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Aggregate Factors in Bituminous Mixture Design

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AGGREGATE FACTORS IN BITUMINOUS MIXTURE DESIGN

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TABLE OF CONTENTS

TABLE OF CONTENTS (Concluded)

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (Concluded)

SYNOPSIS

This report is concerned with properties of 20A and 20B aggregates and bituminous mixtures 4.09 and 4.11 used on state and county secondary road projects. The main purpose of the study was to find factors in gravel mixes which influence their service behavior and outline a method of measurement to compare the aggregates from different sources in various counties.

Gravel and sand samples were gathered from 29 counties in Michigan. From these, 14 pits from 14 counties were investigated. The testing program was conducted in two steps:

(1) Comparison of aggregates and mixes by the measurement of conventional properties; namely, bulk specific gravity, water absorption, asphalt absorption, and selected tests using the Marshall method; and

(2) comparison of aggregates using a recently developed method in which so-called "packing volume" (rather than size) of aggregate particles is considered.

The conventional tests did not indicate much difference between the aggregates, while the "packing volume" measurements showed large practical differences between the 14 gravels tested. This appears to explain the reasons for observed differences of mix behavior on the roads of various counties in Michigan. A simple test procedure for "packing volume" measurement was developed and can be used for measurements with other aggregates.

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INTRODUCTION

For secondary road construction the aggregates used in bituminous mixtures are usually obtained from local sources in each of the 83 counties in Michigan. Field observations show cases where the performance of such mixtures (4.09 and 4.11) using 20A and 20B aggregate grading have been less than satisfactory. The practical problems appear to be in the choosing of proper asphalt content from a given gravel mix so that it can be compacted properly and would not exhibit instability (washboarding) or deterioration under traffic.

At present, several methods can be used for estimating the optimum asphalt content. These include the Centrifuge Kerosene Equivalent method, the Marshall method, and field performance data. These methods are helpful, but in a number of cases are not sensitive enough or are too time-consuming for practical use. They also do not measure or explain the factors which affect the optimum asphalt content.

In view of the above difficulties, it was felt that a study of measurable physical factors of the aggregates which affect the performance of a mix is timely and needed. If a simple and logical method could be found by which practical differences between the various sands and gravels in different counties could be established, a significant step towards designing a mix rationally and explaining its behavior would be achieved.

PURPOSE AND SCOPE

The purpose of this investigation was:

(1) To study in the laboratory the physical characteristics of gravels and sands from various sources which would reflect the asphalt requirements in mixture design;

(2) to come up with a simple and rapid measuring technique for aggregate characterization; and

(3) to compare the laboratory findings with known field behavior of mixes, where possible.

The experimental work was done using gravel and sand from 14 different counties distributed over all of Michigan. This was the maximum number of samples that could be included in the program. The geographic distribution and code numbers for the counties selected are shown in Figure 4.

The aggregates from each source were fractioned by sieving and four one-size fractions were used for the basic data gathering. For each fraction, 6 basic tests were performed with a total of 336 tests. A number of tests on graded aggregates and bituminous mixes were also performed.

THEORETICAL CONSIDERATIONS

The present design methods for bituminous mixtures are mostly based on trial-and-error procedures, or on empirical indices (Marshall method, Hubbard-Field method, Hveem method, and others (1)[1]). For these reasons, the prediction of the behavior of mixes under field service conditions, or the explaining of failure cases, must be based on past experience or through extensive "trial-and-error" type testing.

The main reason for this is the lack of proper physical quantitative parameters which would correlate the physical properties of the mix components (asphalt and rock particles) with the behavior and performance of the compacted bituminous mix in the laboratory and on the road.

Since the irregularity of the rock particles creates a major difficulty in achieving a unified physical concept for mix design and prediction, it was felt that a physical concept for a unique definition of the aggregate properties (aggregate factors) must be the initial basis for a proper mix design. Therefore, the first concern and emphasis was to find physical, quantitative, and measurable parameters which will characterize and unify the properties of rock particles of various types of aggregates and sizes, and which will make more predictable the bulk behavior of a granular system with or without the asphalt binder.

To start with, it was shown by Tons, et al. (2,3) that the volume which a

[1]Numbers in parentheses refer to List of References.

rock particle occupies in a mass of other particles largely determines the density and the voids in bulk, and therefore this volume is important insofar as the resistance of the mix to various forces is concerned.

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 particles encompasses not only the volume of the solids and internal voids, but also the volume of the dips and valleys of the particle surface (surface irregularities or voids).

Based on the above considerations, the "volume which a particle occupies in a mass of particles" was defined by Tons and Goetz (2) as the "packing volume" of the particle. This can be described by a simple equation:

$$V_p = V_{ab} + V_i + V_{sr} \qquad (1)$$

where

V_p = packing volume of a rock piece

V_{ab} = volume of solids of the particle

V_i = volume of internal voids inside the rock

V_{sr} = volume of surface roughness voids.

The packing volume of a particle can be related to "volume enclosed by a dimensionless membrane stretched along the surface of the particle," as illustrated in Figure 1.

In practice the packing volume has been originally measured by immersing the rock in asphalt, removing the excess asphalt down to the peak of the surface, and weighing the piece in air and water.

The packing volume of a particle was also approximated by fitting to it an ellipsoid as a geometric form and measuring the long, medium, and short dimensions (ℓ, m, s, respectively). In this case, the packing volume of a particle was defined as:

$$V_p = \frac{\pi}{6} \ell ms. \qquad (2)$$

The notion of the packing volume was assumed (and also proven experimentally) to serve as a basis for a physical definition of other aggregate factors which may provide a unified concept for evaluation of aggregate properties. The packing volume concept was stated as follows:

> Different types of monovolume (V_p) aggregates[2] will be compacted to the same volume of the bulk ($V_{b\ell}$) when they possess identical total packing volumes (ΣV_p) under identical compaction procedure.

That is, when ΣV_p is fixed, any type of monovolume particles will be compacted to the same volume of the bulk (possessing the same packing porosity[3]) under identical compaction energy input.

If ΣV_p of different aggregates is constant, the ratios of the packing specific gravities (G_p)[4] of different types of monovolume aggregates will be proportional to the ratios of their dry weights, thus the above concept can be formulated now uniquely in one equation:

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[2]Tons, et al. (2,3) considered monovolume aggregates as particles with the coefficient of variation in packing volume restricted to be less than 15%.

[3]The packing porosity was defined as regular porosity but with the packing volume as the total volume of the solids.

[4]The packing specific gravity of a particle (G_p) has been defined as the dry weight of the particle divided by its packing volume. G_p can be considered as the lowest possible specific gravity that a particle can have.

$$\Sigma W_1 : \Sigma W_2 : \Sigma W_3 : \ldots : \Sigma W_n = G_{p1} : G_{p2} : G_{p3} : \ldots : G_{pn} \qquad (3)$$

where

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

It can be seen that the packing volume membrane concept enables a unique partition of the voids of monovolume dry aggregates into two components: (1) the interparticle voids which have been defined as the packing porosity; and (2) inner-membrane voids which characterize the roughness of the particles (V_{sr}).

