	17.05	14.74
										2.400	3.83	15.28	12.93
										2.450	1.82	13.52	11.11
										2.500	-0.18	11.75	9.30
										2.550	-2.18	9.99	7.49
										2.600	-4.19	8.22	5.67
5.50	5.82	0.14	14.99	1.22	3.07	4.60	11.85	.0188	98.12				
										2.100	15.21	26.26	24.16
										2.150	13.19	24.51	22.36
										2.200	11.17	22.75	20.55
										2.250	9.15	21.00	18.75
										2.300	7.13	19.24	16.94
										2.350	5.11	17.49	15.14
										2.400	3.09	15.73	13.33
										2.450	1.08	13.97	11.53
										2.500	-0.94	12.22	9.72
										2.550	-2.96	10.46	7.91
										2.600	-4.98	8.71	6.11

TABLE 30

AVERAGE GRADATION USED FOR THE MARSHALL TESTING

Sieve	Percent Passing
3/4 in.	100
1/2 in.	99
3/8 in.	83
#4	60
#8	47
#16	36
#30	28
#50	14
#100	6.5
#200	5.0

TABLE 31

ACTUAL AND PREDICTED OPTIMUM ASPHALT CONTENTS BASED ON MAXIMUM STABILITY

Aggregate Type	Optimum Asphalt Content at Maximum Stability (%)	Maximum Stability (lb)	New Parameters			Conventional Parameters		
			Optimum Flow Asphalt, w_{fv} (%) (Volume Basis)	Predicted Optimum Asphalt Content (%)	Deviations from Actual Optimum Asphalt Content (%)	Conventional Optimum Effective Asphalt, w_{ev} (Volume Basis) (%)	Predicted Optimum Asphalt Content (%)	Deviations from Actual Optimum Asphalt Content (%)
NG	5.05	1620	6.98	4.75	-0.30	11.08	6.35	+1.30
DL	5.55	2120	5.80	5.80	+0.25	14.95	5.50	-0.05
SS	10.35	2400	6.22	10.40	-0.05	16.44	9.70	-0.65
CG	6.40	1900	5.88	6.60	+0.20	16.35	5.85	-0.55
SL	9.00	2810	5.61	9.10	+0.35	16.30	8.20	-0.55
MR	6.70	2610	6.93	6.40	-0.30	17.67	5.75	-0.95
LS	5.95	1970	5.77	6.20	+0.25	14.69	5.95	0.00
BP	3.75	670	7.17	3.40	-0.35	9.92	5.40	+1.65
Average			6.30			14.68		

TABLE 32

ANOVA FOR THE REGRESSION ANALYSIS BETWEEN w_{fv}* AND MAXIMUM MARSHALL STABILITY

Source of Variation	DF	Sum of Squares	Mean Square	F Ratio	$F_{0.95,1,6}$
Due to Regression	1	0.8435	0.8435	2.58	5.99
Deviation about Regression	6	1.9623	0.3270		
Total	7				

*w_{fv} = percent optimum flow asphalt (volume basis)

TABLE 33

ACTUAL AND PREDICTED OPTIMUM ASPHALT CONTENTS BASED ON STABILITY, SPECIFIC GRAVITY, AND AIR VOIDS

					New Parameters			Conventional Parameters		
Aggregate Type	Asphalt Content at Maximum Stability (%)	Asphalt Content at Maximum Specific Gravity (%)	Asphalt Content at 3% Air Voids (%)	Actual Optimum Asphalt Content (Average) (%)	Optimum Flow Asphalt, W_{fv} (%) (Volume Basis)	Predicted Optimum Asphalt Content (%)	Deviations from Actual Optimum Asphalt Content (%)	Conventional Optimum Effective Asphalt, W_{ev} (Volume Basis) (%)	Predicted Optimum Asphalt Content (%)	Deviations from Actual Optimum Asphalt Content (%)
NG	5.05	5.80	5.00	5.30	7.56	4.80	-0.50	11.79	6.45	+1.15
DL	5.55	5.75	5.30	5.55	5.80	5.85	+0.30	14.95	5.50	-0.05
SS	10.35	11.25	9.50	10.42	6.27	10.45	+0.05	16.57	9.75	-0.60
CG	6.40	7.10	6.25	6.60	6.28	6.65	+0.05	16.95	5.90	-0.70
SL	8.75	9.05	8.50	8.75	5.61	9.15	+0.40	16.30	8.25	-0.65
MR	6.70	6.05	6.20	6.30	6.07	6.45	+0.15	16.41	5.80	-0.50
LS	5.95	6.45	5.70	6.05	5.97	6.25	+0.20	14.99	6.00	-0.05
BP	3.75	4.35	3.85	4.00	7.82	3.45	-0.55	10.62	5.45	+1.45
Average					6.42			14.84		

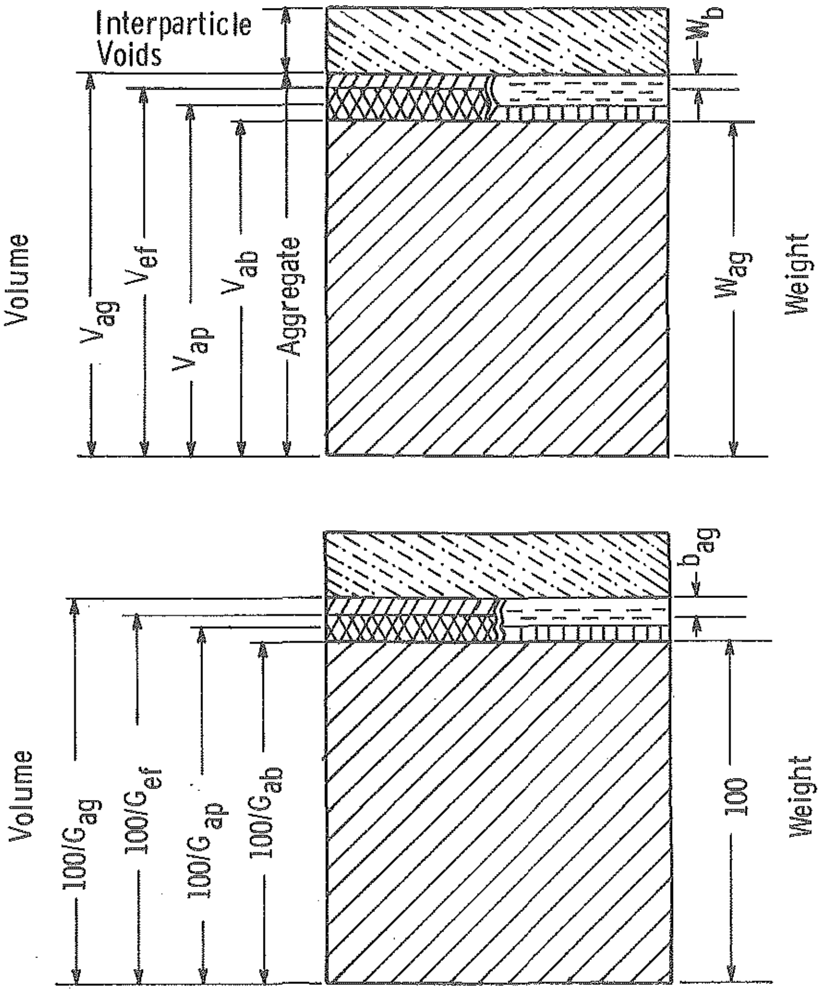
TABLE 34

A SUMMARY OF MIXTURE PROPERTIES AT OPTIMUM STABILITY CONDITIONS AS OBTAINED BY THE MARSHALL METHOD

Aggregate Type	Optimum Asphalt Content (%)	Maximum Stability (lb)	Optimum Flow Asphalt, W_{fv} (Percent by Volume)	Flow (0.01 in.)	Percent Air Voids, U	Percent VMA	Percent Packing VMA	Maximum Specific Gravity of Mixture (G_{mx})*	Total Fines Lost by Rugosity in the Mixture, F_{rt}
NG	5.05	1620	6.98	7.5	2.80	12.60	9.30	2397	0.0564
DL	5.55	2120	5.80	8.5	2.30	15.10	7.80	2517	0.1101
SS	10.35	2400	6.22	11.0	1.00	15.10	6.80	2150	0.0855
CG	6.40	1900	5.88	9.0	2.70	16.40	8.20	2401	0.1204
SL	8.75	2810	5.61	12.0	2.50	16.10	7.60	2303	0.1325
MR	6.70	2610	6.93	12.0	2.80	17.00	8.60	2506	0.1069
LS	5.95	1970	5.77	9.0	2.60	15.30	7.90	2392	0.1102
BP	3.75	670	7.17	7.0	3.10	11.80	9.50	2475	0.0212

*Not at optimum asphalt content.

FIGURES



▧ Interparticle Voids
┄ Aggregate Voids Permeable to Water
▥ Aggregate Voids Impermeable to Water
▨ Aggregate Voids Permeable to Asphalt
▩ Aggregate Voids Impermeable to Asphalt
▨ Aggregate Solids

V_{ag} = Bulk Volume of the Particle

V_{ef} = Effective Volume of the Particle

V_{ap} = Apparent Volume of the Particle

V_{ab} = Absolute Volume of the Particle

G_{ag}, G_{ef}, G_{ap}, G_{ab} = The Correspondent Specific Gravities

Figure 1. Weight-volume relationships for coated aggregate particles (7).

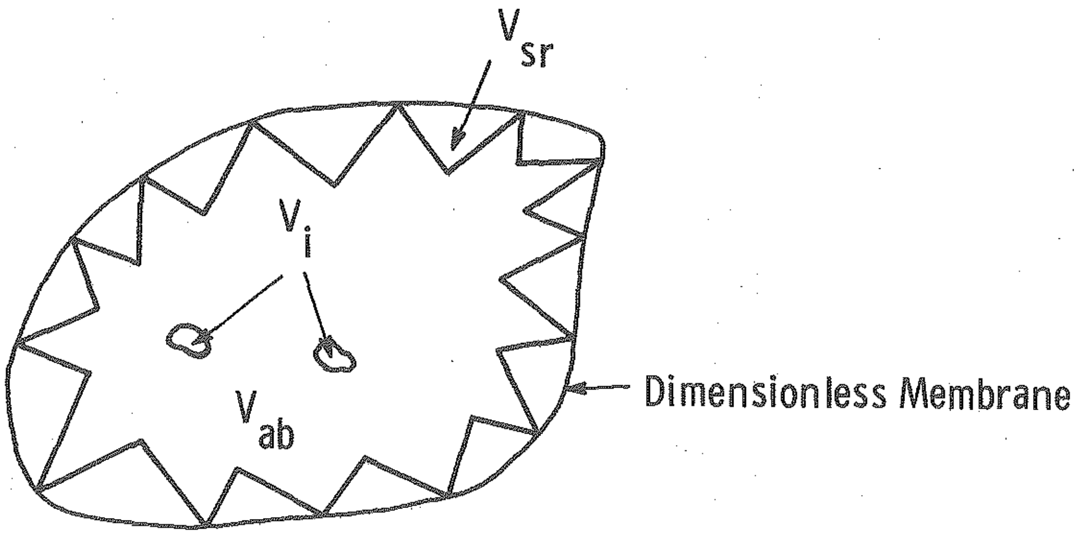


Figure 2. Components of a particle packing volume (2,3).

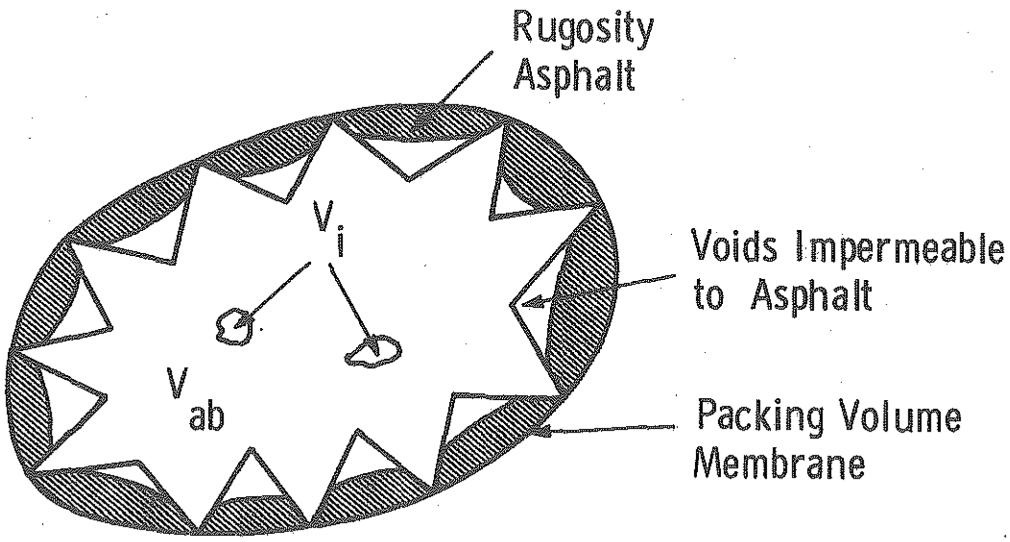


Figure 3. Rugosity asphalt within a particle (2,3).

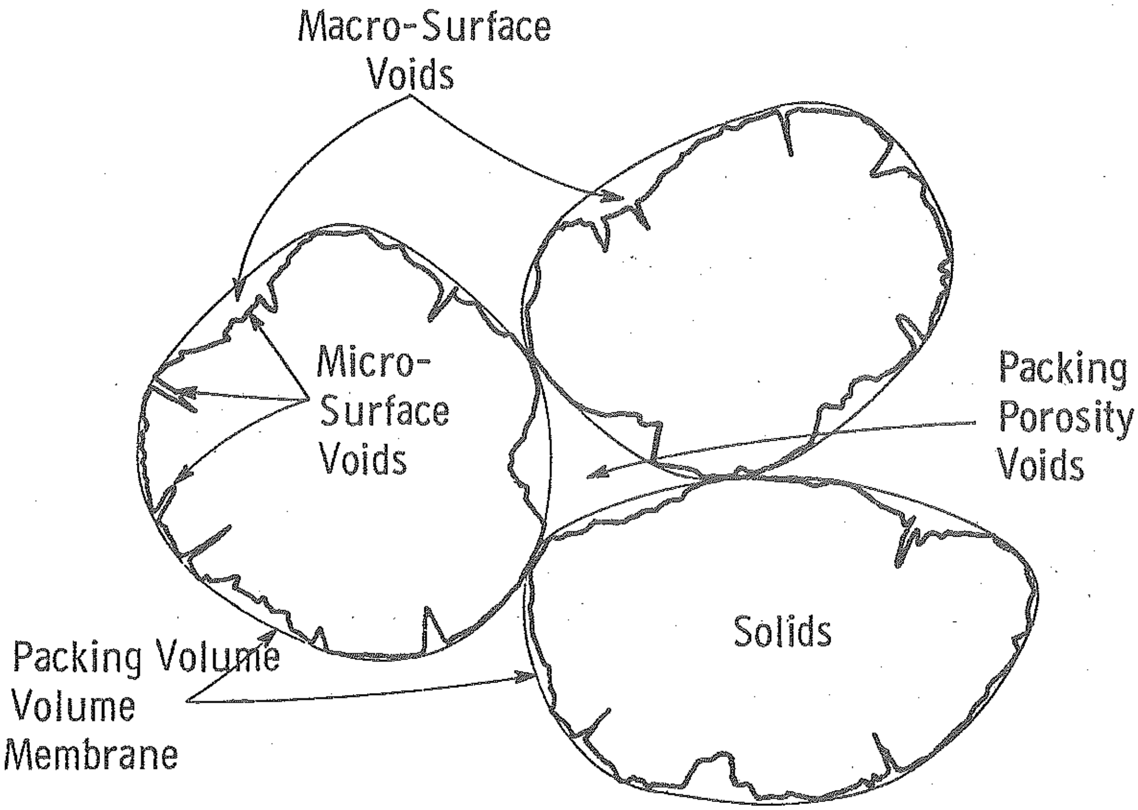


Figure 4. Packing volume, packing porosity, and geometric irregularity of particles.

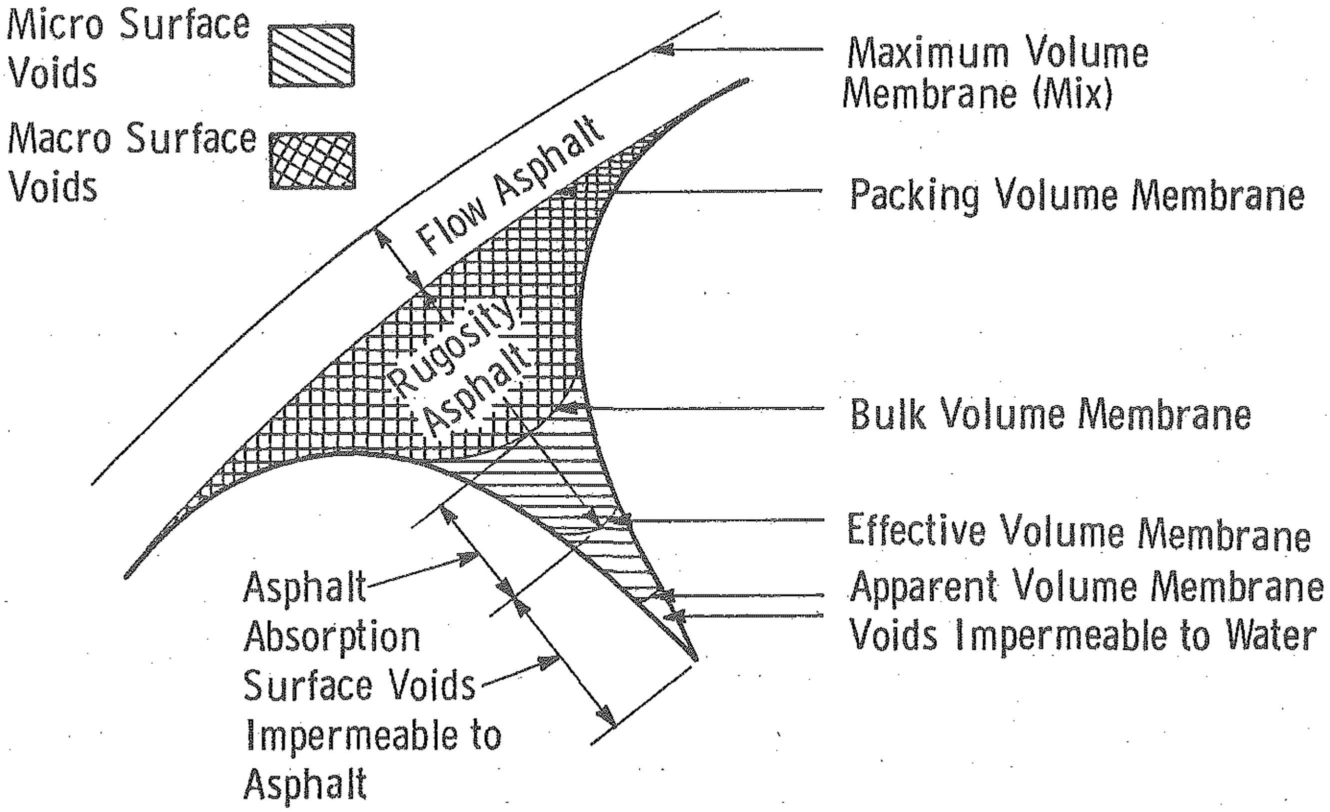


Figure 5. Rugosity and flow asphalt within and outside a surface pore.

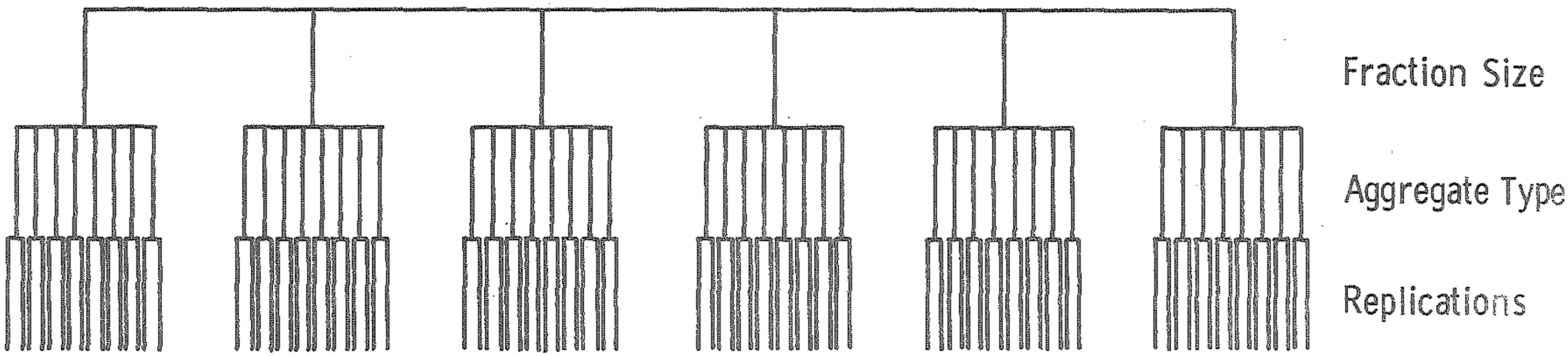


Figure 6. Two-factor nested (hierarchal) design for the main experiment using eight selected aggregates.

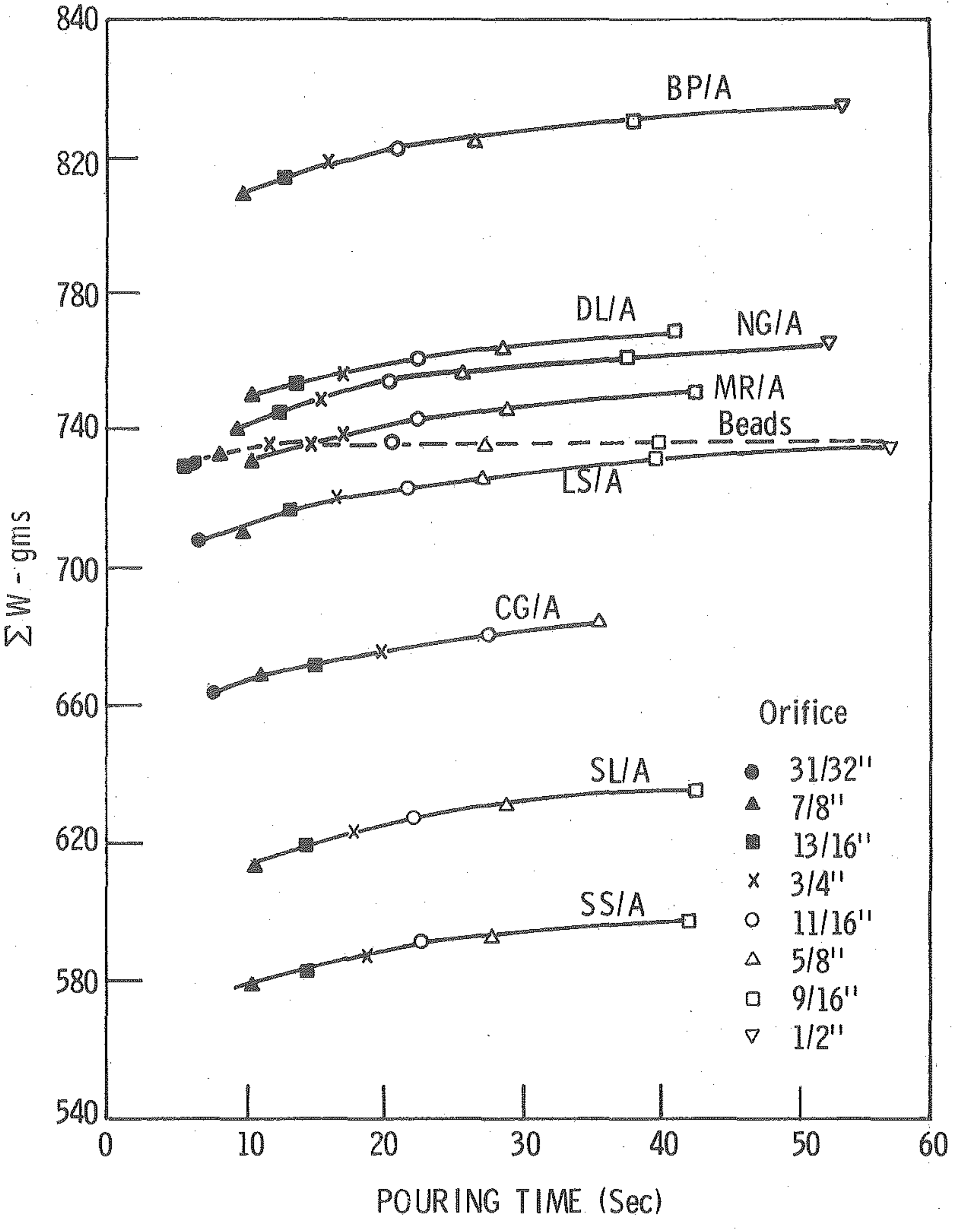
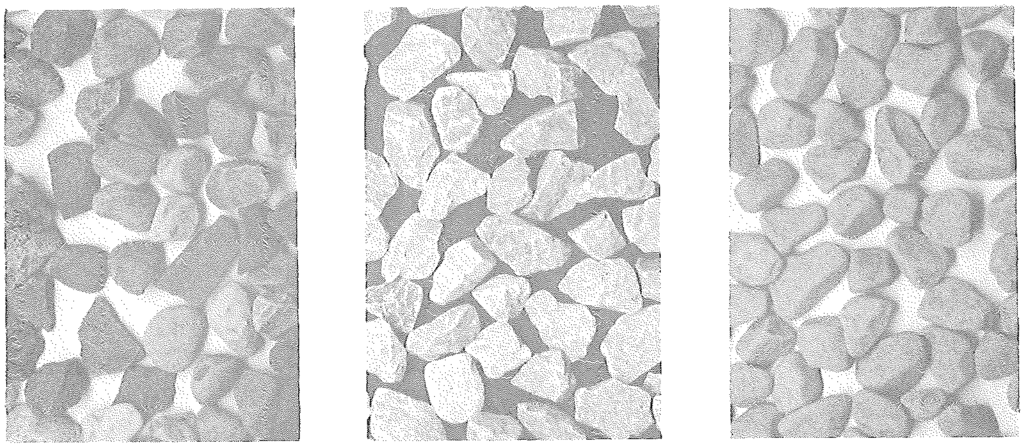
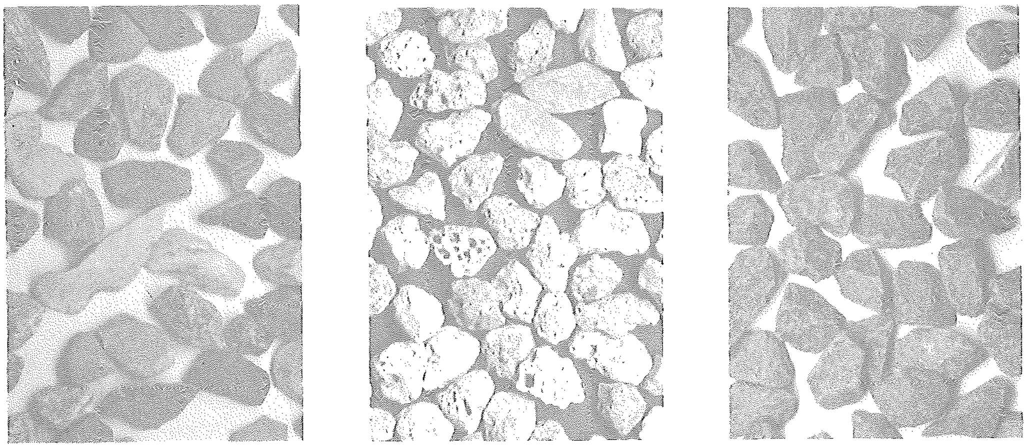


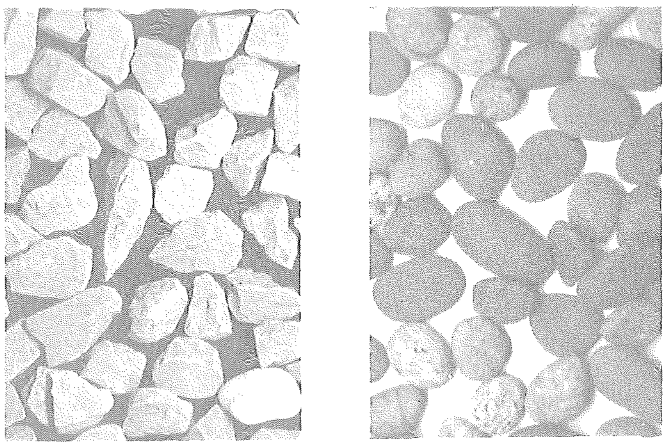
Figure 7. The influence of pouring time on weight of aggregates (ΣW) passing a given orifice for #8-#10 fractions (eight selected aggregates and glass beads).



Natural Gravel (NG) Dolomite (DL) Sandstone (SS)



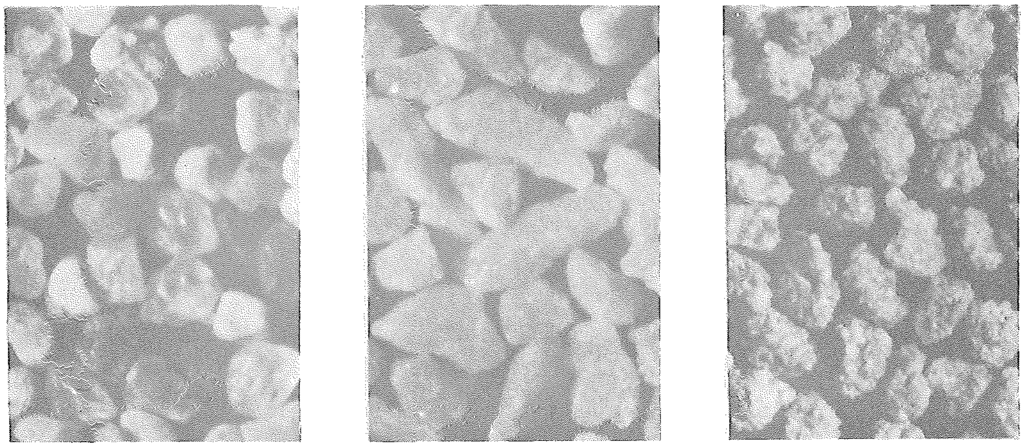
Crushed Gravel (CG) Slag (SL) Mine Rock (MR)



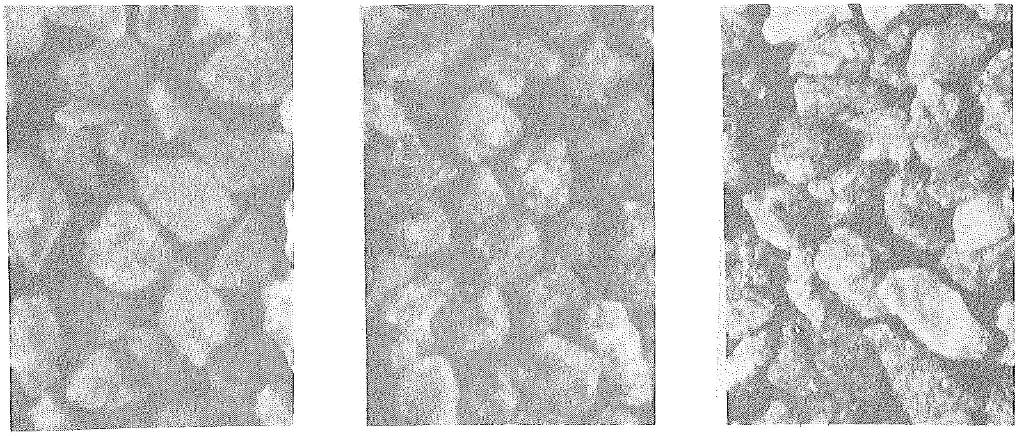
Limestone (LS) Beach Pebbles (BP)

1 cm

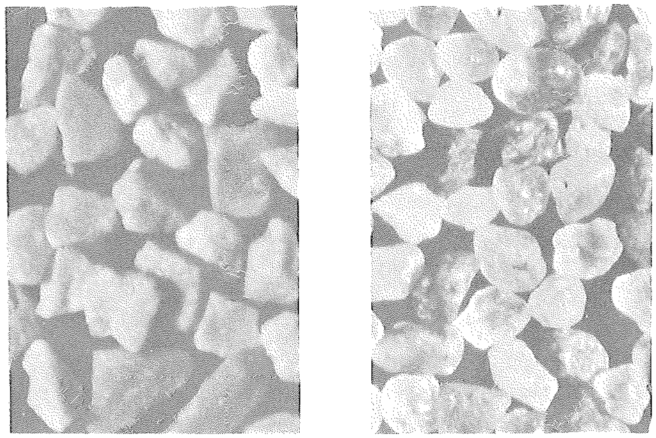
Figure 8. One-size particles from 1/2 in.-5/8 in. fractions (eight selected aggregates).



Natural Gravel (NG) Dolomite (DL) Sandstone (SS)



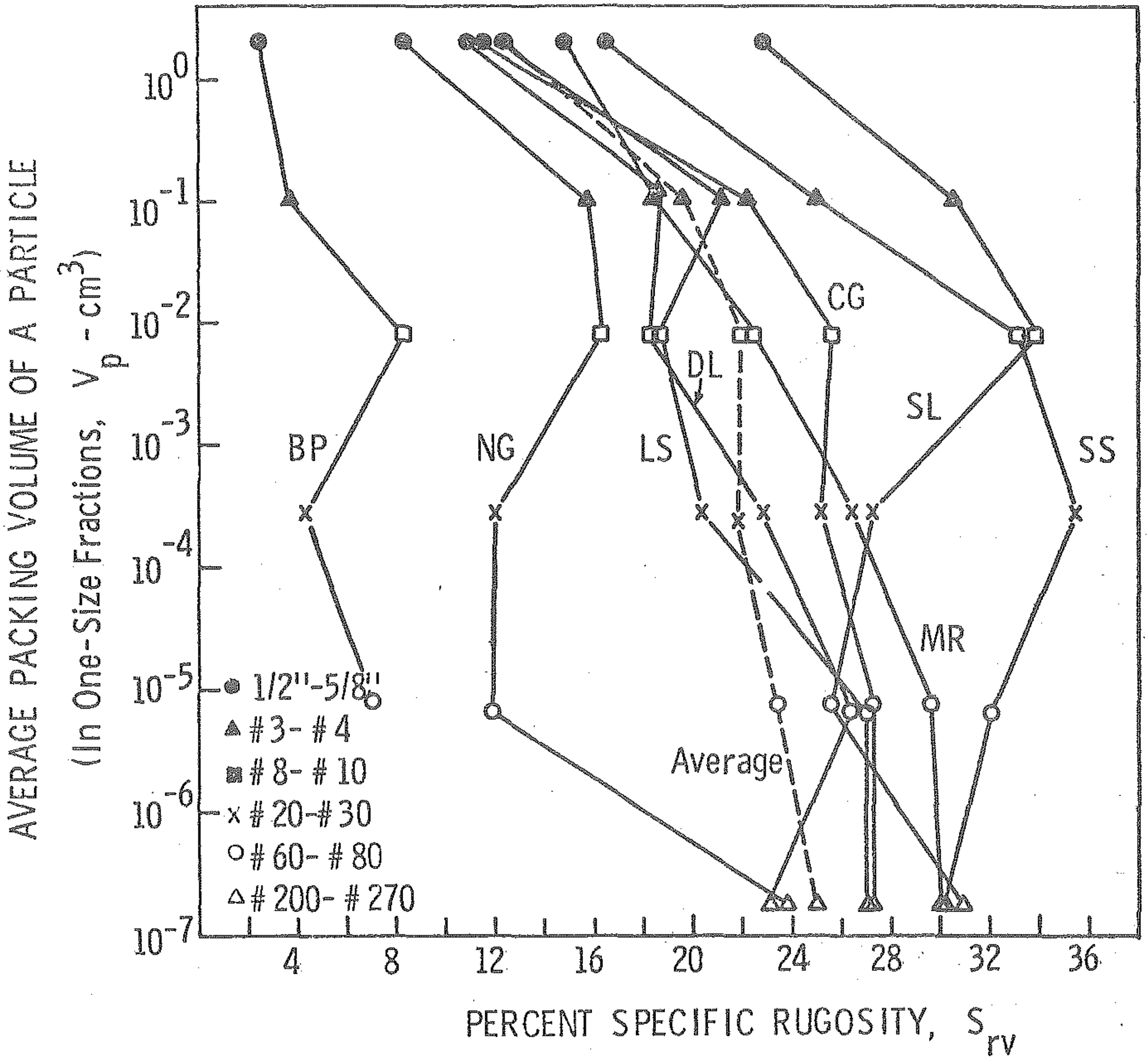
Crushed Gravel (CG) Slag (SL) Mine Rock (MR)



Limestone (LS) Beach Pebbles (BP)

1 mm

Figure 9. One-size particles from #20-#30 fractions (eight selected aggregates).



$$S_{rv} = \frac{\text{Volume of Surface Voids}}{\text{Packing Volume of Aggregates}} 100$$

Figure 10. Relationships between specific rugosity and packing volume of particles for eight selected aggregates.