While the packing porosity serves as a property of the bulk, the inner-membrane voids serve as a property of the particle and a basis for other unique physical definitions for the surface roughness (rugosity) of dry aggregates:

$$R_s = \frac{V_{sr}}{A_s}\left(\frac{cm^3}{cm^2}\right) \qquad (4)$$

where

R_s = surface rugosity (roughness)

V_{sr} = volume of surface irregularity voids under the packing volume membrane

A_s = surface area of the particle.

Another way to characterize the surface roughness can be by "specific rugosity" (S_{rv}, in percent):

$$S_{rv} = 100 \frac{V_{sr}}{V_p} \qquad (5)$$

where

V_p = packing volume of a particle (other terms as above).

In the same manner the packing volume membrane partitions the total amount of asphalt in the mix into two components: (1) the rugosity asphalt (asphalt loss in the inner-membrane voids); and (2) the effective asphalt (binding or flow asphalt) (see Figure 2).

The knowledge of the rugosity asphalt is essential since it determines the amount of the effective asphalt (for a given asphalt content), which was found to be a factor that affects the flow (strength—stress—strain relationship) characteristics of the compacted mixture (3).

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

(1) The original and basic definition (Reference 3) of the asphalt lost below the packing volume membrane is represented by R or rugosity:

$$R = \frac{V_b}{A_s} \left(\frac{cm^3}{cm^2} \right) \qquad (6)$$

where

V_b = the volume of asphalt in the permeable voids and surface crevices of the particle (up to the packing volume membrane)

A_s = surface area of the particle.

The term "rugosity" can be interpreted physically as the average thickness of the asphalt film below the packing volume membrane.

(2) The second way to characterize rugosity is by "asphalt lost by rugosity" (B_{rw}):

$$B_{rw} = 100 \frac{W_{rw}}{W_{ag}} \qquad (7)$$

where

B_{rw} = asphalt lost by rugosity, percent by weight

W_{rw} = the weight of rugosity asphalt

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

Since the packing volume is physically and fundamentally defined, it should provide a basis for the desired unified concept to a physical and unique definition of the aggregate factors in bituminous mixture design.

The packing volume, and its related rugosity terms, are expected to overcome the difficulties caused by the variety of definitions for aggregate properties which are presently used (bulk specific gravity, apparent specific gravity, effective specific gravity, asphalt lost by absorption, etc.).

EXPERIMENTAL APPROACH

Based on the above theoretical considerations, and according to the main goal of this investigation, an experimental approach was adopted based on the following procedures:

(1) Trial evaluation and comparison of graded aggregates and mixes by using conventional testing methods (bulk specific gravities, water absorption, Marshall parameters, etc.);

(2) evaluation of packing volume parameters for different types and sizes of aggregates; and

(3) evaluation of bulk volume parameters for the same types and sizes of aggregates.

In order to check the sensitivity of the present testing methods and to evaluate and distinguish between aggregate blends of a similar nature, a series of preliminary tests were performed on selected aggregates by using an average design gradation which fits both requirements of aggregates 20A and 20B (see Figure 3).

The tests performed were as follows:

(a) Bulk specific gravity and water absorption for the fine aggregates (passing sieve No. 4);

(b) bulk specific gravity and water absorption for the coarse aggregates (passing 3/4 in. sieve and retaining on No. 4 sieve);

(c) Marshall tests for graded blends (three blends were used); and

(d) Marshall tests for washed, graded blends (three blends were tried).

The major emphasis in this investigation was given to the evaluation and analysis of the packing volume parameters as the basic aggregate factors.

The graded system for each of the aggregates[5] was represented by four one-size fractions.[6]

The one-size fractions were defined as aggregates which passed top sieve and were retained on bottom sieve differing in opening by a factor of $\sqrt{2}$. This setup served as a practical modification for the "monovolume" aggregates tested before (2,3), since it was found experimentally that the packing volume concept is still valid for the one-size gravel fractions and they can be considered as monovolume aggregates. Under this procedure the average packing volumes of different types of aggregates from a given one-size fraction may vary, but the coefficient of variation of particle weights[7] was not allowed to exceed 35%. An example for the coefficients of variation for a given one-size fraction (#8-#10) can be seen in Table 1.

Each size (fraction) for a given aggregate represented an "experimental treatment." For each treatment three basic experiments were run:

(a) Determination of average particle weight;

(b) determination of packing specific gravity; and

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[5]Aggregates from 14 sources were tested.

[6]The one-size fractions chosen were 1/2 in.-5/8 in., #3-#4, #8-#10, and #20-#30.

[7]Since each type of aggregate possesses particles with different packing specific gravity, the coefficient of variation of the packing volumes will be less than that of particles weight.

(c) determination of maximum theoretical specific gravity of the particles mixed with asphalt.

Since the important part in this stage was the determination of the packing volume of particles, three different methods of testing were tried.

The packing volume was first evaluated by geometric analysis. Based on particle dimensions measurement, the packing volume was calculated by using Equation (2).

A special wax coating method was used as the second procedure for packing volume determinations. Particles were dipped in hot wax, cooled, and then scraped or wiped down to the packing volume membrane. The packing specific gravity was then evaluated by weighing particles in air and water.

The third method (which was found later to be the best one) was the "pouring method." Fractions of aggregates were poured through cone-shaped bins from a given height into a constant volume container. By the same procedure, one-size smooth glass spheres were poured into the same container. The packing specific gravity of the fractions was calculated on the basis of the packing volume Equation (3):

$$G_{px} = \frac{\Sigma W_x}{\Sigma W_s} G_{ps} \tag{8}$$

where

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

ΣW_x, ΣW_s = weights of the unknown and standard fractions which occupy same bulk volumes.

The maximum theoretical specific gravity of the mixtures was determined by the Michigan Solvent Immersion method (4).

The evaluation of the packing specific gravity and the theoretical maximum specific gravity, together with the known specific gravity of the asphalt, enabled the physical determination of the rugosity terms. For practical reasons, it was decided to evaluate and analyze only the specific rugosity (S_{rv}) and asphalt lost by rugosity (B_{rw}) as parameters for the rugosity terms.

Based on Equation (5), the specific rugosity can be calculated:

$$S_{rv} = 100 \frac{G_{ap} - G_p}{G_{ap}} \tag{9}$$

where

G_{ap} = the apparent specific gravity of the particles.[8]

Based on Equation (7), the asphalt lost by rugosity can be evaluated:

$$B_{rw} = \frac{100}{100-\omega}\left(\omega - 100\frac{G_b}{G_{mm}}\right) + 100\frac{G_b}{G_p} \tag{10}$$

where

ω = asphalt content in the mix (% of total mixture by weight)

G_b = specific gravity of the asphalt

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

The main objective for evaluating the bulk volume parameter for the various aggregates and sizes was to provide a basis for comparison between the new concept and the standard methods for evaluating aggregate and mixes properties.

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[8]The apparent volume gives the best practical estimate for the outside volume of the solids. G_{ap} will be evaluated from the bulk volume parameters which will be measured separately.

The bulk specific gravity and water absorption were evaluated by the bulk specific gravity tests.

The knowledge of the bulk specific gravity, together with the theoretical maximum specific gravity, were used to evaluate the asphalt lost by absorption. Similar to Equation (10) one gets:

$$B_{ag} = \frac{100}{100-\omega}\left(\omega - 100\,\frac{G_b}{G_{mm}}\right) + 100\,\frac{G_b}{G_{ag}} \qquad (11)$$

where

B_{ag} = percent of asphalt lost by absorption

G_{ag} = bulk specific gravity of the aggregates

ω = asphalt content in the mix (% of total mixture by weight)

G_b = specific gravity of the asphalt

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

For most experimental treatments, two replicates for each test were performed in order to eliminate rough experimental errors.

Data have been analyzed statistically and graphically to provide reliable physical correlations.

CHOOSING OF MATERIALS

Originally, 86 samples of aggregate blends were collected from 29 counties in the state. From this collection, 14 blends of gravel type 20A or 20B, from different pits (counties), were selected to represent the various localities of the state.

The above selection was based on the following considerations:

(1) Pit distribution in the state;

(2) natural gradation;

(3) size of sample available; and

(4) problems in service performance.

The geographical distribution of counties selected can be seen in Figure 4. Aggregate (63-7)[9] was chosen for pilot and trial tests.

Each blend was sieved into nine regular fractions. The fractions were stored in paper bags for future testing.

In the first stage of the investigation, an average design gradation was selected for all aggregates. The selection was based on the average natural gradation of the aggregates as well as on the standard gradation limits specified for gravel type 20A and 20B (see Figure 3).

At the same time three blends were selected for Marshall testing (81-21, 2-34, 63-7).

The asphalt used in all stages of the investigation was of the same

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[9]Each blend is designated by the county number and pit number, respectively.

grade as used frequently in actual construction , namely; 120-150 penetration (see Table 2).

LABORATORY WORK

PRELIMINARY PREPARATIONS

After collection and selection of the 14 aggregates, they were sieved through rectangular large mesh sieves (23 in. x 15 in.) by vibratory sieve shaker. Nine sieves were used to form nine fractions from each blend. The sieves were 3/4 in., 3/8 in., #4, #8, #16, #30, #50, #100, and #200. The fractions were stored in closed paper bags.

BULK SPECIFIC GRAVITIES OF AGGREGATES

The bulk specific gravity and water absorption were evaluated separately for fine (- #4) and coarse (3/4 in.-#4) fractions. Samples were prepared by combining the sieved fractions according to the design gradation. Tests were performed according to ASTM C127 and C128. Sample sizes were 5000 grams and 1000 grams for the coarse and the fine aggregates, respectively. Results are given in Table 3 and in Figures 5 and 6.

MARSHALL TESTING

A series of Marshall tests were performed on three aggregates. Tests included graded aggregates combined from natural fractions and washed fractions.

For the unwashed fractions, two asphalt contents were used (4.5% and 5.5%). Only one asphalt content (4.5%) was used for the washed fractions.

For each asphalt content, three identical standard specimens were prepared for the same mix. Mixing temperature was 300°F. After mixing by mechanical mixer for 2 minutes, mixes were divided into three parts and stored in sealed cans. The mixes were reheated to 275°F just before the compaction. The compaction was accomplished by a mechanical Marshall compactor, applying 50 blows on each side of the specimen. Samples were cured, weighed, and tested according to the standard procedure of the Marshall test (1). A summary of test results is given in Table 4 and Figure 7 and will be discussed later.

MEASURING PACKING AND BULK VOLUME PARAMETERS

Two experimental factors were used in designing the basic experiment for evaluation of the packing volume parameters. The factors were aggregate type (14 levels, see list in Figure 4) and monovolume fraction sizes (4 levels - 1/2 in.-5/8 in., #3-#4, #8-#10, and #20-#30). Each size from each type represented the basic experimental treatment. Since tests have been performed by blocking the size factors and randomly choosing group of types within the blocks, the basic design can be considered as similar to a 14 x 4 split plot factorial experiment.

For each one of the 56 treatments, the following tests and operations were performed:

(1) Subsieving the regular fraction to the desired one-size fraction;

(2) washing and drying;

(3) measuring mean particle weight;

(4) measuring particle dimensions for geometrical analysis;

(5) measuring packing specific gravity by the pouring test;

(6) measuring bulk specific gravity and water absorption;

(7) mixing with asphalt;

(8) measuring maximum theoretical specific gravity;

(9) evaluating asphalt content by extraction; and

(10) measuring packing specific gravity by wax coating.

Since each treatment involved a large number of tests and operations, a special time schedule was designed for parallel work. Figure 8 represents the flow chart which describe order of operations.[10] This order was repeated for each fraction size. A special program was written for data analysis by a computer.

The above operations and tests were 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 in. diameter sieves.

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

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

Particle dimensions (long, medium, and short) were measured for random samples of about 50 particles. Measurements were performed by a caliper.

The pouring test was run by using a special device which was originally

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[10] Since the pouring test was adopted after completion all tests for #8-#10 and 1/2 in.-5/8 in. sizes, special timing was assigned for testing those sizes in the pouring devices.

designed for this investigation. For each size, particles were stored in a cone-shaped bin to have a constant drop height. The particles were then poured into a calibrated constant volume container centered below until it overflowed. The top of the aggregate pile was leveled by a ruler down to the edge of the mold and the aggregate from the container was weighed on a balance. Each pouring test was repeated four times for the same sample. The diameter of bin opening, diameter of bin cylinder, and diameter of the calibrated containers varied with size of each fraction.[11] By the same procedure, glass beads were tested using 6 mm size for comparing 1/2 in.-5/8 in. and #3-#4 fractions, while 3 mm beads were used for #8-#10 and #20-#30. An approximate time for each measurement in the pouring device was 2 minutes. For further details see the Appendix.

The bulk specific gravities and water absorption were measured according to ASTM standards. Fractions 1/2 in.-5/8 in. and #3-#4 were tested according to C127, fraction #20-#30 according to C128. Fraction #8-#10 was surface dried according to C127, but the volumetric measurements were done according to C128.

The bituminous mixes for the maximum theoretical specific gravity test 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 mixes 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 coating

[11]Larger particles require larger containers for free flow and packing.

was observed.

The maximum theoretical specific gravities were evaluated according to the Michigan Department of State Highways standards for the "solvent immersion test" (4).

From the solvent immersion flasks, mixtures were placed in centrifuge extractors for asphalt content determination.

The wax coating method for packing specific gravity was found to be adequate only for coarse particles. Therefore, it was used only for #8-#10, #3-#4, and 1/2 in.-5/8 in. fractions. Basically, particles were dipped in hot wax, taken out and scraped or wiped down to the assumed packing volume membrane. The particles were then weighed in air and water for packing specific gravity determination. Particles from fraction 1/2 in.-5/8 in. were scraped individually by a straightedge spatula, while from particles of finer fractions the excess wax was removed by wiping and rolling the coated particles on a soft rag.