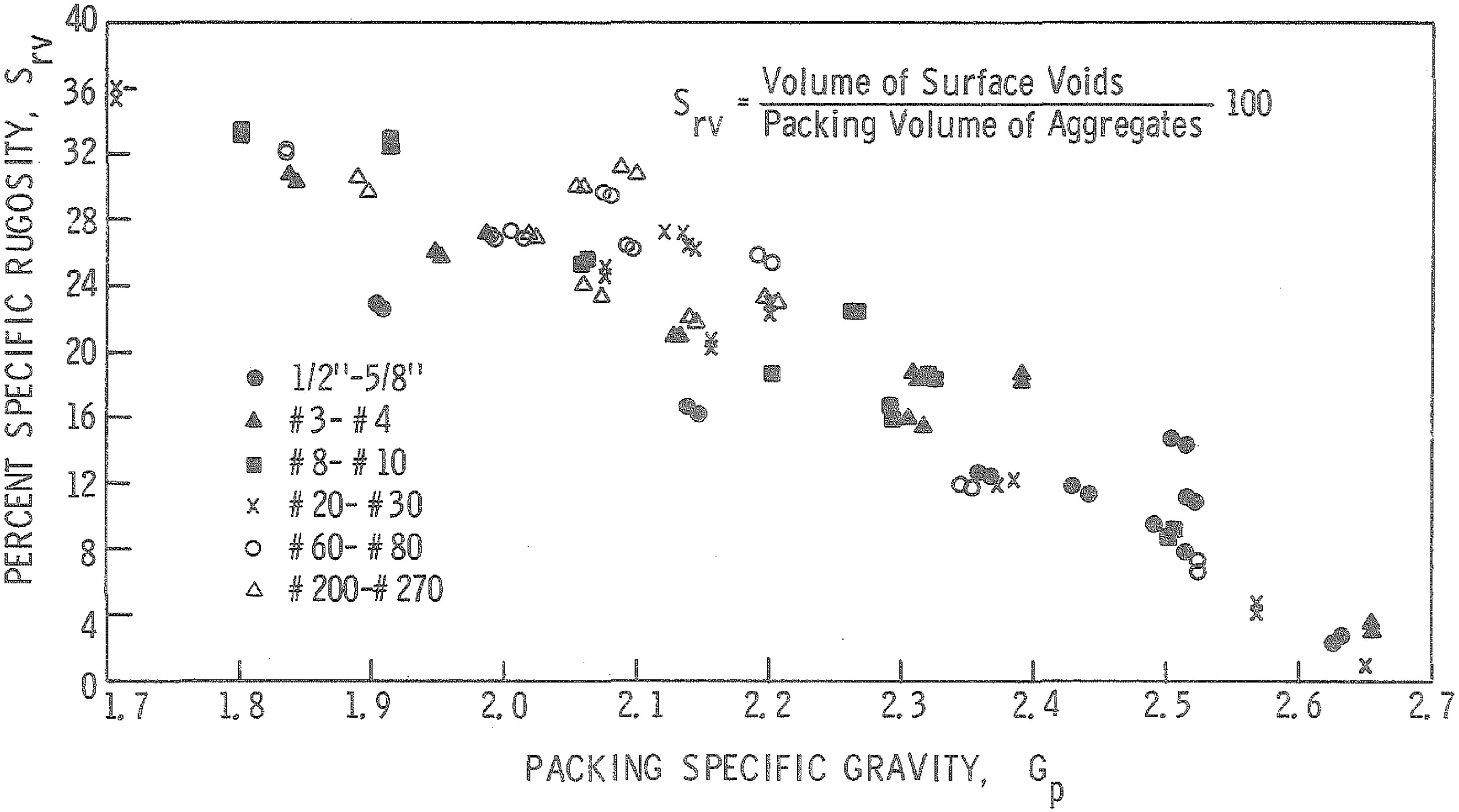


Figure 11. Specific rugosity vs. packing specific gravity for all sizes and all eight selected aggregates. (Differences in solid specific gravities are not accounted for.)

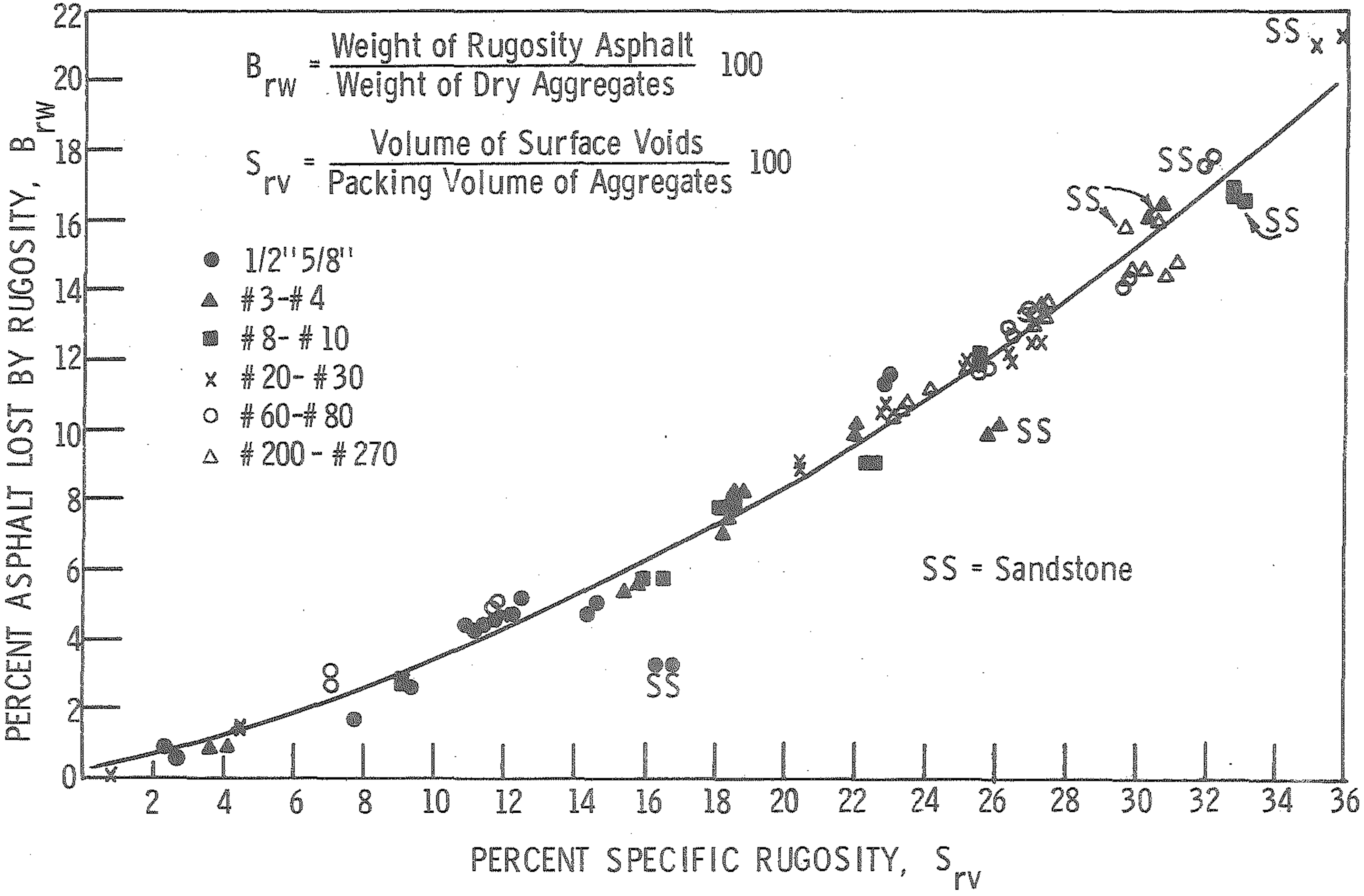
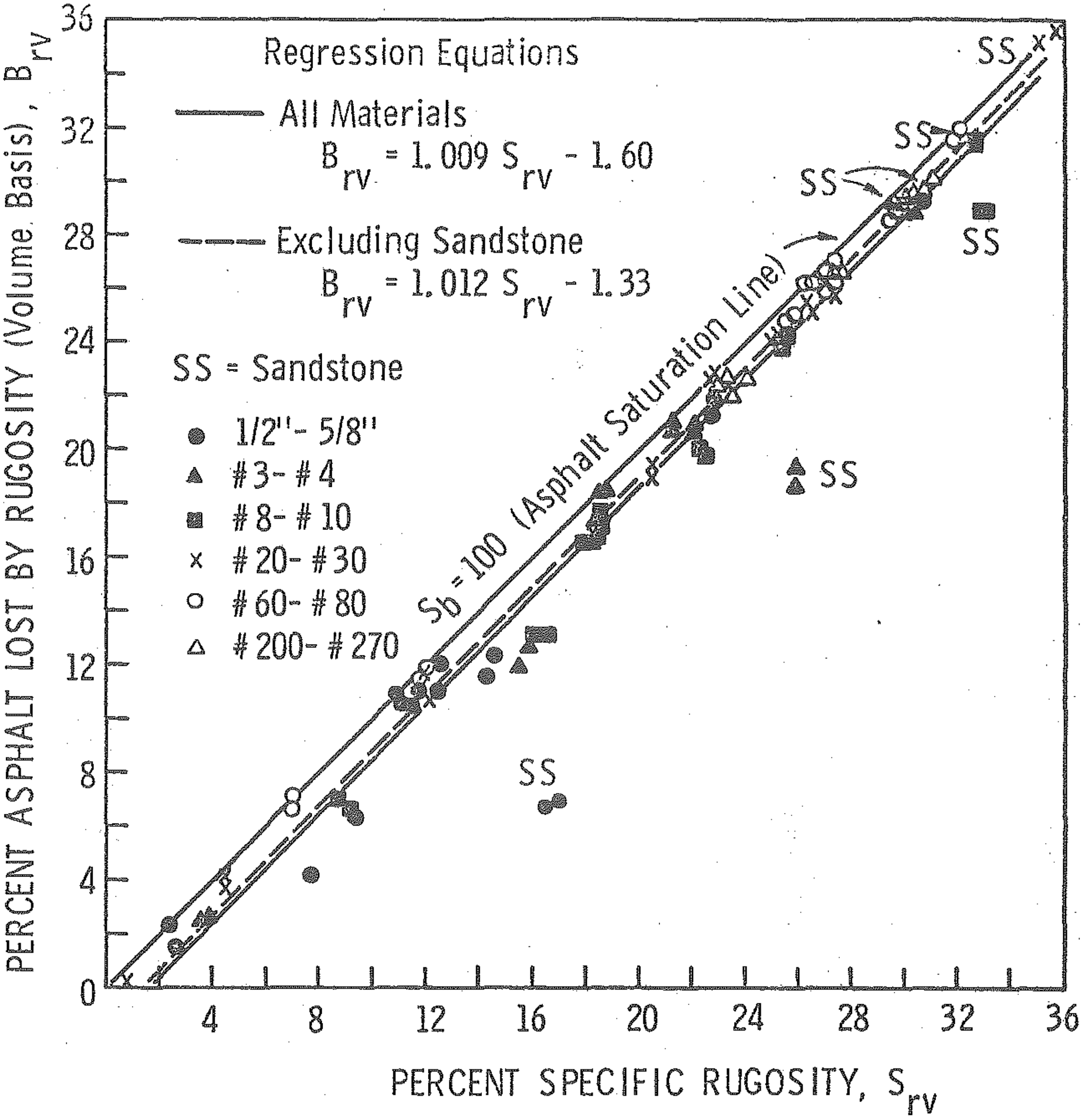


Figure 12. Asphalt lost by rugosity (weight basis) vs. specific rugosity for all sizes and all eight selected aggregates. (Differences in solid specific gravities are not accounted for.)



$$B_{rv} = \frac{\text{Volume of Rugosity Asphalt}}{\text{Packing Volume of Aggregates}}\,100$$

$$S_{rv} = \frac{\text{Volume of Surface Voids}}{\text{Packing Volume of Aggregates}}\,100$$

Figure 13. Asphalt lost by rugosity (volume basis) vs. specific rugosity for all sizes and all eight selected aggregates. (Differences in solid specific gravities are accounted for.)

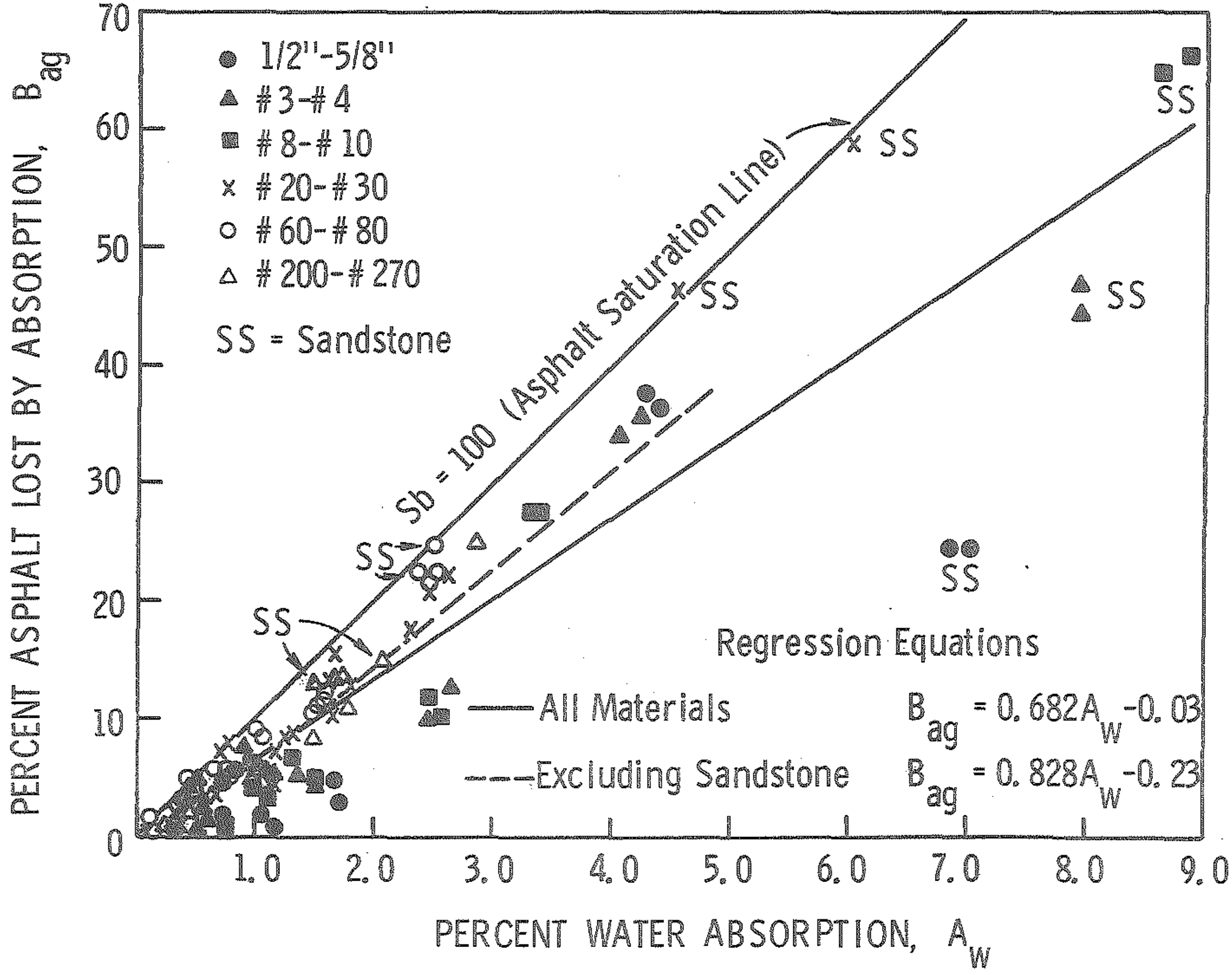


Figure 14. Asphalt lost by absorption vs. water absorption for all sizes and all eight selected aggregates.

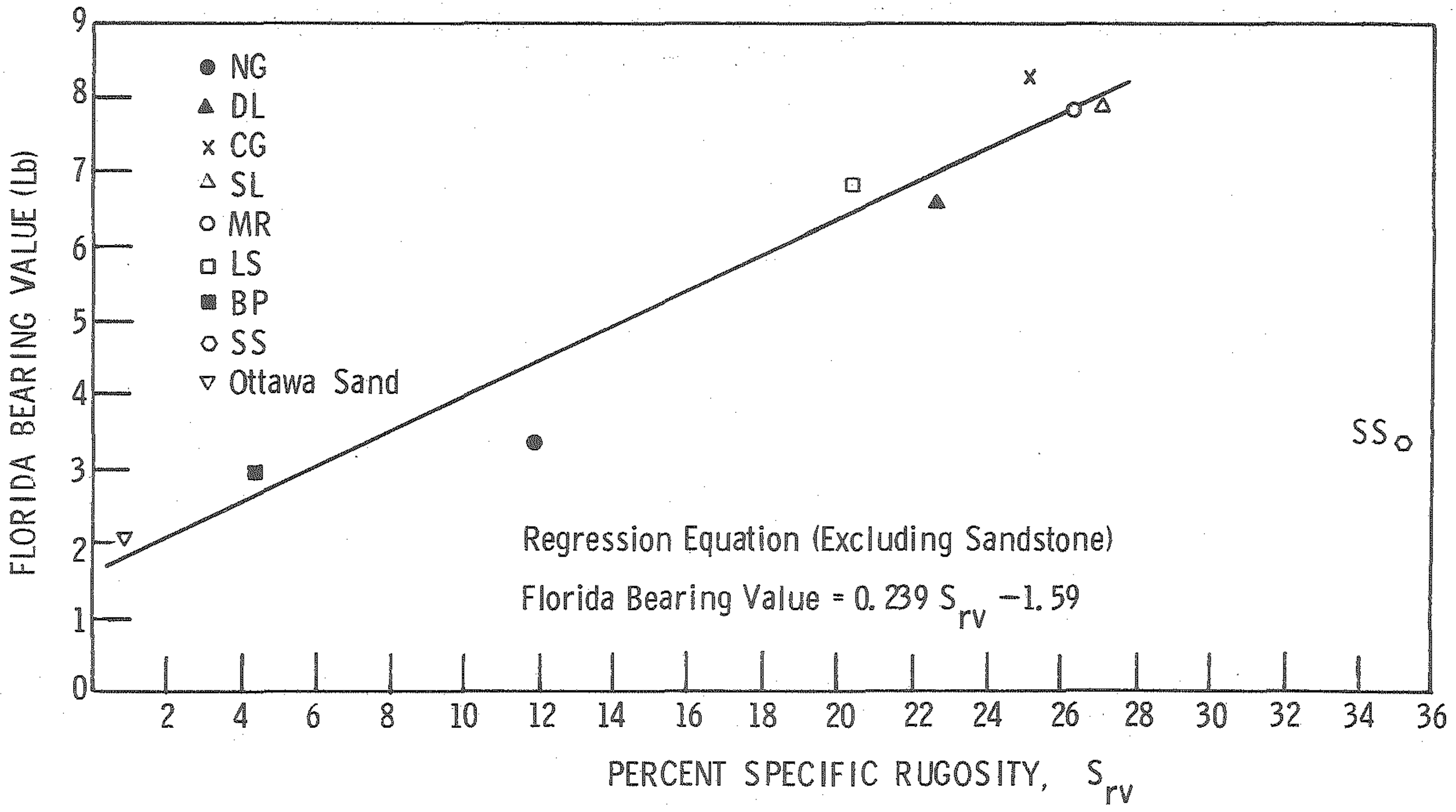


Figure 15. Florida bearing value vs. specific rugosity for #20–#30 fractions (eight selected aggregates).