Test results were computed and analyzed by computer for each size. The general analyses have been performed after the end of the general testing program.

Test results, data, and analyses are presented in Tables 5 through 12 and Figures 5 through 27.

RESULTS AND DISCUSSION

BULK SPECIFIC GRAVITY FOR GRADED AGGREGATES

Values of bulk specific gravities and water absorption for fine and coarse graded fractions are shown in Table 3. The relationships between water absorption and bulk specific gravity were plotted separately for fine and coarse in Figures 5 and 6.

Except for aggregate 63-54 which represents in both cases high specific gravity and low absorption, and aggregate 49-16 which represents high specific gravity with intermediate absorption, it is difficult to find consistent trends for the individual gravels. Therefore, it is almost impossible to use the above data as a significant criteria for physical evaluation and rating for the 14 aggregates.

MARSHALL TESTS

In order to obtain an idea on strength-void characteristics of the mixes, three batches of aggregates (81-21, 63-7, and 2-34) were mixed with asphalt and compacted. Aggregate 81-21 was expected to give a relatively low stability in the Marshall test, while 63-7 had no known deficiency. Also, aggregate 2-34 was expected to behave unconventionally.

The optimum asphalt content for all three mixes was assumed to be around 4.5% and specimens were also prepared at 5.5% asphalt content. Table 4 and Figure 7 give the summary of these trial tests. Although the stability of the mixture with 63-7 aggregate is somewhat higher (statistically different) than that for the other two mixes, generally speaking all are similar from a practical viewpoint. The gradation used, however, produced low voids and low VMA values for all mixes. This is not desirable, since traffic on the road could reduce the voids still further and may convert the stable mixes into unstable.

Since the gradation of the aggregates used appeared to be reasonable, the cause of the low voids was suspected to be with the aggregates. It was observed that the gravel and sand particles of the three mixes had coatings of fine particles (dust) on their surfaces (see Figure 9).

The three aggregates were subsequently washed and the Marshall properties were again measured using 4.5% asphalt content. The stabilities for the mixes did not change substantially, but the voids went up to 3.3, 3.3, and 2.1%, respectively, for mixes 63-7, 2-34, and 81-21. The main conclusions from this brief mix study indicate that initial stability of mixtures 4.09 and 4.11 appears to be adequate, but that void contents may be low, especially if fines (filler) present in the aggregates are not accounted for. The results also indicate that the Marshall method may not be very sensitive.

PACKING AND BULK VOLUME FACTORS

General Presentation of Results

Tables 5 through 8 represents data of the geometric analyses for all four one-size fractions (1/2 in.-5/8 in., #3-#4, #8-#10, and #20-#30).

The equivalent sphere diameter d was taken as the diameter of a sphere which possesses the same volume as the measured rock particle, that is:

$$d = \sqrt[3]{lms} \tag{12}$$

where

ℓ, m, and s are long, medium, and short dimensions of a particle.

The sphericity factor ψ [as originally presented by Wadel (5-7)] is defined as follows:

$$\psi = \frac{d}{\ell} \tag{13}$$

where

d and ℓ are as defined for Equation (12).

The surface area of the particle (area of the packing volume membrane) was calculated using simplified equation of a prolate spheroid:

$$A = \frac{1}{2} \pi t \left(t + \frac{\ell}{k} \sin^{-1} k\right) \tag{14}$$

where

A = surface area of the particle

t = (m + s)/2

$k = \dfrac{\sqrt{\ell^2 - t^2}}{\ell}$

The specific surface area (U) was defined as follows:

$$U = \frac{A}{W} \left(\frac{cm^2}{gr}\right) \tag{15}$$

where

W = average particle weight as determined for the 50 particles measured

A = surface area of the particle.

The packing volume of the particle (V_p) was determined by Equation (2), and the packing specific gravity was calculated from:

$$G_p = \frac{W}{V_p} \tag{16}$$

Tables 9 through 12 represent data of the experimental measurements for all one-size fractions. The data represents a summary of the bulk volume parameters and the packing volume parameters obtained by wax coating as well as by the pouring method.

The packing volume of particle was determined by the aid of Equation (16), but with the use of the average particle weight as determined for 1000 particles.

Asphalt lost by absorption (B_{ag}) and asphalt lost by rugosity (B_{rw}) were determined by Equations (11) and (10), respectively.

The specific rugosity (S_{rv}) was calculated using Equation (9).

Figure 11 represents relationships between the packing volume of the particles and their sphericity as determined by the geometric analysis.

Relationships between the packing volume and asphalt lost by rugosity, as determined by the second method of wax coating, are given in Figure 12. The same measurements using the pouring test are shown in Figure 13. Figure 14 relates the packing volume to the packing specific gravity as determined by the pouring test. All above relationships represent the general picture for all types of aggregates and all sizes. A general rating of aggregates by means of average amount of asphalt lost by rugosity (for all sizes) is given in Figure 15.

Relationships between asphalt lost by rugosity and packing specific gravity as obtained by pouring for each fraction (size) are given in Figures 16 through 19. Similar presentation for specific rugosity vs. packing specific gravity are shown in Figures 20 through 23. The above relationships have been compared with the bulk volume parameters by the asphalt lost by absorption vs. the bulk specific gravity, as shown in Figures 24 through 27.

General Physical Trends

Based on the above data and analyses, the following general physical trends for all aggregates of all sizes can be observed:

(1) Gravels (and sands) from different sources have different characteristics.

(2) Particles tend to be more spherical with decreasing of their size (see Figure 11).

(3) The amount of asphalt lost by rugosity and the value of specific rugosity tends to decrease with particle size (both in wax and pouring tests, see Figures 12 and 13).

(4) The packing specific gravity tends to increase with particle size (wax and pouring) (see Figure 19 and Tables 9 through 12).

(5) No similar consistent trends have been observed for asphalt lost by absorption and bulk specific gravity.

(6) Based on pouring test results (which will be adopted as the basic test for packing volume parameters evaluation), blends

63-54, 81-21, and 2-34 possess the lowest amount of surface roughness and asphalt lost by rugosity while blends 49-16 and 48-6 possess the highest amount. Other blends fall between as shown by Figures 13 and 15 and Tables 9 through 12.

Testing Method Evaluation

Based on aggregate properties which have been measured by the different testing methods, the following has been found:

Between tests:

(1) There is no correlation between the packing specific gravities obtained by pouring and the bulk specific gravities for all sizes ($r < 0.50$ and $F < 4.75$).[12]

(2) There is no correlation between asphalt lost by rugosity (pouring) and asphalt lost by absorption for two sizes - 1/2 in.-5/8 in., #3-#4 ($r < 0.23$, $F < 4.75$) and poor correlation for sizes #8-#10, #20-#30 ($0.67 < r < 0.73$, $14.0 < F < 17.0$).