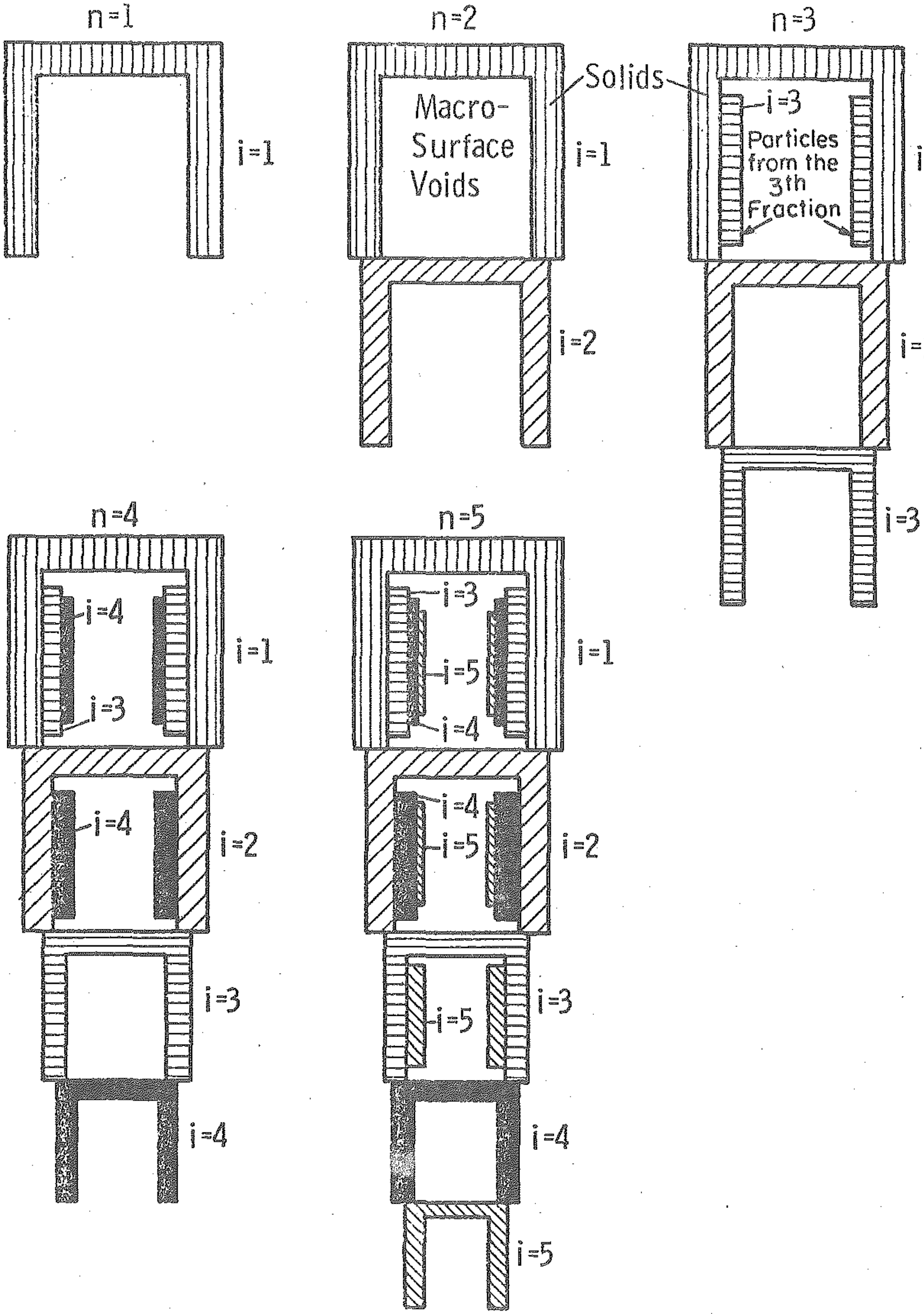
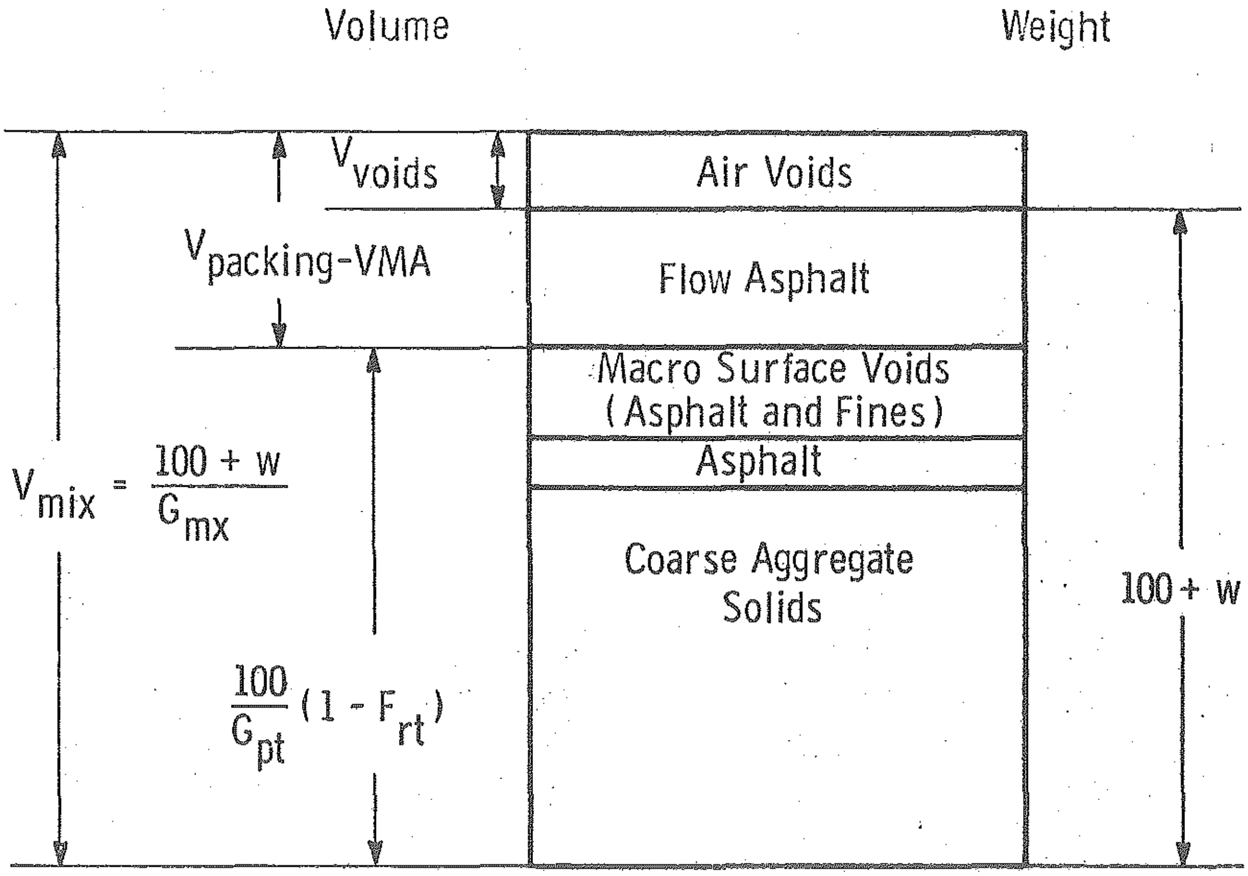


Figure 16. Hypothetical illustration of consecutive fines loss in graded mixture where $d_i/d_{i+1} \cong 2$.



$$VMA_p = 100 \frac{\frac{100 + w}{G_{mx}} - \frac{100}{G_{pt}}(1 - F_{rt})}{\frac{100 + w}{G_{mx}}}$$

where

w = asphalt content, percent of total mixture weight

G_{pt} = average packing specific gravity of the aggregates

Figure 17. Weight volume relationships for the determination of percent packing-VMA in compacted bituminous mixtures.

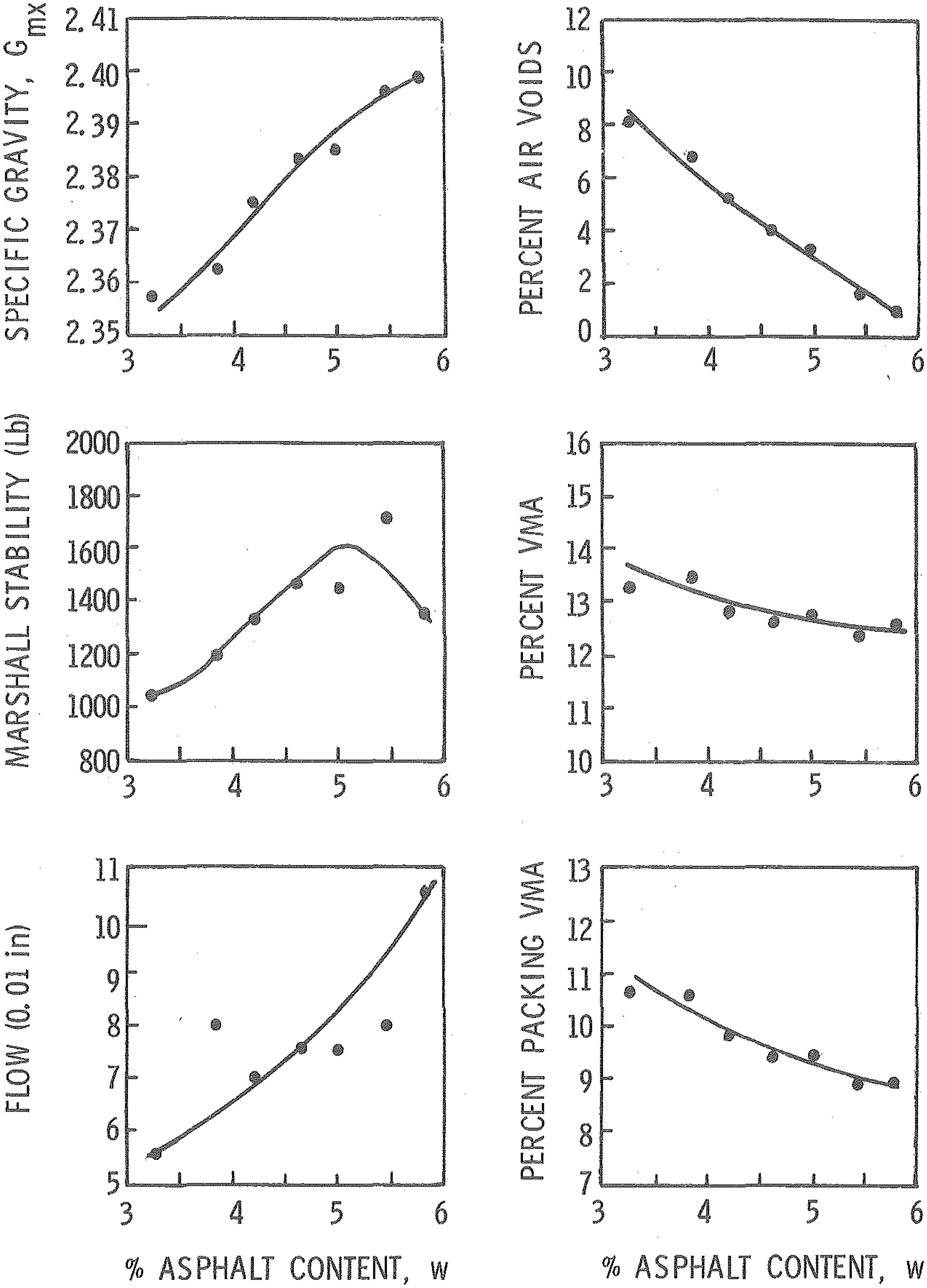


Figure 18. Marshall data for natural gravel (NG).

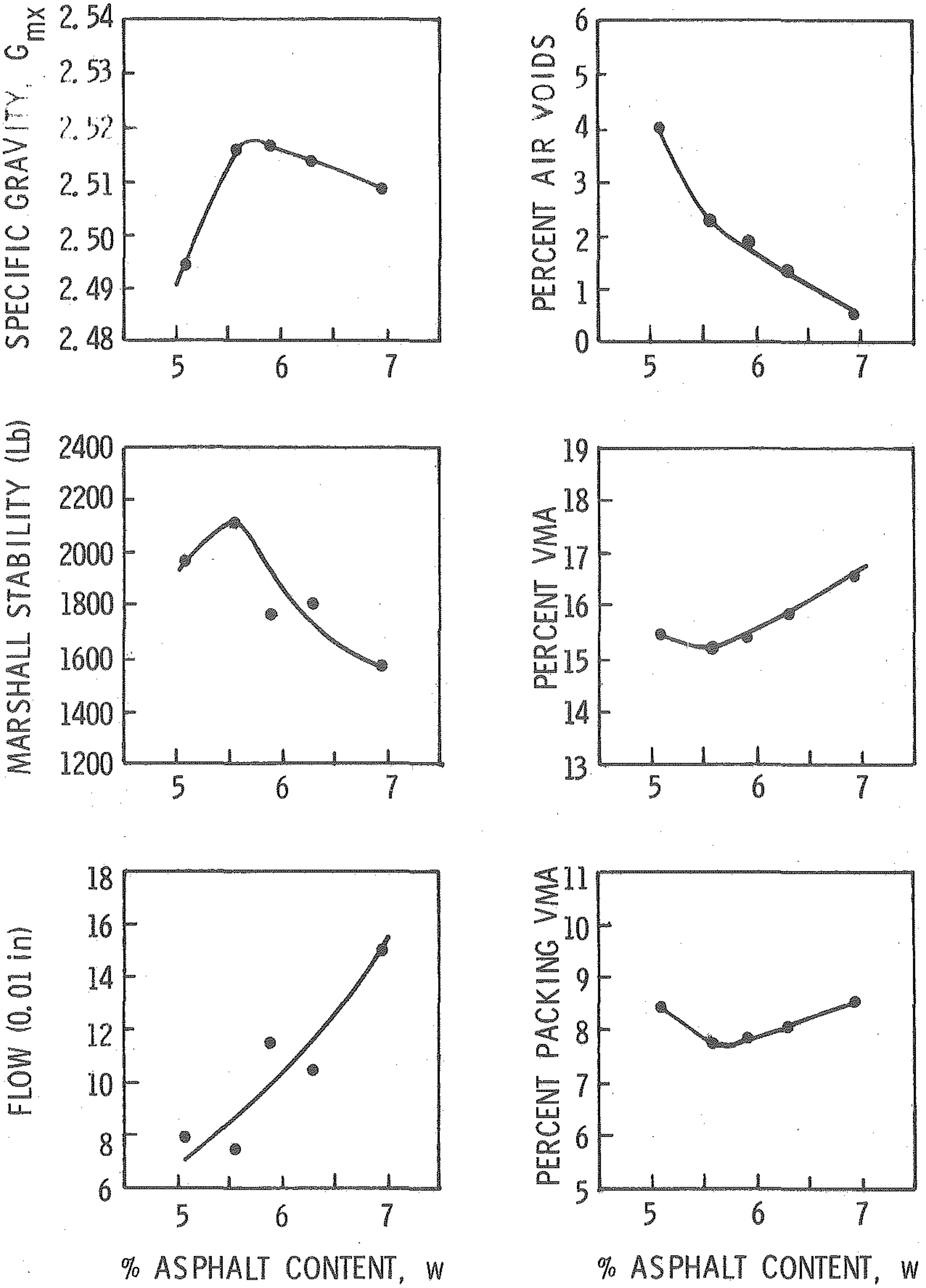


Figure 19. Marshall data for dolomite (DL).