(3) There is no correlation between packing specific gravity (wax) and bulk specific gravity for size 1/2 in.-5/8 in. ($r = 0.30$, $F = 1.1$). Only poor correlation exists for sizes #3-#4 and #8-#10 ($0.64 < r < 0.74$, $13.0 < F < 14.0$).

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[12] Based on the physical nature of the phenomena, a linear regression has been fitted where r is the correlation coefficient. $F > 4.75$ represents a test statistic value required for accepting the hypothesis that a meaningful correlation exists.

(4) There is no correlation between asphalt lost by rugosity (wax) and asphalt lost by absorption for size 1/2 in.-5/8 in. ($r = 0.05$, $F = 0.04$). Only poor correlation exists for #3-#4 and #8-#10 ($0.55 < r < 0.82$, $5.0 < F < 29.0$).

(5) There is no correlation between packing specific gravity (pouring) and packing specific gravity (wax) for all sizes ($r < 0.40$, $F < 4.75$).

(6) There is no correlation between packing specific gravity (pouring) and packing specific gravity (geometric) for size 1/2 in.-5/8 in. ($r = 0.17$, $F = 0.37$). Only poor correlation exists for sizes #3-#4, #8-#10 ($0.68 < r < 0.71$, $10.0 < F < 13.0$).

Within tests:

(1) Only poor correlation exists between asphalt lost by absorption and bulk specific gravity ($-0.74 < r < -0.67$, $9.7 < F < 14.0$) for all sizes (see also Figures 24 through 27).

(2) Only poor correlation exists between asphalt lost by rugosity (wax) and packing specific gravity (wax) for all sizes ($-0.72 < r < -0.69$, $10.9 < F < 12.9$).

(3) A good correlation exists between asphalt lost by rugosity (pouring) and packing specific gravity (pouring) for size 1/2 in.-5/8 in. ($r = -0.85$, $F = 31.6$). Very good correlation exists for sizes #3-#4, #8-#10, and #20-#30 ($-0.986 < r < -0.958$, $135.4 < F < 420.9$) (see also Figures 16 through 19).

(4) A good correlation exists between specific rugosity (pouring) and packing specific gravity (pouring) for 1/2 in.-5/8 in. ($r = -0.85$, $F = 30.4$). Very good correlation exists for sizes #3-#4, #8-#10, #20-#30 ($-0.991 < r < -0.962$, $149.8 < F < 711.6$) (see also Figures 20 through 23).

It can be seen that poor correlations or none at all were found between different test methods for measuring similar physical quantities. Only one method—the pouring method for measuring the packing specific gravity of particles—was found to give good and very good correlations between the physical parameters which characterize the aggregate factors.

The wax coating method and the geometric method for measuring packing volume parameters were found to be quite tedious and very time consuming. These methods are applicable only for coarse particles. On the other hand, the pouring method was found to be simple, fast and reliable, and resulted in unique and repeatable measurements. Therefore, it was decided to adopt this method as the basic method for packing volume parameters measurement.

All further analyses in this report will be based on the packing volume as measured by the pouring test.

Specific Rugosity and Asphalt Lost by Rugosity

Figures 20 through 23 show the relationships between the specific rugosity (S_{rv}), a physical measurement which characterizes the surface roughness of particles, and packing specific gravity (G_p).

These relationships possess high degrees of correlation as obtained for each size ($-0.99 < r < -0.84$, $30.4 < F < 711.0$).

The correlation coefficient (r) is a numerical measure of how well data follows a given curve and it has meaning only if there is a sound basis for assuming that there is a relationship between two variables. In our case a physical relationship has been assumed and adopted by physical consideration prior to testing. Therefore, it can be concluded that the above results represent a unique physical characteristic for the surface roughness of the aggregate used. The above characteristic of the surface roughness is a property of the aggregate alone.

Based on regression analyses, unique equations can be obtained to describe the physical relationship between specific rugosity and the packing specific gravity for each individual size (see detailed equations in Figures 20 through 23).

Furthermore, a combined relationship for all four sizes has also been tried. It came out that the unique relationship for all sizes possesses a very high degree of correlation ($r = -0.925$, $F = 319.6$) and this can be considered as a general physical function to describe the aggregate factor (see Figure 28).

This combined relationship can be described in the following equation (for all aggregates tested):

$$S_{rv} = 92.88 - 33.504 G_p \tag{17}$$

This unique behavior can be explained physically: By looking at Equation (9), which represents the physical phenomena, it can be seen that two factors influence the specific rugosity (S_{rv}): (1) The specific gravity of the solid [which is approximated by the apparent specific gravity (G_{ap})], and (2) the packing specific gravity (G_p). Since all the above aggregates possess similar solid properties, G_{ap} varied only slightly, and most of the variability of the specific rugosity (S_{rv}) can be explained by the surface characteristics which is expressed by G_p. Statistically it can be said that about 85%[13] of the variability of S_{rv} can be explained by the variation in G_p.

Since the determination of G_p by the pouring test is so fast and simple, a prediction of specific rugosity can be made by a single and fast test in the pouring device, and without any other tests. It must be mentioned here that such predictions will only hold for aggregates which possess similar types of solids (Michigan-type gravel), since any careless extrapolation can lead to false conclusions. (Equations can be derived, however, to compensate for differences in apparent specific gravities.)

Similar considerations and conclusions are valid also for the amount of asphalt lost by rugosity (B_{rw}).

Unique relationships between B_{rw} and G_p also had a high degree of correlation for each size ($-0.99 < r < -0.85$, $31.6 < F < 420.9$). The combined relationship for all sizes is also highly correlated ($r = -0.959$, $F = 402.2$) (see Figure 29) and this represents a physical unique function for the loss of asphalt. This function is expressed in the following equation:

$$B_{rw} = 44.95 - 16.696\, G_p \qquad (18)$$

[13] $r^2 = 0.924^2 = 0.85$.

In comparison with the specific rugosity, the above relationships are only valid for the specific type of asphalt and mixing temperature total (asphalt cement 120-150 at 300°F) because different asphalt viscosities at mixing will generate different quantities of B_{rw}. Thus, the asphalt lost by rugosity is not a property of the aggregate alone but is a combined property of the mix.

Similar to the specific rugosity, the amount of asphalt lost inside the surface of the aggregate can be estimated (for the given type of asphalt) by a single determination of G_p in the pouring device.

The asphalt lost by rugosity, as defined here, is a property of the one-size fraction. If several fractions are combined into a graded blend, the total amount of asphalt lost by rugosity for the blend can be calculated as follows:

$$B_{rw}\,(\text{total}) = \frac{1}{100} \sum_{i=1}^{n} X_i \, B_{rwi} \qquad (19)$$

where

n = number of one-size fractions in the graded blend

X_i = percentage by weight of the i^{th} fraction in the blend

B_{rwi} = asphalt lost by rugosity of the i^{th} fraction.

By similar physical considerations, the total packing specific gravity of the graded blend can be found:

$$G_p\,(\text{total}) = \frac{100}{\sum_{i=1}^{n} \frac{X_i}{G_{pi}}} \qquad (20)$$

where

G_{pi} = packing specific gravity of the i^{th} fraction.

At this stage one might ask: "How can it be that a graded mixture possesses so much rugosity asphalt which is just a portion of the total asphalt content?" As seen in Figure 15, mix 48-6 possesses 7.6% rugosity asphalt (about 7.0% of total mix weight), while the same mix may require only 4.5% total asphalt content under a practical construction conditions.

To answer this question the phenomena of "fines lost by rugosity" must be introduced.

Similar to the asphalt, fine particles can be "trapped" inside the packing volume membrane of coarse particles; that is, fine particles can overlap the roughness of coarse ones. This phenomena has been discussed before in this report and was defined qualitatively as adhering fine particle coatings (see Figures 9 and 10).

When asphalt is present, the loss of fines will decrease the amount of the rugosity asphalt, since the fine particles occupy volume which was filled with asphalt when only one-size particles were involved.

By careful inspection it was found that fine particles can be lost in coarse ones if the ratio of their diameters is greater than five; that is, particles from #20-#30 fraction can already be partially lost in the cavities of #3-#4 size particle surfaces, etc.

It is suggested here to define the "fines lost by rugosity" (F_r) as the ratio between the packing volume of the fines which were lost and the packing volume of the coarse particles involved; that is:

$$F_r = \frac{V_{p\ fines}}{V_{p\ coarse}} 100 \qquad (21)$$

Since no fine particles will be able to penetrate into the surface pores any more than asphalt, it is natural to conclude that:

$$F_r < B_{rv} < S_{rv} \qquad (22)$$

where

B_{rv} = asphalt lost by rugosity (volume basis)

S_{rv} = specific rugosity.

Based on intuitive physical considerations, three major factors are assumed to influence the F_r in bituminous mixes:

(1) Surface roughness of particles.

(2) Amount of potential fines.

(3) The total asphalt content.

Since no previous theory on experimental data are available on this subject, a full-scale research program is needed for evaluation of the fines lost by rugosity in bituminous mixes.

The knowledge of the relationships between F_r and some of the aggregate and asphalt factors will enable the correction of the total asphalt lost by rugosity as expressed in Equation (19).

The corrected form of Equation (19) is as follows:

$$B_{rw}\ (\text{total}) = \frac{1}{100} \sum_{i=1}^{n} X_i \left(B_{rwi} - \frac{G_b}{G_{pi\ coarse}} F_{ri} \right) \qquad (23)$$

where

G_b = specific gravity of the asphalt

G_{pi} = packing specific gravity of the i^{th} fraction

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

B_{rw} and X_i are as defined by Equation (19).

An estimation of the total asphalt content of the mixture is now possible. The total asphalt content consists of the total asphalt lost by rugosity, as corrected for F_r (Equation (23)), plus the effective asphalt needed for the flow of the mixture. The effective asphalt content will be determined mainly by strength-flow consideration.

It is assumed here that this estimation will provide a good correlation with the optimum asphalt content needed for stable mixes under field and service conditions.

Aggregate Types and Sizes

As discussed before, the packing volume parameters, which were based on the pouring device measurements, provided unique and physical measurements to characterize the aggregate factors affecting bituminous mixes. These parameters were also found to provide a sensitive measurement for distinction and rating of aggregates from a similar origin. This sensitivity was not found by applying the presently used parameters and tests.

Figures 13, 14, and 15 represent a general picture for characterizing the different aggregates used.

Aggregates can be rated on the basis of their average surface characteristics for all sizes. From Figures 14 and 15 it can be seen that blends 63-54, 81-21, and 2-34 possess high packing specific gravities, and, therefore, have low surface roughness and low amounts of asphalt lost by rugosity. On the other hand, blends 48-6 and 49-16 possess a high degree of surface roughness and asphalt lost by rugosity.

A further and finer distinction can be made on the basis of the sizes considered (see Figures 13 and 14). Blend 2-34 possesses a fairly constant, low degree of roughness for all sizes, while blends 81-21 and 63-54 possess a low degree of roughness for the coarser sizes (#8-#10, #3-#4, and 1/2 in.-5/8 in.), but shift to a much higher degree of roughness for the finest fraction (#20-#30).

It must be noted that the variability of aggregate properties with fraction sizes is significant and must be considered in any future mix design. This variability may be explained by a different surface resistance to natural crushing and abrasion which characterized different sizes.

Based on the above variability a regional tendency may also be noted, since blends 81-21, 63-54, and 44-45 are from the same geographic region; the same can be said for blends 49-16 and 48-6 (see also Figure 4).

CONCLUSIONS

From literature study, laboratory work, and limited field data, the following conclusions are apparent:

(1) Although all 14 aggregates were natural gravels and sands from Michigan, measurements show that sizeable practical differences in required optimum asphalt content can be expected in the field when using natural aggregates from different pits;

(2) the main differences between the aggregates tested were found in the surface roughness (rugosity) of the particles. The present measurements show that aggregates 48-6 and 49-16 had the highest surface roughness in the series and aggregates 81-21 and 63-54 had the lowest. The highest rugosity (aggregate 48-6) was about 1.7 times higher than the lowest rugosity (aggregate 65-54);

(3) a simple and fast method has been evolved for measuring the rugosity of various aggregates. It is based on packing volume theory for irregular particles and is accomplished by pouring particles in calibrated containers and measuring their bulk volumes;

(4) in addition to rugosity, the amount of fine particle coatings affect mix properties;

(5) practical application of the results of this study can be made with a small amount of additional empirical testing. If the optimum asphalt content is established for the high and low rugosity mixes, and maybe one in between, optimum asphalt prediction for other aggregates with rugosities between the high and low could be predicted. A completely analytical method for design needs a measurement for fines lost by rugosity; and

(6) according to field observations, aggregate 81-21 should have low rugosity. This is shown in Figure 15.

SUGGESTIONS

It is suggested:

(1) To adopt the packing volume parameters as unique and physical measurements of the aggregate factors;

(2) to adopt the pouring test as the basic method for aggregate factors evaluation and as a simple, efficient, and reliable test for prediction of properties and quality control; and

(3) to dedicate future research for:

(a) evaluation of the physical factors which influence the fines lost by rugosity (F_r); and

(b) extension of the packing volume concept to graded aggregate systems and graded bituminous mixtures.