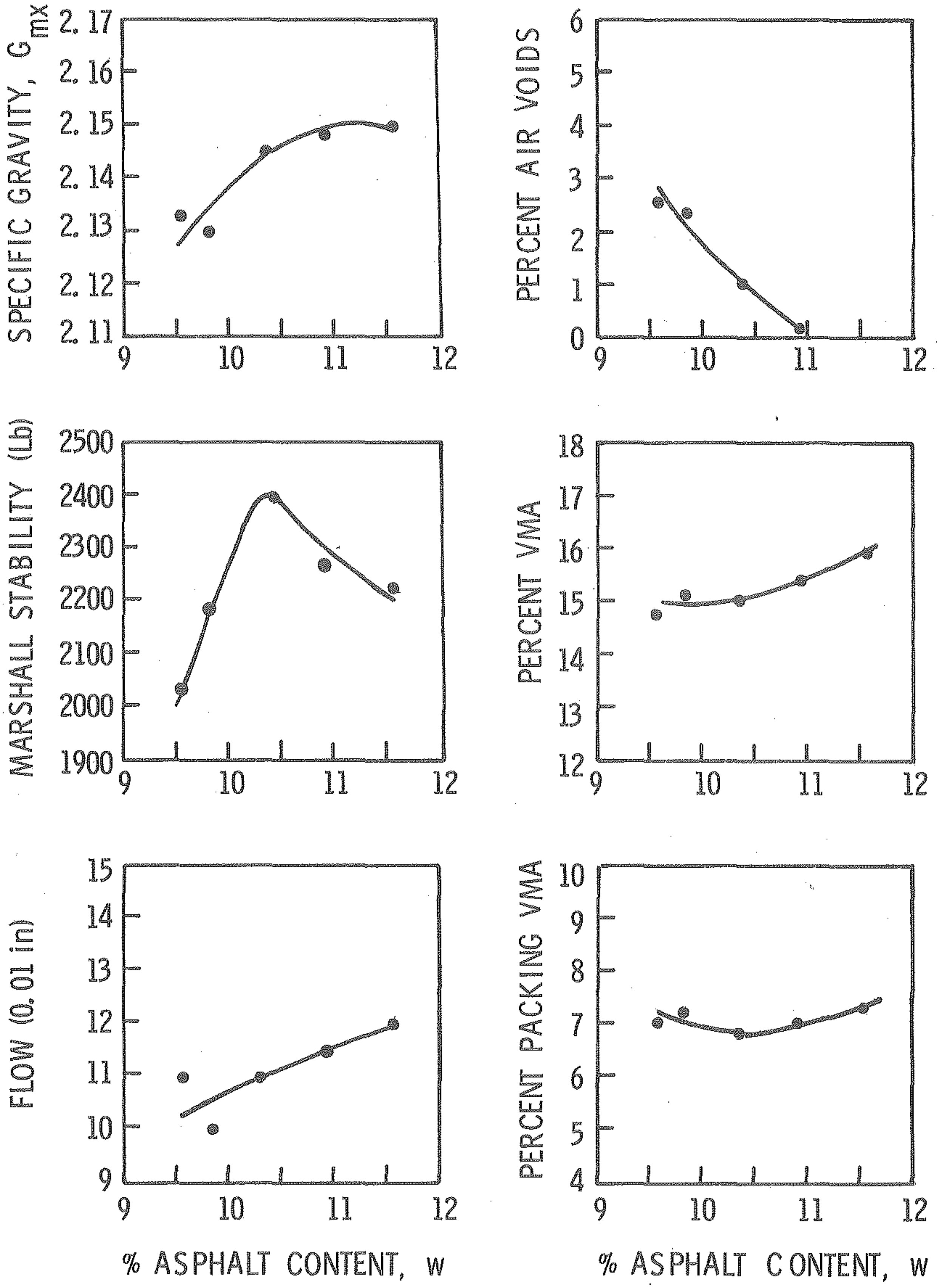


Figure 20. Marshall data for sandstone (SS).

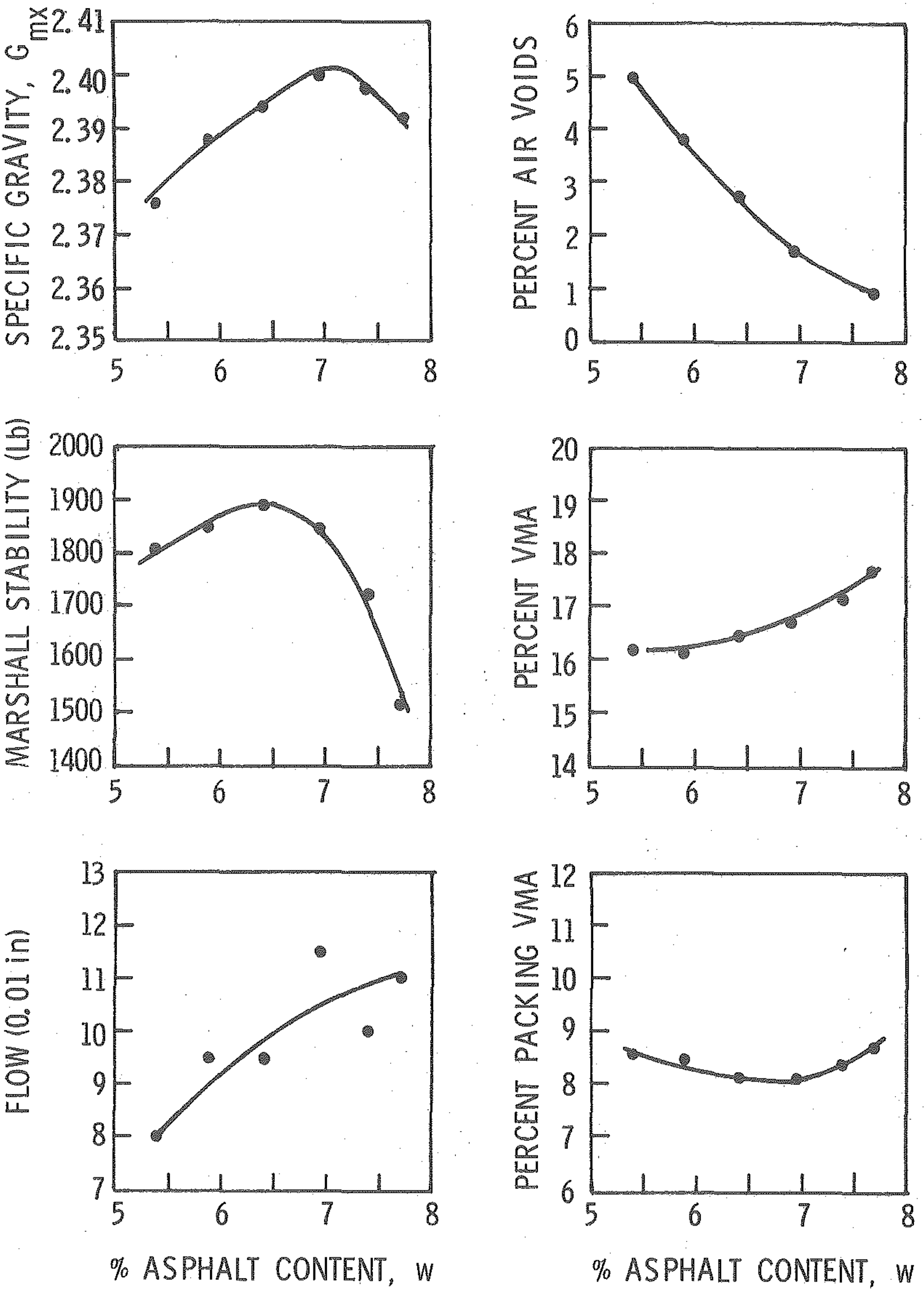


Figure 21. Marshall data for crushed gravel (CG).

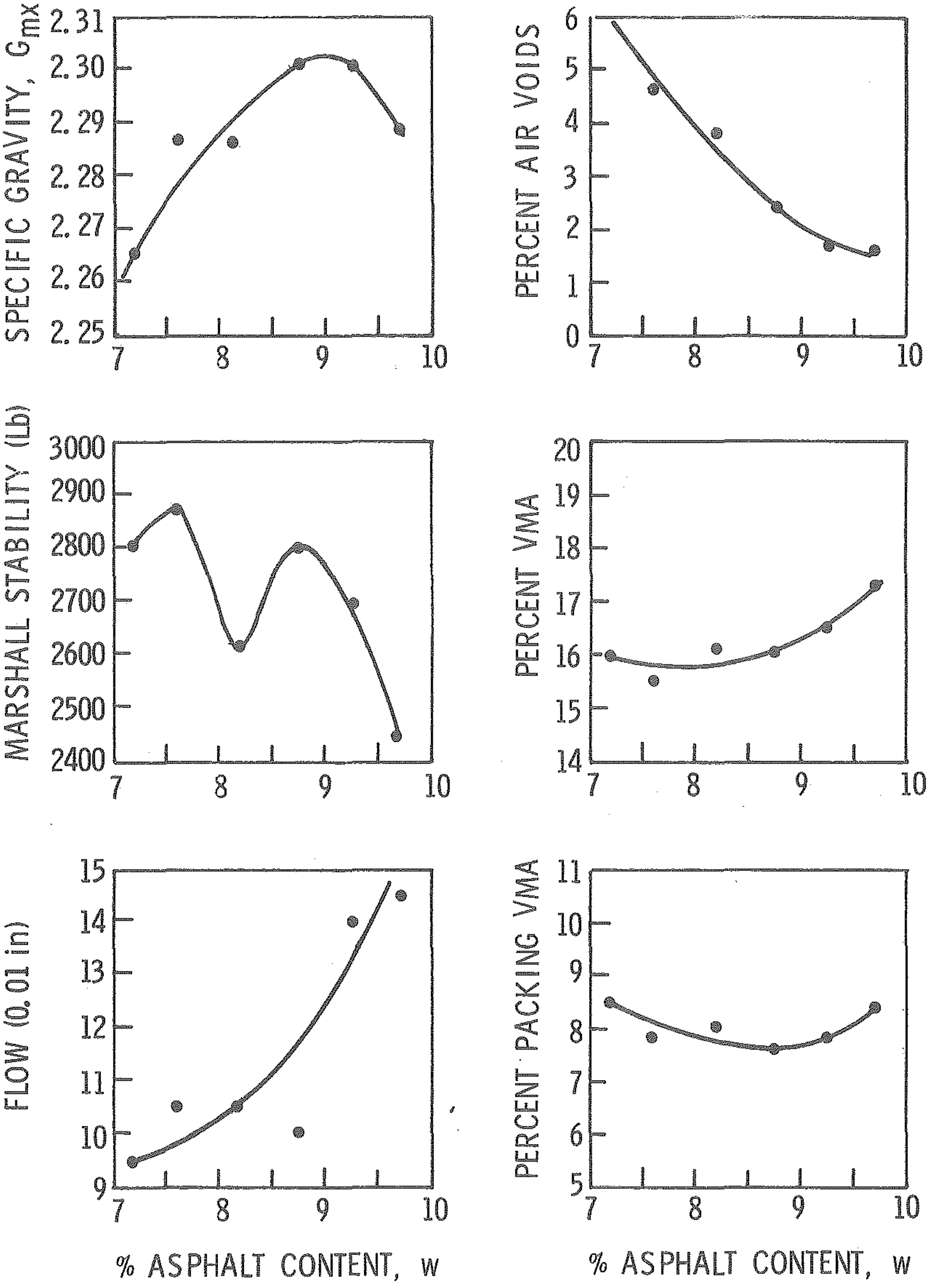


Figure 22. Marshall data for slag (SL).

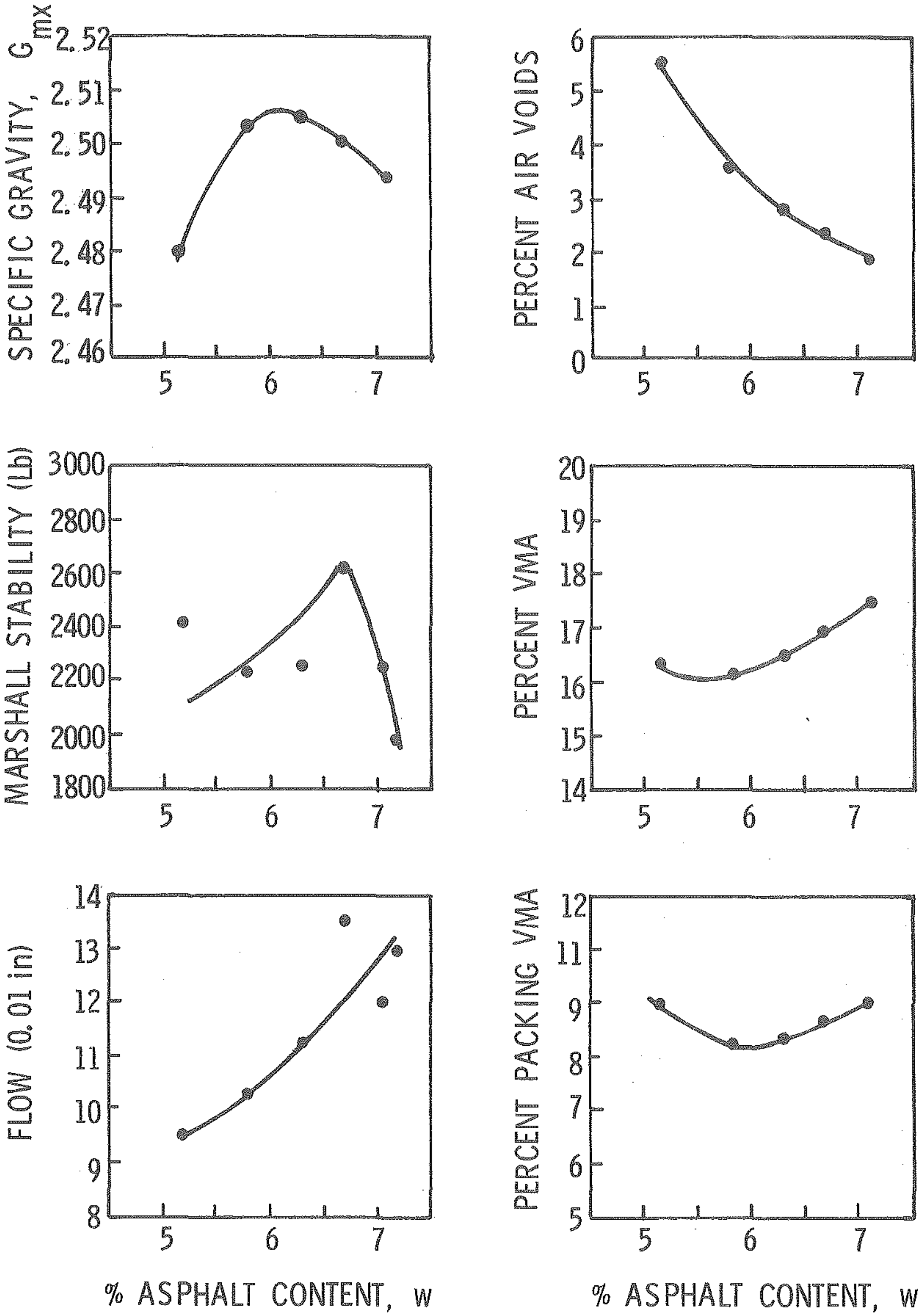


Figure 23. Marshall data for mine rock (MR).

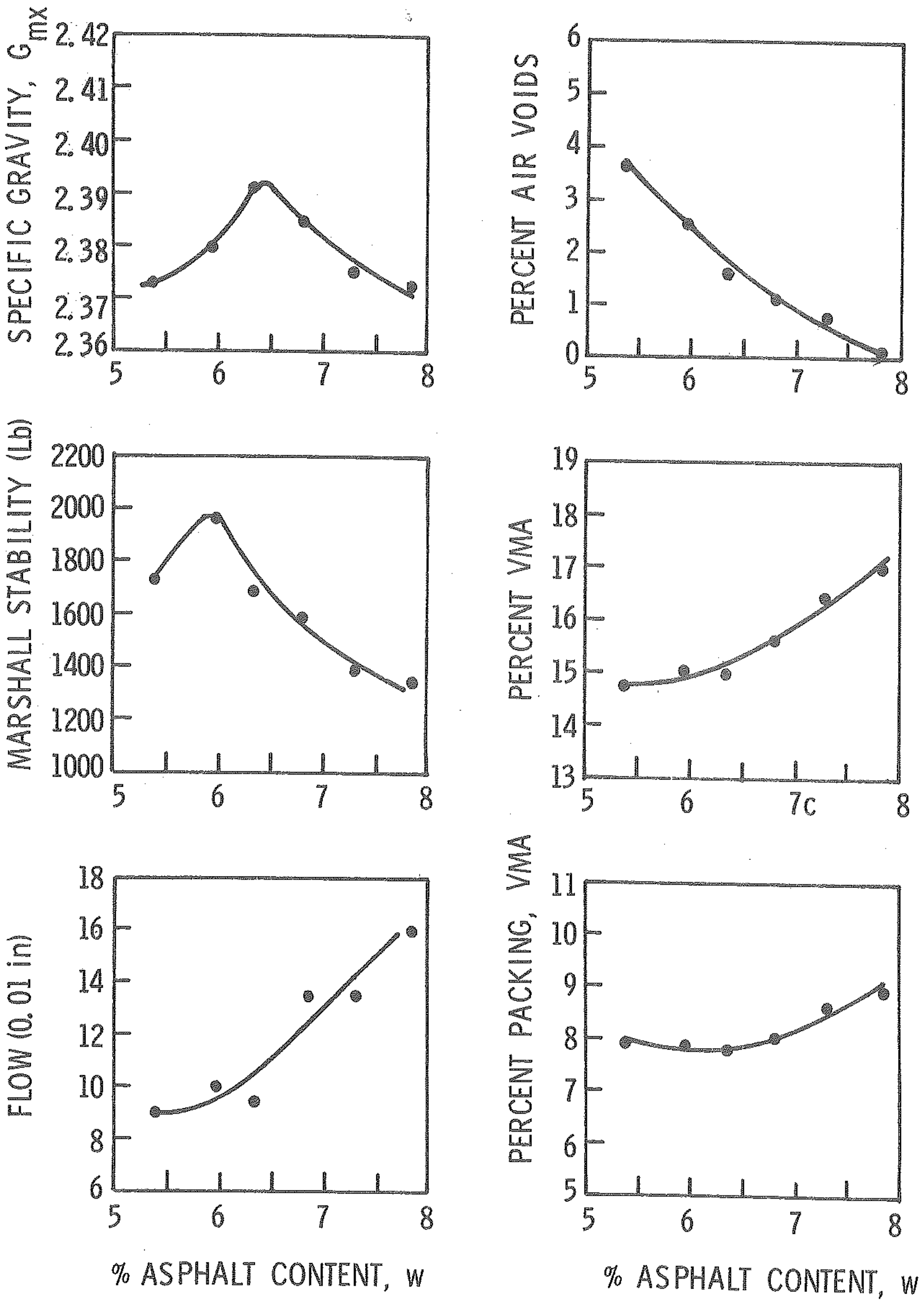


Figure 24. Marshall data for limestone (LS).