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TABLE 1

COEFFICIENT OF VARIATION FOR WEIGHTS IN ONE-SIZE FRACTION (#8-#10)

Aggregate Blend	Coefficient of Variation, percent
2-34	23.93
21-58	24.56
30-58	29.16
44-45	30.97
48- 6	30.86
49-16	29.95
59-65	31.69
62-54	27.16
63-54	19.05
65-46	24.50
71- 6	27.73
79-77	22.63
80-45	29.33
81-21	23.98
Average	26.68

TABLE 2

PROPERTIES OF ASPHALT USED

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

REPORT OF TEST

Project General

Laboratory No. 70B-3031

Date August 19, 1970

Report on sample of ASPHALT CEMENT

Date sampled August 6, 1970 Date received August 7, 1970

Source of material Leonard Refineries, Incorporated, Alma, Michigan

Sampled from Not stated Quantity represented 10 gallons

Submitted by P.J. Serafin, Testing Laboratory Section

Intended use U of M Research Project Specification 120-150, 1970 Std Specs

TEST RESULTS

Laboratory Number				
Specific Gravity @ 25/25 C	1.022			
Penetration @ 25 C, 100 g, 5 sec, dmm	133			
Penetration @ 46.1 C, 50 g, 5 sec, dmm				
Penetration @ 0 C, 200 g, 1 min, dmm				
Flash Point, Cleveland Open Cup, C	288			
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	99.88			
Oliensis Spot Test	Neg.			
THIN FILM OVEN TEST, 1/8 inch, 163 C, 5 hr				
Loss on Heating, per cent by weight	0.20			
Penetration of Residue, per cent of original	60			
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, 135C c.s.	291			
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 3

BULK SPECIFIC GRAVITY AND WATER ABSORPTION
FOR GRADED AGGREGATE BLENDS

Aggregate Blend	Coarse Fractions		Fine Fractions	
	Bulk Specific Gravity	Percent Water Absorption	Bulk Specific Gravity	Percent Water Absorption
2-34	2.575	1.95	2.600	1.50
21-58	2.621	1.99	2.583	1.90
30-58	2.646	1.67	2.547	2.33
44-45	2.603	1.90	2.531	2.50
48- 6	2.615	2.15	2.588	1.67
49-16	2.653	1.91	2.614	1.63
59-65	2.566	2.19	2.567	1.54
62-54	2.613	2.33	2.572	1.81
63- 7	2.659	1.33	2.571	1.87
63-54	2.640	1.44	2.610	1.13
65-46	2.643	1.50	2.615	1.61
71- 6	2.620	1.68	2.588	1.69
79-77	2.550	2.35	2.562	1.73
80-45	2.587	2.67	2.547	1.85
81-21	2.591	1.87	2.555	2.04

TABLE 4

MARSHALL DATA FOR BITUMINOUS MIXTURES USING AGGREGATES 81-21, 63-7, AND 2-34

Mixture →	81-21			63-7			2-34		
Percent Asphalt Content →	4.5		5.5	4.5		5.5	4.5		5.5
	Unwashed	Washed	Unwashed	Unwashed	Washed	Unwashed	Unwashed	Washed	Unwashed
Sp. gravity	2.453	2.424	2.413	2.470	2.427	2.453	2.450	2.441	2.430
Stability—lb	1801	1705	902	2303	1830	1322	1828	2095	1171
Flow—1/100 in.	16	11	34	12	8	22	12	11	14
Percent air voids	0.82	2.02	0.93	1.37	3.25	0.68	1.66	3.26	0.70
Percent VMA	9.70	10.95	12.20	10.50	12.20	12.20	10.10	11.71	11.80
Percent voids filled	91.40	81.61	92.40	87.10	73.01	94.60	83.90	72.21	94.10

TABLE 5

GEOMETRIC ANALYSIS OF 1/2 in.-5/8 in. FRACTIONS

Aggregate Blend	ℓ, cm	m, cm	s, cm	m/ℓ	s/ℓ	s/m	Equivalent Sphere Diameter, cm (d)	Sphericity (ψ)	Surface Area, cm^2 (A)	Specific Surface Area, cm^2/gr (U)	Packing Volume, cm^3 (V_p)	Packing Specific Gravity (G_p)
2-34	2.16	1.51	0.99	0.70	0.46	0.65	1.478	0.68	7.4195	1.710	1.69048	2.566
21-58	2.26	1.56	0.96	0.69	0.43	0.62	1.503	0.67	7.7766	1.819	1.77718	2.406
30-58	2.11	1.47	1.00	0.70	0.47	0.68	1.458	0.69	7.1726	1.859	1.62411	2.375
44-45	2.15	1.54	1.06	0.72	0.49	0.69	1.523	0.71	7.7639	1.813	1.85010	2.315
48- 6	2.19	1.56	1.02	0.71	0.47	0.65	1.515	0.69	7.7687	1.850	1.82093	2.306
49-16	2.13	1.53	1.08	0.72	0.51	0.71	1.523	0.72	7.7240	1.861	1.85019	2.243
59-65	2.21	1.54	1.03	0.70	0.47	0.67	1.516	0.69	7.7782	1.809	1.82563	2.355
62-54	2.22	1.52	1.00	0.68	0.45	0.66	1.502	0.68	7.6750	1.791	1.77453	2.415
63-54	2.13	1.53	0.99	0.72	0.46	0.65	1.478	0.69	7.4059	1.843	1.69107	2.376
65-46	2.17	1.51	1.03	0.70	0.47	0.68	1.498	0.69	7.5599	1.758	1.75875	2.446
71- 6	2.01	1.44	1.03	0.72	0.51	0.71	1.439	0.72	6.8923	1.754	1.56119	2.517
79-77	2.12	1.56	1.03	0.74	0.49	0.66	1.502	0.71	7.5881	1.816	1.77592	2.352
80-45	2.17	1.56	1.01	0.72	0.47	0.65	1.506	0.69	7.6878	1.846	1.78991	2.326
81-21	2.03	1.46	1.11	0.72	0.55	0.76	1.491	0.73	7.3152	1.707	1.73535	2.469
Average	2.15	1.52	1.02	0.71	0.48	0.67	1.495	0.69	7.6091	1.803	1.75181	2.390

TABLE 6

GEOMETRIC ANALYSIS OF #3-#4 FRACTIONS

Aggregate Blend	ℓ, cm	m, cm	s, cm	m/ℓ	s/ℓ	s/m	Equivalent Sphere Diameter, cm (d)	Sphericity (ψ)	Surface Area, cm^2 (A)	Specific Surface Area, cm^2/gr (U)	Packing Volume, cm^3 (V_p)	Packing Specific Gravity (G_p)
2-34	0.84	0.59	0.43	0.71	0.51	0.73	0.599	0.71	1.1920	4.506	0.11254	2.351
21-58	0.89	0.61	0.39	0.69	0.44	0.64	0.600	0.67	1.2312	4.563	0.11333	2.361
30-58	0.92	0.61	0.37	0.66	0.41	0.61	0.591	0.65	1.2141	4.812	0.10801	2.336
44-45	0.83	0.60	0.39	0.72	0.47	0.65	0.578	0.70	1.1302	4.687	0.10114	2.384
48- 6	1.01	0.59	0.38	0.58	0.37	0.63	0.608	0.60	1.3080	5.026	0.11787	2.208
49-16	0.95	0.58	0.37	0.61	0.39	0.65	0.589	0.62	1.2108	4.937	0.10712	2.290
59-65	0.86	0.59	0.38	0.69	0.45	0.66	0.578	0.68	1.1387	4.546	0.10129	2.473
62-54	0.87	0.62	0.40	0.71	0.46	0.65	0.599	0.69	1.2196	4.599	0.11279	2.351
63-54	0.86	0.61	0.41	0.71	0.47	0.67	0.601	0.70	1.2173	4.239	0.11353	2.529
65-46	0.93	0.60	0.35	0.65	0.38	0.59	0.584	0.63	1.2021	4.986	0.10435	2.311
71- 6	0.88	0.59	0.38	0.67	0.44	0.66	0.582	0.67	1.1584	4.900	0.10336	2.287
79-77	0.87	0.57	0.40	0.66	0.47	0.71	0.587	0.67	1.1639	4.450	0.10590	2.470
80-45	0.86	0.60	0.40	0.71	0.47	0.66	0.591	0.69	1.1826	4.555	0.10819	2.400
81-21	0.86	0.58	0.39	0.68	0.46	0.68	0.580	0.68	1.1400	4.465	0.10225	2.497
Average	0.89	0.60	0.39	0.67	0.44	0.66	0.590	0.67	1.1935	4.662	0.10798	2.376