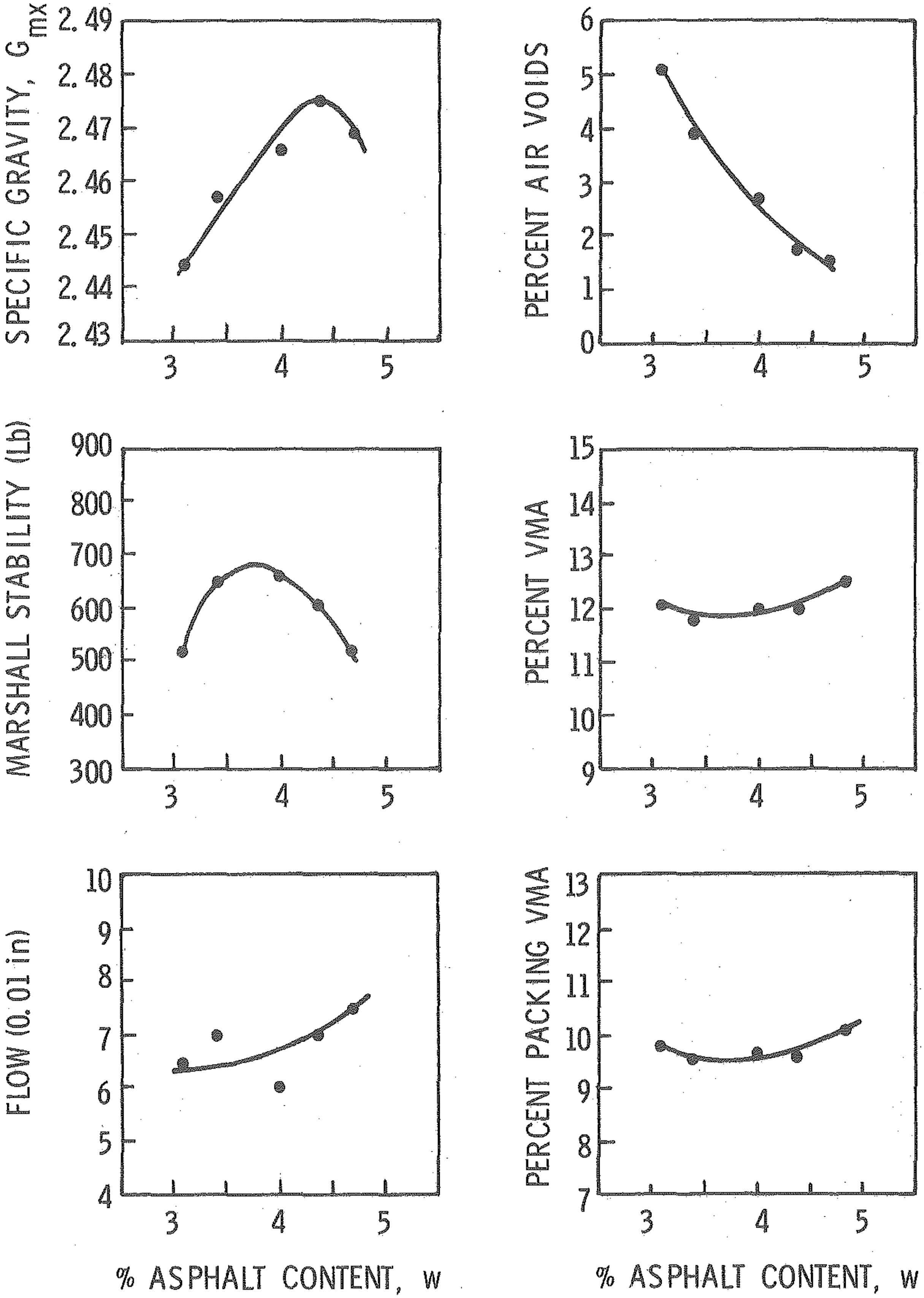


Figure 25. Marshall data for beach pebbles (BP).

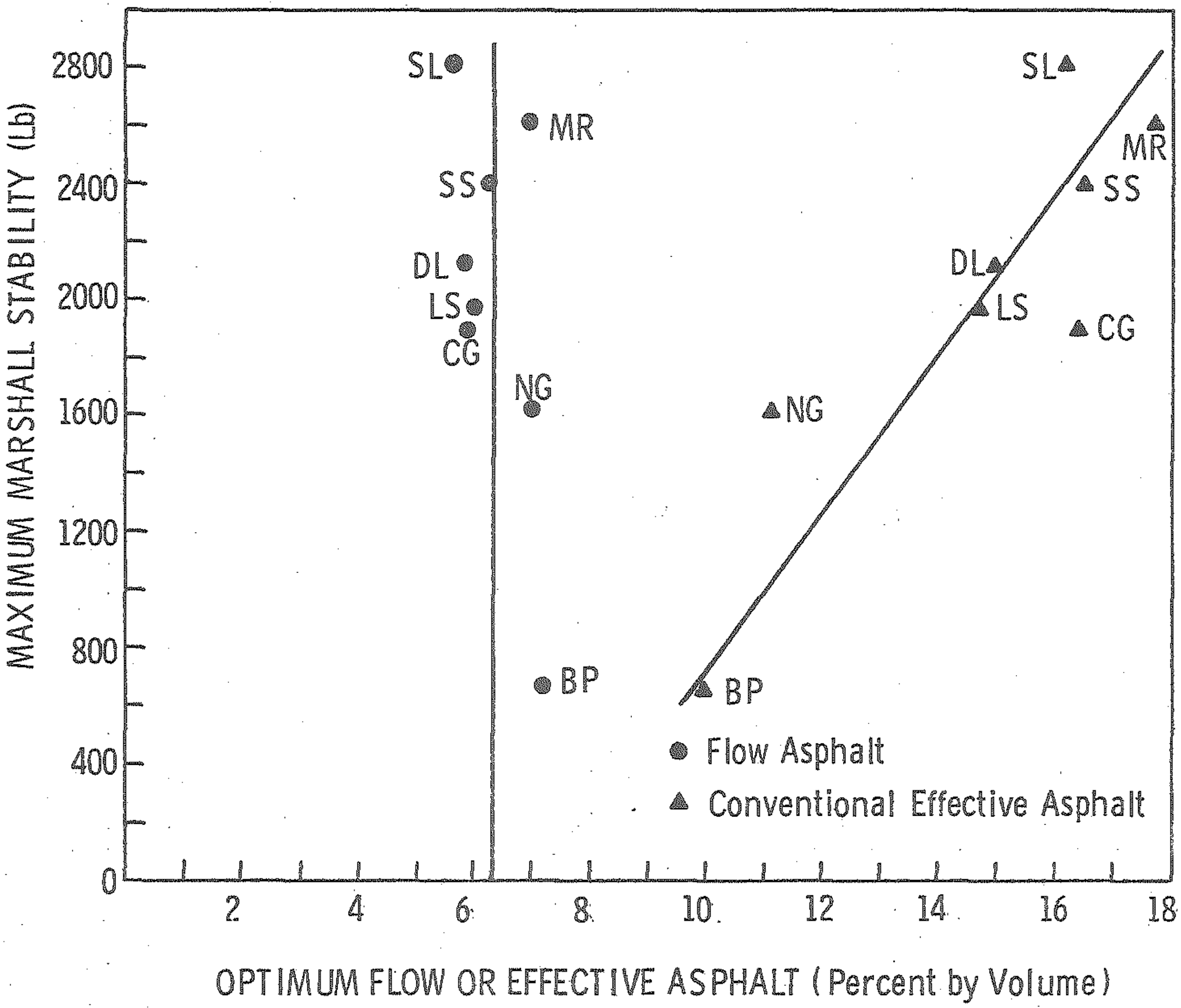


Figure 26. Unified optimum stability conditions obtained by the optimum flow asphalt (w_{fv}).

APPENDICES

APPENDIX A

DERIVATION OF EQUATION FOR B_{rw}

(All terms are defined at the end)

Based on volume relationships (see Figure 5) one can write:

$$V_{br} = V_b - (V_{mm} - V_p) ,$$

$$W_{br} = V_{br}\, G_b = (V_b - V_{mm} - V_p)\, G_b .$$

By definition: asphalt lost by rugosity:

$$B_{rw} = \frac{W_{br}}{W_{ag}} 100 = \frac{V_b - V_{mm} + V_p}{W_{ag}} 100\ G_b$$

$$= \frac{\dfrac{\omega\, W_{mm}}{100\ G_b} - \dfrac{W_{mm}}{G_{mm}} + \dfrac{W_{ag}}{G_p}}{W_{ag}} 100\ G_b$$

$$= \frac{W_{mm}}{W_{ag}} \omega - 100 \frac{W_{mm}}{W_{ag}} \frac{G_b}{G_{mm}} + 100 \frac{G_b}{G_p} ,$$

but since $\dfrac{W_{mm}}{W_{ag}} = \dfrac{100}{100 - w}$, one gets

$$B_{rw} = \frac{100}{100 - w} w - \frac{100}{100 - w} \frac{G_b}{G_{mm}} 100 + 100 \frac{G_b}{G_p} ,$$

and finally

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

where,

V_{br} = volume of rugosity asphalt

V_{mm} = maximum volume of the mixture

V_p = packing volume of the particle

W_{br} = weight of rugosity asphalt

W_{ag} = weight of dry aggregates

W_{mm} = weight of the mixture

G_b = specific gravity of the asphalt

G_p = packing specific gravity of the particles

G_{mm} = maximum specific gravity of the mixture

w = asphalt content (percent by weight of total mixture)

B_{rw} = percent asphalt lost by rugosity

V_b = total volume of asphalt.

APPENDIX B

DERIVATION OF EQUATION FOR F_r

Based on the total volume of asphalt lost by rugosity as found for a given one-size coarse fraction, the following equation is derived:

$$V_{fr} = V_{rv} - (V_{ag} + V_{bm}) \, , \tag{41}$$

where

V_{fr} = packing volume of the fine particles lost inside the macro surface voids of the coarse fraction

V_{rv} = total volume of asphalt lost by rugosity within the given coarse fraction

V_{ag} = volume of asphalt lost by absorption of the coarse fraction (inside the micro surface voids)

V_{bm} = volume of asphalt which was lost together with the fines inside the macro surface voids.

By replacing V_{rv} and V_{ag} with the one-size aggregate parameters of the coarse fraction; namely, asphalt lost by rugosity (B_{rw}), the asphalt lost by absorption (B_{ag}), one can obtain:

$$V_{fr} = \frac{B_{rw}\ G_{pc}}{100\ G_b}\ V_{pc} - \frac{B_{ag}\ G_{pc}}{100\ G_b}\ V_{pc} + V_{bm} \, , \tag{42}$$

where

G_{pc} = packing specific gravity of the coarse fraction

V_{pc} = packing volume of the coarse fraction

G_b = specific gravity of the asphalt.

By substituting Equation (23) into (42):

$$V_{fr} + \frac{V_{fr}}{C_{fv}} = \frac{V_{pc}}{100}\frac{G_{pc}}{G_b}\left(B_{rw} - B_{ag}\right),$$

from which

$$V_{fr} = \frac{V_{pc}\ G_{pc}\left(B_{rw} - B_{ag}\right)}{100\ G_b\left(1 + \frac{1}{C_{fv}}\right)} . \tag{43}$$

By the definition of the fines-lost by rugosity (F_r):

$$F_r = \frac{V_{fr}}{V_{pc}} = \frac{G_{pc}\left(B_{rw} - B_{ag}\right)}{100\ G_b\ \left(1+ \frac{1}{C_{fv}}\right)} . \tag{44}$$

But since the volume of macro surface voids (S_{ma}) is equal to the volume of the rugosity asphalt minus the volume of the asphalt lost by absorption,

$$S_{ma} = \frac{G_{pc}}{G_b}\left(B_{rw} - B_{ag}\right) .$$

A volumetric form of Equation (44) is as follows:

$$F_r = \frac{S_{ma}}{100\left(1+ \frac{1}{C_{fv}}\right)} , \tag{45}$$

where

G_{pc} = packing specific gravity of the coarse fraction
G_b = specific gravity of the asphalt
S_m = percent micro surface voids of the coarse fraction.

APPENDIX C

DERIVATION OF EQUATION FOR W_{fv}

Using volumetric relationships

$$V_{bf} = V_{bt} - V_{rt} , \tag{46}$$

where

V_{bf} = volume of the flow asphalt in the mixture

V_{bt} = total volume of asphalt in the mixture

V_{rt} = total volume of rugosity asphalt in the mixture (in micro and macro surface voids).

Substituting Equation (28) into Equation (46):

$$V_{bf} = V_{bt} - \sum_{i=0}^{n} (V_{rvi} - V_{fri}) \tag{47}$$

By introducing the specific parameters for asphalt lost by rugosity (B_{rv}) and fines-lost by rugosity (F_r), one can obtain:

$$V_{bf} = V_{bt} - \sum_{i=1}^{n} (\frac{B_{rvi}}{100} V_{pi} - F_{ri} V_{pi}) \ . \tag{48}$$

Finally, by dividing both sides by the total packing volume of the particles in the mixture (V_{pt}),[1] and multiplying by 100:

$$w_{bf} = w_{bt} - \sum_{i=1}^{n} Y_i \left(\frac{B_{rvi}}{100} - F_{ri}\right), \qquad (49)$$

where

w_{bf} = flow asphalt content in percent of total packing volume of aggregates in the mixture

w_{bt} = total asphalt content in percent of total packing volume of aggregates in the mixture

Y_i = percentage by volume of the i-th fraction in the mixture (packing volume basis)

Brvi = asphalt lost by rugosity of the i-th fraction in the mixture, percent by volume

F_{ri} = fines-lost by rugosity of the i-th fraction

n = number of fraction in the mixture.

Similar to the rugosity asphalt, the particles which are lost by rugosity are considered as stationary particles which do not participate in the flow of the mixture. Therefore, a more accurate presentation of the flow asphalt content will be achieved by relating the volume of the flow asphalt to the packing volume of the active particles in the mixture (the volume of the particles which have not been lost in the surface voids of other particles).

---

[1] $V_{pt} = \sum_{i=1}^{n} V_{pi}$, where V_{pi} is the packing volume of all particles in the i-th fraction.

The total quantity of fines-lost by rugosity in the mixture (F_{rt}) can be expressed as follows:

$$F_{rt} = \sum_{i=1}^{n} Y_i F_{ri} \frac{1}{100} , \tag{50}$$

therefore:

$$V_{pa} = (1 - F_{rt}) \sum_{i=1}^{n} V_{pi} = (1 - F_{rt}) V_{pt} , \tag{51}$$

where

V_{pt} = the total packing volume of particles in the mixture

V_{pa} = the total packing volume of active particles in the mixture.

So finally, one can get the proper physical equation for the flow asphalt content in the mixture (w_{fv}):

$$\boxed{w_{fv} = w_{bf} \frac{V_{pt}}{V_{pa}} = \frac{w_{bt} - \sum_{i=1}^{n} Y_i \left(\frac{B_{rvi}}{100} - F_{ri}\right)}{1 - F_{rt}} ,} \tag{52}$$

where

w_{bt} = total asphalt content in percent of total packing volume of aggregates in the mixture

Y_i = percentage by volume of the i-th fraction in the mixture (packing volume basis)

B_{rvi} = asphalt lost by rugosity of the i-th fraction percent by volume

F_{ri} = fines-lost by rugosity of the i-th fraction

F_{rt} = total fines-lost by rugosity in the mixture

n = number of one-size fractions in the mixture.

APPENDIX D

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. This method was developed during the first stage of this investigation (see Chapter II) and modified in the second stage of the research (see Chapter III).

Equipment

The equipment and material used were as follows:

1) Pouring setup, which consisted of (see Figures D-1 and D-2):
    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.

---

[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 D-1):

In the first stage:

Fraction Dimension	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:

Fraction Dimension	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 Equation (3). An example and a working sheet, similar to those used (including actual data for #8-#10 fraction) can be seen in Table D-1.

TABLE D-1

AN EXAMPLE OF A WORK SHEET USED IN THE POURING TEST

POURING TEST FOR #8 -#10 FRACTION

Bin Diameter (D): 160 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	724.58		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
DL/A	765.9	761.7	761.8	762.1	762.8	762.86		2.318
DL/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

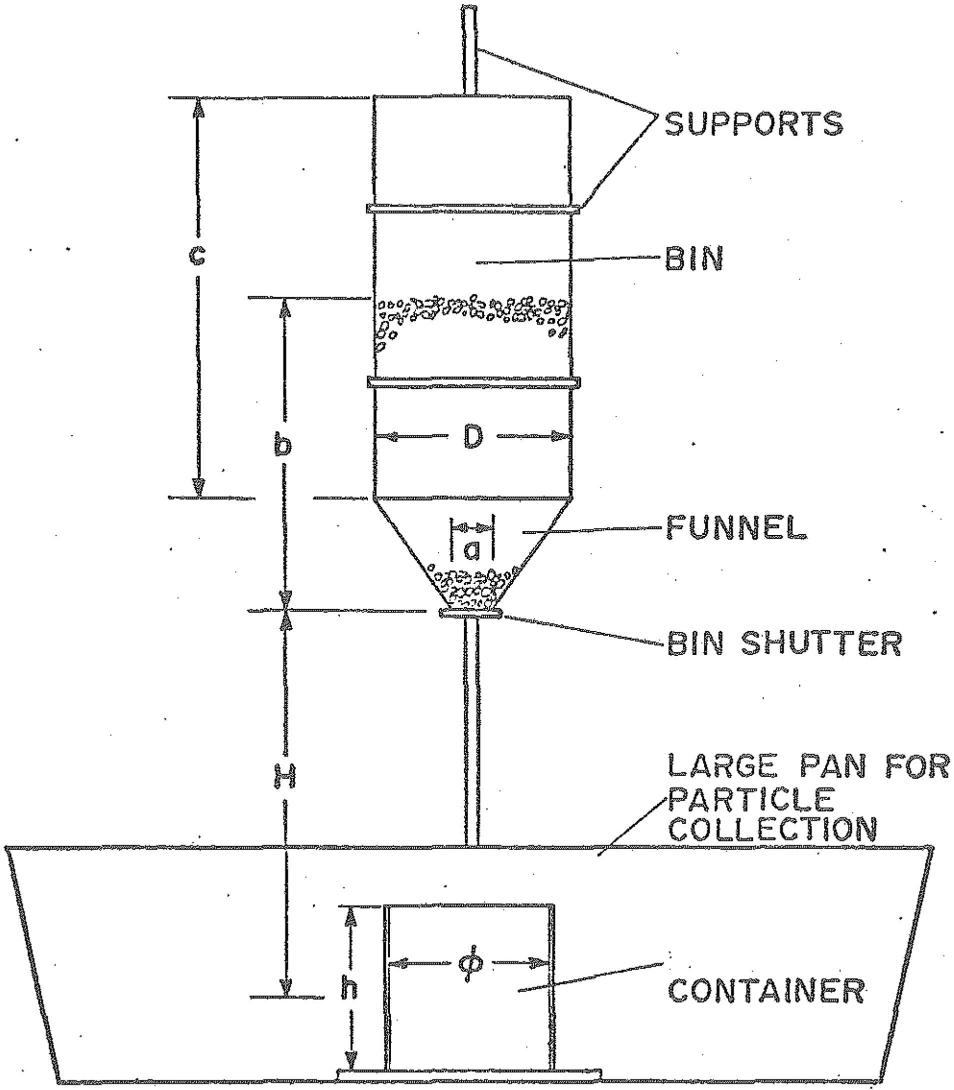
* G_{px} = packing specific gravity of the aggregate tested,

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 D-1. Schematic description of the pouring device setup.

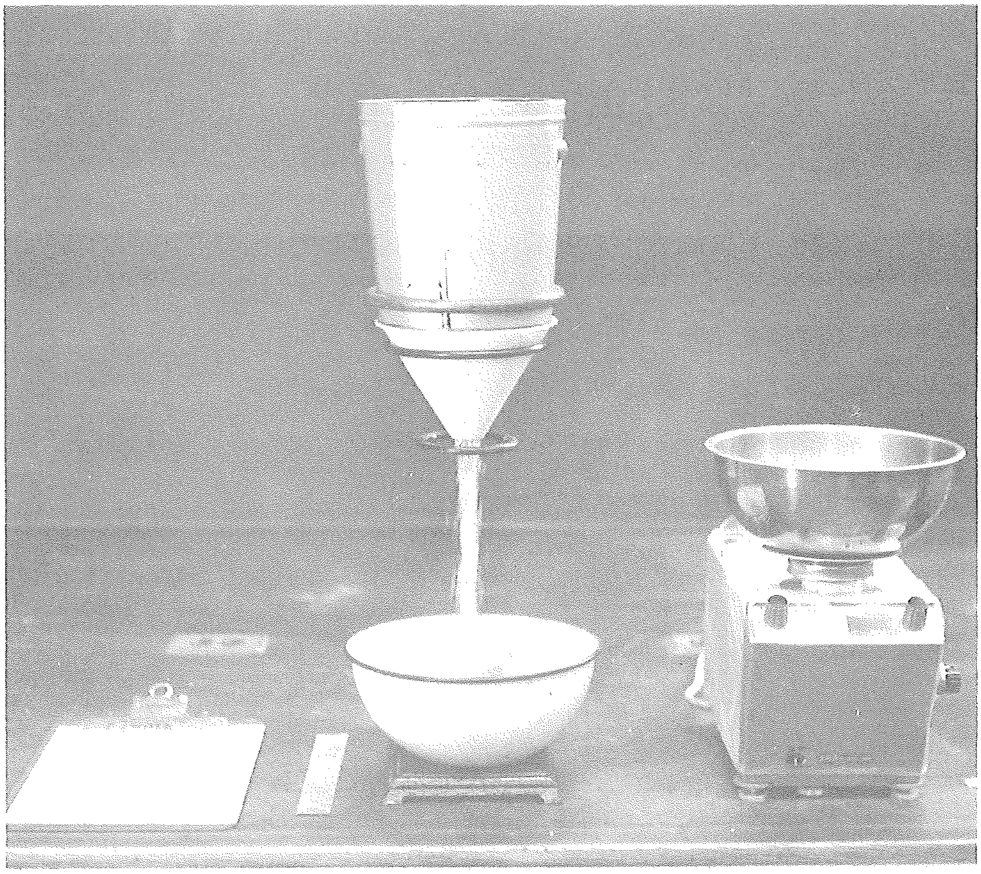


Figure D-2. Pouring device setup for #8-#10 fractions.

APPENDIX E

METHANOL IMMERSION TEST FOR MEASURING THE MAXIMUM SPECIFIC GRAVITY OF BITUMINOUS MIXTURES

General

The procedure of the methanol immersion test which was used for measuring the maximum specific gravity of bituminous mixtures is essentially similar to the solvent immersion test adopted by the Michigan State Highway Department (see references 10,15).

Equipment

The equipment and material used were as follows:

1) Michigan specific gravity bottle (flask) (see dimensions and details in Figure E-1).

2) Scoops and pans for handling the bituminous mixture samples.

3) Balance, 5 kg capacity. Sensitive to 0.1 g.

4) Constant temperature water bath.

5) Vacuum pump and pressure regulator.

6) Methyl Alcohol tech. (Methanol).

Testing Procedure and Calculation

The following procedure was used for measuring the maximum specific gravity (see working sheet with actual results Table E-1). All weights were recorded to the nearest 0.1 gram and all temperatures to the nearest 0.2 C:

1) Calibration of the Michigan Specific Gravity Bottle:
    a. Weigh the empty flask and record its weight under (C).
    b. Weigh the flask filled to mark with methanol brought to a temperature of 25 C.
    c. Subtract from this weight the weight of the empty flask and record the methanol content under (E).
2) Determine the specific gravity of the methanol[1] by a pycnometer using ASTM D 2111 test.
3) Determination of the maximum specific gravity for each sample:
    a. Break up the bituminous mixture sample sufficiently small to go through the large neck of the flask.
    b. Place 300 to 500 grams of the mixture fragments in the flask.
    c. Weigh flask plus mixture and record under (B).
    d. Add about 700 ml. of methanol to the flask containing the mixture.
    e. Shake the flask and tap it on a table covered with soft cloth in order to help expel air bubbles. When necessary apply a partial vacuum (around 20 cm of Mercury) for 3 minutes while shaking and tapping occasionally.

---

[1] It is advisable to form an adjusted table which corrects the methanol content for each flask based on actual specific gravity values of the methanol.

f. Immerse the flask and the contents in a 25 C water bath, and let stand for one hour.

g. Remove the flask from the bath, tap it on the cloth to check for trapped bubbles, and fill it to mark with methanol (which was also kept in the bath).

h. Weigh the filled flask and record under (A).

i. Calculate the maximum specific gravity of the mixture as instructed in Table E-1.

An experienced technician can perform about twenty tests in one day (including calculations). The variations between replicates were restricted to be less than 0.015 unit of specific gravity. The methanol was reused about five times after filtering and checking for specific gravity.

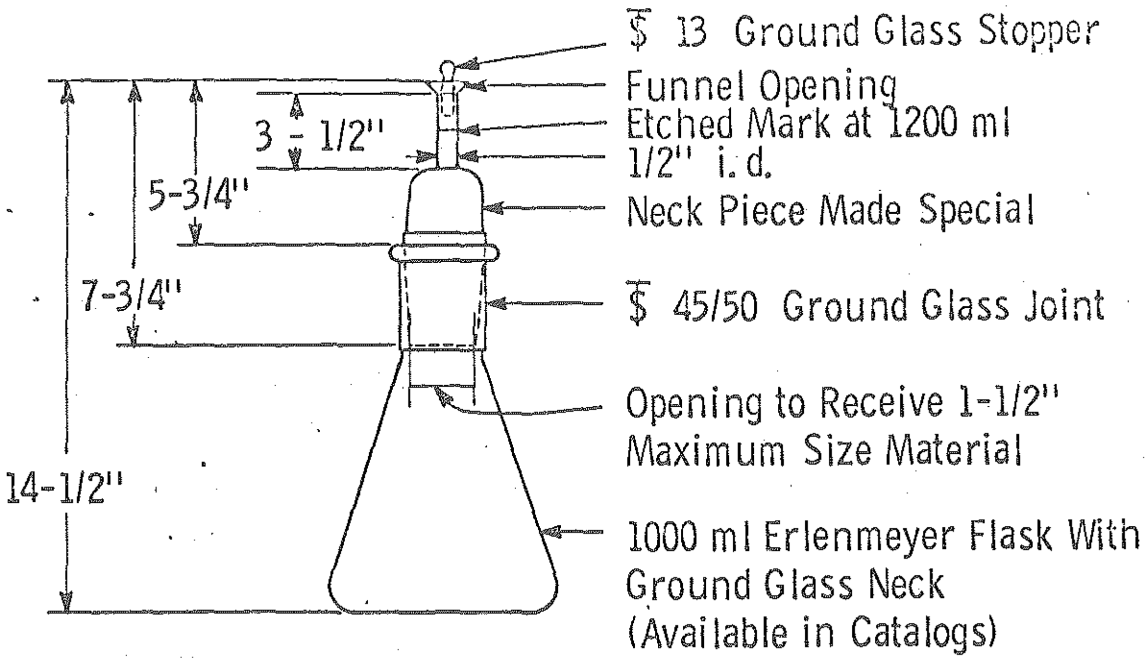


Figure E-1. Dimensioned diagram of the Michigan Specific Gravity Bottle.

TABLE E-1

AN EXAMPLE OF A WORKING SHEET USED IN THE METHANOL TEST

Project No. Aggregate Factors Date Sampled 2-22-72 Sample Nos. 4

Aggregate: Limestone #8-#10 Asphalt: A.C. 120-150

Sample Identification	LS/A	LS/A		LS/B	LS/B	
Laboratory Number	1	2	Average	1	2	Average
Flask No.	S	T		V	X	
(A) Wt. flask + mix + methanol g.	1884.6	1863 2		1935.2	1881.1	
(B) Wt. flask + mix g.	1136.5	1094.9		1209.1	1081.4	
(C) Wt. flask g.	806.1	769.8		877.3	752.1	
(D) Wt. mix (B - C) g.	330.4	325.1		331.8	329.3	
(E) Wt. meth. only (flask filled) g.	865.9	884.6		844.3	916.9	
(F) Wt. meth. above mix (A - B) g.	748.1	768.3		726.1	799.7	
(G) Wt. meth. disp. by mix (E - F) g.	117.8	116.3		118.2	117.2	
(H) Spec. Grav. methanol 25/25°C	0.7895	0.7895		0.7895	0.7895	
(I) Volume of mix (G/H) ml.	149.21	147.31		149.72	148.45	
(J) MAXIMUM SPECIFIC GRAVITY (D/I)	2.214	2.207	2.211	2.216	2.218	2.217

APPENDIX F

RECOMMENDED PROCEDURE FOR BITUMINOUS MIXTURE DESIGN

General

At this stage, the specific optimum value of flow asphalt (w_{fv}) (which is used for estimating the conventional optimum asphalt content), and the developed mixture design tables, are applicable only for the specific asphalt cement, gradation, and fraction separation used in this investigation. However, since most highway departments and agencies usually specify standard gradations and asphalts for each layer in the pavement, only a modest amount of laboratory work is needed prior to a routine mixture design, for determining standard mixture design tables and standard optimum flow asphalt content (w_{fv}) values for each specific gradation and asphalt cement.[1]

---

[1] This laboratory work is described in detail in Chapter IV of this work.

It must be pointed out again that this procedure is applicable, for any type of aggregate with a specified gradation and asphalt cement.

Procedure

(1) Sieve the graded blend of aggregate and obtain the specified one-size fractions. The six actual one-size fractions tested in this work were: 1/2in.-5/8in., #3-#4, #8-#10, #20-#30, #60-#80, #200-#270. The graded aggregates in the mixture can be represented by other fraction sequence provided that the fraction will be one-size[1] and will be uniformly spaced on the gradation chart (uniformly logarithmic spacing of sieves opening). An example for one-size separation to six (actually tested), nine and nineteen one-size fraction can be seen in Figure F-1.

(2) Wash the fractions under water and dry them in an oven.

(3) Find the Packing Specific Gravity (G_p) of each fraction by the pouring test (see Appendix D).

---

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

(4) Find the Bulk Specific Gravity (G_{ag}) and water absorption (A_w) of each fraction by using ASTM C 127 and C 128 tests.

(5) Heat fractions and asphalt to 300 F and mix each fraction. Assure uniform coating of particles. The amount of asphalt should be at least the quantity of the asphalt lost by rugosity (B_{rw}). For estimating B_{rw} find S_{rv} by the following equation:

$$S_{rv} = 100 \frac{G_{ap} - G_p}{G_{ap}}$$

S_{rv} = percent specific rugosity

G_{ap} = apparent specific gravity

G_p = packing specific gravity.

Now use Figure 13 and based on S_{rv} estimate B_{rv}. Find B_{rw} by the following equation:

$$B_{rw} = B_{rv} \frac{G_b}{G_p} ,$$

where

B_{rw} = percent asphalt lost by rugosity (percent by weight of aggregate)

G_b = specific gravity of the asphalt

G_p = packing specific gravity.

Use B_{rw} plus about 10 percent as the minimum amount of asphalt to add to the mixture.

(6) Divide each mixture into two samples by quartering.

(7) On one sample for each fraction find the maximum (theoretical) specific gravity of the mixture (G_{mm}) by the Methanol test (see Appendix E).

(8) Extract the second sample of each fraction, and find the exact asphalt content (w) by using ASTM 02172.

(9) By using Equations (8), (5), (17), (12), (13), (14) and (15), calculate B_{rw}, S_{rv}, B_{ag}, B_{rv}, S_b, S_{ma}, and S_{mi}, respectively, or use the prepared computer program for direct evaluation and tabulation of these parameters, as presented in Tables 4 through 9 (see Appendix G).

(For all fractions, check the relationship between B_{rv} and S_{rv} with the aid of Figure 13. If the points fall within the given range of deviations, all asphalt rugosity terms (B_{rw}, B_{ag}, B_{rv} and S_b) could have been accurately predicted by S_{rv} alone. Thus steps (5) through (8) can be eliminated in any future mixture design using these specific materials, gradation and asphalt).

(10) For the given gradation find the proportions (percent by weight) of each fraction in the mixture.

(11) With the aid of Equations (50), (51), (52), (32), (35), (36), (37) and (38), or by using the prepared computer program, form the mixture design table for a reasonable range of asphalt contents (w), and specific gravities of the mixture (G_{mx}), as presented in Tables 22 through 29 (see Appendices G and H).

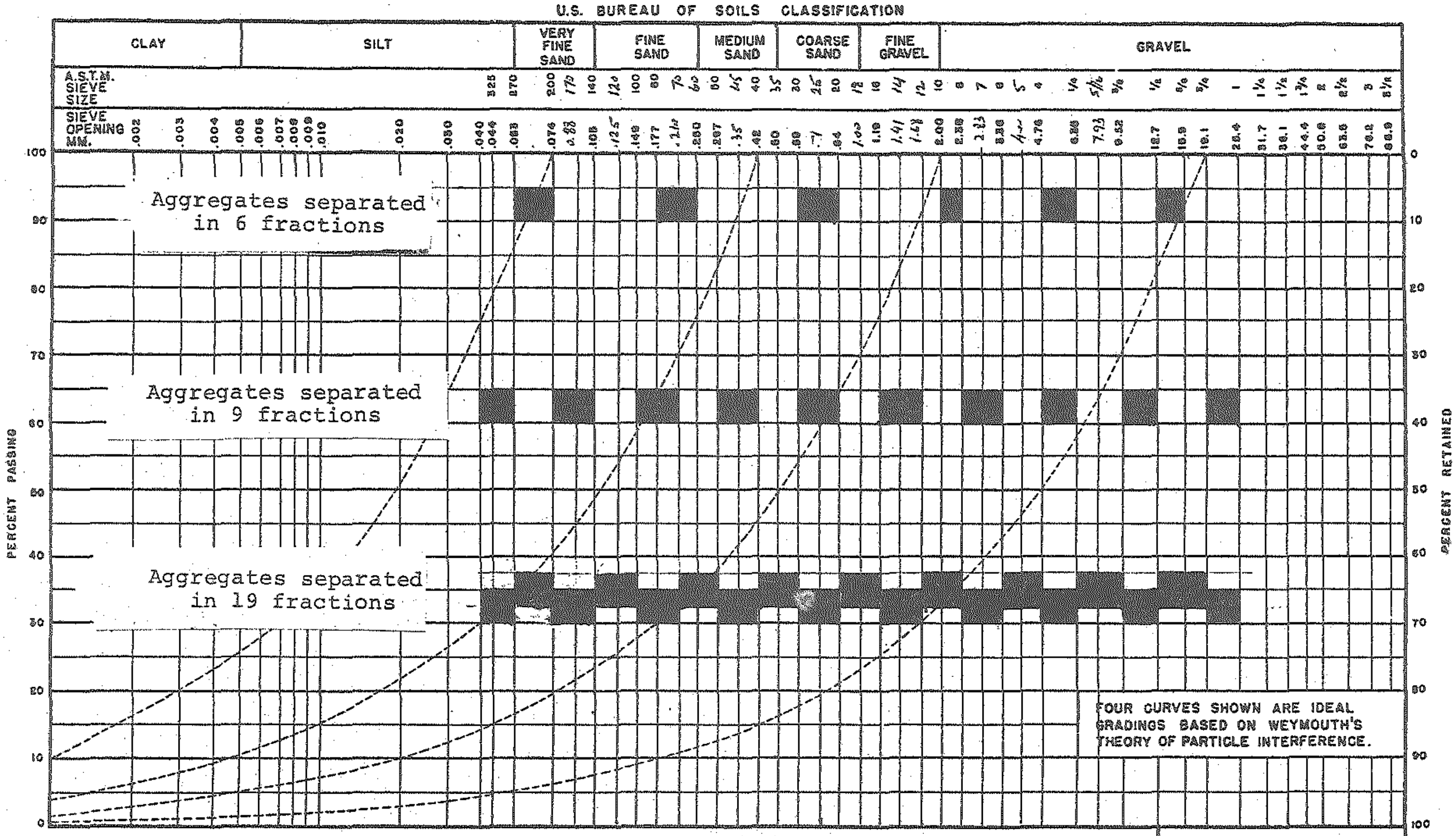
(12) Use the unified value of flow asphalt content (w_{fv}) (assigned to the specific gradation and asphalt) to find the corresponding optimum asphalt content for the aggregate tested by reading from the mixture design table.

(13) Using this optimum asphalt content, mix, compact, and test four Marshall specimens.

(14) With the aid of G_{mx}, obtain from mix specific gravity and using the mix design tables the percent air voids (U), percent VMA and packing-VMA.

(15) Check all mixture properties against design criteria. Perform minor corrections in asphalt content if necessary.

Form 1855



FIELD SAMPLE NO. ____________ DATE SAMPLED ____________ DATE OF TEST ____________

SAMPLE LOCATION ____________ TESTED BY ____________

SOILS CLASSIFICATION ____

REMARKS ____________

MICHIGAN
STATE HIGHWAY DEPARTMENT

LAB NO. ____________
PROJECT ____________

Figure F-1. Examples of possible one-size fractions to be used in tests for mix design.

APPENDIX G

COMPUTER PROGRAM FOR CALCULATION AND TABULATION OF THE AGGREGATE FACTORS

MAIN PROGRAM

```
 10     READ (5,200) SIZE1,SIZE2
        READ (5,202) N
        WRITE (6,100) SIZE1,SIZE2
        WRITE (6,101)
        WRITE (6,102)
        WRITE (6,103)
        I=0
C
C                        ACTUAL PROGRAM
C
 20     I=I+1
        IF (I.GT.N) GO TO 10
        READ (5,201) AGG,W,GAG,WAB,GPE,GMM,ACT
        GAC=1.02
        VPE=W/GPE
        DIA=(6.*VPE/3.1416)**(1./3.)
        GAP=1./(1./GAG-WAB/100.)
        SRV=(GAP-GPE)*100./GAP
        GEO=GPE/GAP
        TEM=(ACT-100.*GAC/GMM)*100./(100.-ACT)
        BAB=TEM+100.*GAC/GAG
        BRW=TEM+100.*GAC/GPE
        BRV=BRW*GPE/GAC
        SAT=BRV*100./SRV
        SUR=(GAG-GPE)*100./GAG
C
C
        WRITE (6,104) AGG,W,DIA,GAG,GAP,WAB,BAB,VPE,GPE,SRV,GEO,BRW,BRV,SA
       1T,SUR
        GO TO 20
C
C                 OUTPUT FORMATS
C
 100    FORMAT ('1',50X,'FRACTION SIZE: ',A4,'-',A4)
 101    FORMAT ('-',20X,'CONVENTIONAL PARAMETERS',42X,'PACKING VOLUME PARA
       1METERS')
 102    FORMAT ('0','AGG.',5X,'AVERAGE',5X,'EQUIVALENT',4X,'BULK',4X,'APP.
       1',4X,'WAT.',3X,'ASP.',7X,'PACKING',4X,'PACK.',2X,'SPEC.',2X,'GEOM.
       2',3X,'ASP.',3X,'ASP.',3X,'ASP.',3X,'SURF.')
```

```
       103   FORMAT (' ',7X,'PAR. WEIGHT',3X,'SPHERE DIA.',3X,'SP.GR',3X,'SP.GR
            1',3X,'ABS.',3X,'ABS.',8X,'VOLUME',4X,'SP.GR',2X,'RUG.V',2X,'FACTOR
            2',2X,'RUG.W',2X,'RUG.V',2X,'SAT.',3X,'RUG.V')
       104   FORMAT ('0',A4,3X,E11.5,3X,E11.5,3X,F5.3,3X,F5.3,3X,F4.2,3X,F4.2,5
            1X,E11.5,2X,F5.3,2X,F5.2,2X,F6.4,2X,F5.2,2X,F5.2,2X,F5.2,2X,F5.2)
      C
      C               INPUT FORMATS
      C
       200   FORMAT (A4,A4)
       201   FORMAT (A4,1X,E10.5,1X,F5.3,1X,F5.3,1X,F5.3,1X,F5.3,1X,F6.3)
       202   FORMAT (I2)
      C
             END
```

LIST OF VARIABLES

PROGRAM SYMBOLS		MATHEMATICAL SYMBOLS
N	= NUMBER OF AGGREGATE TYPES TO BE CALCULATED AND TABULATED	
SIZE1	= DESIGNATION OF THE UPPER SIEVE SIZE	
SIZE2	= DESIGNATION OF THE LOWER SIEVE SIZE	
AGG	= TYPE OF AGGREGATE	
W	= AVERAGE PARTICLE WEIGHT	— W
GAG	= BULK SPECIFIC GRAVITY	— G_{ag}
WAB	= PERCENT WATER ABSORPTION	— A_w
GPE	= PACKING SPECIFIC GRAVITY	— G_p
GMM	= MAXIMUM SPECIFIC GRAVITY OF THE MIXTURE	— G_{mm}
ACT	= ASPHALT CONTENT (PERCENT OF TOTAL WEIGHT OF THE MIXTURE)	— ω
GAC	= SPECIFIC GRAVITY OF THE ASPHALT	— G_b
VPE	= AVERAGE PACKING VOLUME OF PARTICLES	— V_p
DIA	= EQUIVALENT SPHERE DIAMETER OF PARTICLES	— d
GAP	= APPARENT SPECIFIC GRAVITY	— G_{ap}
SRV	= PERCENT SPECIFIC RUGOSITY	— S_{rv}
GEO	= GEOMETRIC IRREGULARITY NUMBER	— I_g
BAB	= PERCENT ASPHALT LOST BY ABSORPTION	— B_{ag}
BRW	= PERCENT ASPHALT LOST BY RUGOSITY (WEIGHT BASIS)	— B_{rw}
BRV	= PERCENT ASPHALT LOST BY RUGOSITY (VOLUME BASIS)	— B_{rv}
SAT	= PERCENT ASPHALT SATURATION	— S_b
SUR	= PERCENT MACRO SURFACE VOIDS	— S_{ma}

OPERATION INSTRUCTIONS

1) PROGRAM IS WRITTEN IN FORTRAN VI.

2) INPUT DATA:

- (A) THERE ARE THREE GROUPS OF DATA CARDS FOR EACH ONE-SIZE FRACTION:
  - (1) ONE CARD TO SPECIFY THE UPPER AND LOWER SIEVES OF THE FRACTION. FORMAT IS GIVEN IN STATEMENT NO. 30.
  - (2) ONE CARD TO SPECIFY THE NUMBER OF AGGREGATE TYPES WITHIN EACH FRACTION (N). FORMAT IS GIVEN IN STATEMENT NO. 32.
  - (3) A GROUP OF N CARDS TO SPECIFY THE AGGREGATE TYPE AND THE MEASURED ONE-SIZE AGGREGATE FACTORS, AS SHOWN IN STATEMENT NO. 10. FORMAT IS GIVEN IN STATEMENT NO. 31.
- (B) THE PROGRAM CAN HANDLE ANY NUMBER OF FRACTIONS, AND ANY NUMBER OF AGGREGATE TYPES WITHIN THE FRACTION AT A TIME. THE GROUPES OF DATA CARDS SHOULD BE PLACED CONSEQUITIVELY IN THE DATA LOCATION AT THE END OF THE MAIN PROGRAM.

3) OUTPUT FORMAT , AS SPECIFIED BY STATEMENTS 25 THROUGH 29 IS SIMILLAR TO THOSE OF TABLES 14 THROUGH 19.

APPENDIX H

COMPUTER PROGRAM FOR MIXTURE DESIGN TABLES

MAIN PROGRAM

```
      DIMENSION ACWM(22),GMIX(17)
      ACWM(1)=2.00
      DO 1 I=1,20
    1 ACWM(I+1)=ACWM(I)+0.50
      GMIX(1)=2.100
      DO 2 I=1,10
    2 GMIX(I+1)=GMIX(I)+0.050
C
C
    3 READ (5,200,END=91) N,GB,AGG
      DIMENSION X(6),GP(6),BBW(6),BRV(6),GAG(6),BAG(6),VP(6),Y(6),VAG(6)
     1,VBAG(6),CFV(6),FR(6)
      DO 10 I=1,N
   10 READ (5,201) X(I),GP(I),BBW(I),BRV(I),GAG(I),BAG(I)
C
C
      WRITE (6,100) AGG
      WRITE (6,101) N
      WRITE(6,102) X(1),X(2),X(3),X(4),X(5),X(6)
      WRITE (6,103)
      WRITE (6,104)
      WRITE (6,105)
      WRITE (6,106)
      WRITE (6,107)
      WRITE (6,108)
C
C
      VPT=0
      VAGT=0
      BAGT=0
      DO 20 I=1,N
      VP(I)=X(I)/GP(I)
      VPT=VPT+VP(I)
      VAG(I)=X(I)/GAG(I)
      VBAG(I)=BAG(I)*X(I)/(100.*GB)
      VAGT=VAGT+VAG(I)
      BAGT=BAGT+X(I)*BAG(I)/100.
   20 CONTINUE
C
      DO 21 I=1,N
   21 Y(I)=100.*VP(I)/VPT
      GPT=100./VPT
      GAGT=100./VAGT
C
```

```
C
      DO 90 L=1,21
      ACWA=ACWM(L)/(1.-ACWM(L)/100.)
      ACVA=ACWA*GPT/GB
      CACWAE=ACWA-BAGT
      CACVAE=CACWAE*GAGT/GB
      VBT=ACWA/GB
C
C
      M=N-1
      DO 50 I=1,M
      VPTT=0
      LL=I+1
      DO 30 J=LL,N
   30 VPTT=VPTT+VP(J)
      VBAGTT=0
      DO 40 K=1,I
   40 VBAGTT=VBAGTT+VBAG(K)
C
      CFV(I)=VPTT/(VBT-VBAGTT)
C
      FR(I)=GP(I)*(BRW(I)-BAG(I))/(100.*GB*(1.+1./CFV(I)))
   50 CONTINUE
      FR(N)=0
C
C
      ACVAL=0
      DO 60 I=1,N
   60 ACVAL=ACVAL+Y(I)*(BRV(I)-100.*FR(I))/100.
      ACVAE=ACVA-ACVAL
      ACWAE=ACVAE*GB/GPT
      ACWAL=ACWA-ACWAE
C
C
      FRT=0
      DO 70 I=1,N
   70 FRT=FRT+FR(I)*Y(I)/100.
      EVP=(VPT-VPT*FRT)*100./VPT
      ACVEF=ACVAE*100./EVP
C
C
      WRITE (6,109) ACWM(L),ACWA,BAGT,CACVAE,ACWAL,ACVAL,ACWAE,ACVEF,FRT
     1,EVP
      WRITE (6,110)
C
C
      DO 80 I=1,11
      VMIX=(100.+ACWA)/GMIX(I)
      AIRV=(VMIX-(100./GAGT+(ACWAE/GB))*100./VMIX
      CVMA=(VMIX-100./GAGT)*100./VMIX
      EVPGT=VMIX-VMIX*AIRV/100.-ACWAE/GB
      EPVMA=(VMIX-EVPGT)*100./VMIX
      TPVMA=(VMIX-VPT)*100./VMIX
      EVPG=EVPGT*100./VPT
      FRTG=(VPT-EVPGT)/VPT
C
C
   80 WRITE (6,111) GMIX(I),AIRV,CVMA,EPVMA
C
```

```
   90 CONTINUE
      GO TO 3
   91 CALL SYSTEM
C
C
  200 FORMAT (I2,1X,F5.3,1X,A2)
  201 FORMAT (F4.1,1X,F5.3,1X,F5.2,1X,F5.2,1X,F5.3,1X,F4.2)
C
C
  100 FORMAT ('1','AGGREGATE TYPE - ',A2)
  101 FORMAT (' ','NUMBER OF FRACTIONS N=',I2)
  102 FORMAT (' ','X(1),.....X(N)=',F4.1,',',F4.1,',',F4.1,',',F4.1,',',
     1F4.1,',',F4.1,2X,'(FRACTIONS PROPORTION - WEIGHT BASIS)')
  103 FORMAT ('0','PERC.',3X,'PERC.',11X,'EFF.',4X,'PERC.',3X,'PERC.',3X
     1,'FLOW',4X,'FLOW',4X,'ICIAL')
  104 FORMAT (' ','ASPH.',3X,'ASPH.',3X,'PERC.',3X,'ASPH.',3X,'RUG.',4X,
     1'RUG.',4X,'ASPH.',3X,'ASPH.',3X,'FINES',3X,'PERC.',4X,'SPEC.')
  105 FORMAT (' ','CONT.',3X,'CONT.',3X,'TOTAL',3X,'CONT.',3X,'ASPH.',3X
     1,'ASPH.',3X,'CONT.',3X,'CONT.',3X,'LOST',4X,'ACTIV',4X,'GRAV.',3X,
     2'PERC.',3X,'PERC.',3X,'PERC.')
  106 FORMAT (' ',' MIX',4X,'AGG.',4X,'ASPH.',3X,'VOL.',5X,'WT.',4X,'VOL
     1.',5X,'WT.',4X,'VOL.',5X,'BY',5X,'PACK.',5X,'OF',6X,'AIR',4X,'CONV
     2.',3X,'PACK.')
  107 FORMAT (' ','BASIS',3X,'BASIS',3X,'ABS.',4X,'BASIS',3X,'BASIS',3X,
     1'BASIS',3X,'BASIS',3X,'BASIS',3X,'RUG.',4X,'VOL.',6X,'MIX ',3X,'VO
     2IDS',4X,'VMA',5X,'VMA')
  108 FORMAT ('0',' ')
  109 FORMAT ('0',F5.2,7F8.2,3X,F5.4,3X,F5.2)
  110 FORMAT (' ',56X,'-----')
  111 FORMAT (' ',81X,F5.3,3F8.2)
C
      END
```

LIST OF VARIABLES

PROGRAM SYMBOLS		MATHEMATICAL SYMBOLS
ACWM	= ASPHALT CONTENT (PERCENT OF TOTAL MIXTURE WEIGHT)	– w
GMIX	= SPECIFIC GRAVITY OF THE COMPACTED MIXTURE	– G_{mx}
N	= NUMBER OF ONE-SIZE FRACTIONS IN THE MIXTURE	– N
GB	= SPECIFIC GRAVITY OF ASPHALT	– G_b
AGG	= AGGREGATE TYPE DESIGNATION	
X(I)	= PERCENT BY WEIGHT OF THE I-TH FRACTION IN THE MIXTURE	– X_i
GP(I)	= PACKING SPECIFIC GRAVITY OF THE I-TH FRACTION	– G_{pi}
BRW(I)	= PERCENT ASPHALT LOST BY RUGOSITY OF THE I-TH FRACTION (WEIGHT BASIS)	– B_{rwi}
BRV(I)	= PERCENT ASPHALT LOST BY RUGOSITY OF THE I-TH FRACTION (VOLUME BASIS)	– B_{rvi}
G(I)	= BULK SPECIFIC GRAVITY OF THE I-TH FRACTION	– G_{agi}
BAG(I)	= PERCENT ASPHALT LOST BY ABSORPTION OF THE I-TH FRACTION	– B_{agi}
VP(I)	= TOTAL PACKING VOLUME OF THE I-TH FRACTION	– V_{pi}
Y(I)	= PERCENT BY VOLUME OF THE I-TH FRACTION IN THE MIXTURE (IN PACKING VOLUME UNITS)	– Y_i
VAG(I)	= TOTAL BULK VOLUME OF THE I-TH FRACTION	– V_{agi}

VBAG(I) = TOTAL VOLUME OF THE ASPHALT ABSORPTION WITHIN THE I-TH FRACTION
CFV(I) = FINES CONCENTRATION OF THE I-TH FRACTION IN THE MIXTURE — C_{fvi}
FR(I) = FINES LOST BY RUGOSITY OF THE I-TH FRACTION IN THE MIXTURE — F_{ri}
VPT = TOTAL PACKING VOLUME OF THE AGGREGATE IN THE MIXTURE — V_{pt}
VAGT = TOTAL BULK VOLUME OF THE AGGREGATES IN THE MIXTURE — V_{ag}
BAGT = AVERAGE ASPHALT LOST BY ABSORPTION IN THE MIXTURE — B_{ag}
ACWA = ASPHALT CONTENT (PERCENT OF TATAL AGGREGATE WEIGHT) — w
ACVA = ASPHALT CONTENT (PERCENT OF TOTAL PACKING VOLUME OF THE AGGREGATES)
CACWAE = EFFECTIVE ASPHALT CONTENT (PERCENT OF TOTAL AGGREGATE WEIGHT) — w_{ew}
CACVAE = EFFECTIVE ASPHALT CONTENT (PERCENT OF TOTAL BULK VOLUME OF THE AGGREGATES) — w_{ev}
VBT = TOTAL VOLUME OF ASPHALT IN THE MIXTURE
VPTT =} TEMPORARY VALUES OF VPT AND VBAG, RESPECTIVELY, AS
VBAGTT =} APPEAR IN EQUATION (65) FOR V_{pk} AND V_{agl}.
FRT = TOTAL FINES LOST BY RUGOSITY IN THE MIXTURE (PERCENT OF TOTAL PACKING VOLUME OF AGGREGATES) — F_{rt}
EVP = ACTIVE PARTICLES IN THE MIXTURE (PERCENT OF TOTAL PACKING VOLUME OF AGGREGATES) — V_{pa}
ACWAL = ASPHALT LOST IN THE MACRO SURFACE VOIDS OF AGGREGATES (PERCENT OF TOTAL WEIGHT OF AGGREGATES)
ACVAL = ASPHALT LOST IN THE MACRO SURFACE VOIDS OF AGGREGATES (PERCENT OF TOTAL PACKING VOLUME OF AGGREGATES)
ACWAE = FLOW ASPHALT CONTENT (PERCENT OF TOTAL AGGREGATE WEIGHT) — w_{fw}
ACVAE = FLOW ASPHALT IN THE MIXTURE (PERCENT OF TOTAL PACKING VOLUME OF AGGREGATES)
ACVEF = FLOW ASPHALT CONTENT (PERCENT OF PACKING VOLUME OF THE ACTIVE PARTICLES IN THE MIXTURE) — $\underline{w_{fv}}$
VMIX = TOTAL VOLUME OF THE COMPACTED MIXTURE
AIRV = PERCENT AIR VOIDS IN THE COMPACTED MIXTURE — U
CVMA = PERCENT VMA (CONVENTIONAL) — VMA
EPVMA = PERCENT PACKING VMA — VMA_p

OPERATION INSTRUCTIONS

1) PROGRAM IS WRITTEN IN FORTRAN IV.
2) INPUT DATA:
   (A) RANGE AND INTERVALS OF ASPHALT CONTENT CAN BE INSERTED IN STATEMENTS 02 THROUGH 04 (WITHIN THE PROGRAM).
   (B) RANGE AND INTERVALS OF GMIX CAN BE INSERTED IN STATEMENTS 05 THROUGH 07 (WITHIN THE PROGRAM).
   (C) THE DIMENSION SPECIFICATION IN STATEMENT NO.01 ARE ACCORDING TO (A) AND (B).
   (D) THERE ARE TWO GROUPS OF DATA CARDS FOR EACH AGGREGATE:
      (1) ONE CARD TO SPECIFY THE MATERIALS AND NUMBER OF FRACTIONS, AS SHOWN IN STATEMENT NO. 08. THE FORMAT IS SPECIFIED IN STATEMENT NO. 81.
      (2) A GROUPE OF N CARDS TO SPECIFY THE ONE-SIZE

AGGREGATE PARAMETERS FOR EACH FRACTION, AS SHOWN IN STATEMENT NO. 11. THE FORMAT IS SPECIFIED IN STATEMENT 82.

(E) THE DIMENSION SPECIFICATION IN STATEMENT 09 IS ACCORDING TO THE NUMBER OF THE ONE-SIZE FRACTIONS (N).

(F) THE PROGRAM CAN HANDLE ANY NUMBER OF AGGREGATE TYPES AT A TIME FOR A GIVEN RANGE OF ASPHALT CONTENT AND GMIX. THE GROUPS OF DATA CARDS FOR THE DIFFERENT TYPES SHOULD BE PLACED CONSEQUITIVELY IN THE USUAL DATA LOCATION AT THE END OF THE MAIN PROGRAM.

3) OUTPUT FORMAT, AS SPECIFIED BY STATEMENTS 83 THROUGH 94 IS IDENTICAL TO THOSE OF TABLES 34 THROUGH 41.