TABLE 7

GEOMETRIC ANALYSIS OF #8-#10 FRACTIONS

Aggregate Blend	ℓ, cm	m, cm	s, cm	m/ℓ	s/ℓ	s/m	Equivalent Sphere Diameter, cm (d)	Sphericity (ψ)	Surface Area, cm^2 (A)	Specific Surface Area, cm^2/gr (U)	Packing Volume, cm^3 (V_p)	Packing Specific Gravity (G_p)
2-34	0.34	0.25	0.18	0.74	0.53	0.71	0.248	0.73	0.2045	10.972	0.00803	2.321
21-58	0.36	0.26	0.18	0.71	0.50	0.71	0.256	0.71	0.2194	11.234	0.00883	2.211
30-58	0.35	0.25	0.16	0.71	0.47	0.66	0.242	0.69	0.1980	11.870	0.00742	2.247
44-45	0.34	0.25	0.17	0.75	0.50	0.67	0.244	0.72	0.1995	12.559	0.00763	2.081
48- 6	0.40	0.27	0.15	0.69	0.38	0.56	0.253	0.64	0.2270	13.776	0.00852	1.935
49-16	0.41	0.26	0.17	0.64	0.41	0.64	0.260	0.64	0.2338	11.876	0.00918	2.146
59-65	0.35	0.26	0.17	0.75	0.51	0.68	0.250	0.72	0.2086	11.425	0.00818	2.232
62-54	0.36	0.26	0.18	0.73	0.49	0.68	0.256	0.71	0.2196	12.040	0.00879	2.075
63-54	0.35	0.25	0.17	0.73	0.50	0.69	0.248	0.72	0.2062	11.061	0.00803	2.322
65-46	0.36	0.26	0.16	0.72	0.45	0.63	0.247	0.69	0.2074	11.990	0.00786	2.202
71- 6	0.35	0.26	0.16	0.74	0.45	0.61	0.242	0.70	0.1999	11.807	0.00741	2.285
79-77	0.36	0.26	0.17	0.72	0.47	0.65	0.254	0.70	0.2179	12.660	0.00856	2.010
80-45	0.34	0.26	0.17	0.74	0.48	0.65	0.245	0.71	0.2024	11.678	0.00771	2.249
81-21	0.33	0.25	0.16	0.75	0.49	0.66	0.239	0.72	0.1922	11.259	0.00719	2.376
Average	0.36	0.26	0.17	0.72	0.47	0.66	0.249	0.70	0.2097	11.872	0.00810	2.192

TABLE 8

GEOMETRIC ANALYSIS OF #20-#30 FRACTIONS

Aggregate Blend	ℓ, cm	m, cm	s, cm	m/ℓ	s/ℓ	s/m	Equivalent Sphere Diameter, cm (d)	Sphericity (ψ)	Surface Area, cm^2 (A)	Specific Surface Area, cm^2/gr (U)	Packing Volume, cm^3 (V_p)	Packing Specific Gravity (G_p)
2-34	0.10	0.08	0.07	0.81	0.64	0.80	0.084	0.80	0.0226	37.342	0.00031	1.971
21-58	0.11	0.09	0.06	0.75	0.54	0.72	0.085	0.74	0.0237	37.025	0.00032	2.008
30-58	0.10	0.08	0.06	0.79	0.62	0.78	0.079	0.79	0.0201	39.680	0.00026	1.977
44-45	0.10	0.08	0.07	0.79	0.64	0.82	0.083	0.80	0.0222	39.835	0.00030	1.862
48- 6	0.10	0.08	0.06	0.75	0.57	0.76	0.079	0.75	0.0205	37.357	0.00026	2.111
49-16	0.10	0.08	0.06	0.80	0.57	0.72	0.079	0.77	0.0206	35.994	0.00026	2.192
59-65	0.10	0.08	0.07	0.80	0.68	0.85	0.083	0.82	0.0219	37.909	0.00030	1.952
62-54	0.10	0.08	0.06	0.82	0.66	0.80	0.080	0.81	0.0208	36.875	0.00027	2.070
63-54	0.11	0.08	0.06	0.74	0.58	0.78	0.082	0.75	0.0221	37.373	0.00029	2.029
65-46	0.10	0.08	0.06	0.82	0.63	0.78	0.079	0.80	0.0200	34.683	0.00025	2.263
71- 6	0.10	0.08	0.06	0.80	0.62	0.78	0.080	0.79	0.0208	36.884	0.00027	2.090
79-77	0.11	0.08	0.06	0.77	0.54	0.70	0.079	0.75	0.0207	35.089	0.00026	2.274
80-45	0.11	0.08	0.06	0.79	0.60	0.76	0.083	0.78	0.0223	37.475	0.00030	1.997
81-21	0.10	0.08	0.06	0.78	0.60	0.77	0.079	0.78	0.0201	35.386	0.00025	2.229
Average	0.10	0.08	0.06	0.78	0.61	0.77	0.081	0.78	0.0213	37.065	0.00028	2.073

TABLE 9

EXPERIMENTAL MEASUREMENTS OF 1/2 in.-5/8 in. FRACTIONS

				Wax Coating Method				Pouring Method				
Aggregate Blend	Bulk Specific Gravity (G_{bl})	Percent Water Absorption	Percent Asphalt Lost by Absorption (B_{ag})	Packing Specific Gravity (G_p)	Packing Volume, cm^3 (V_p)	Percent Asphalt Lost by Rugosity (B_{rw})	Percent Specific Rugosity (S_{rv})	Packing Specific Gravity (G_p)	Packing Volume, cm^3 (V_p)	Percent Asphalt Lost by Rugosity (B_{rw})	Percent Specific Rugosity (S_{rv})	Average Particle Weight, gr
2-34	2.570	2.10	1.71	2.435	1.89025	3.91	10.37	2.377	1.93637	4.94	12.50	4.60276
21-58	2.623	1.98	1.63	2.534	1.74072	3.00	8.41	2.341	1.88423	6.32	15.39	4.41099
30-58	2.669	1.32	0.99	2.478	1.74598	3.94	10.43	2.421	1.78708	4.92	12.49	4.32653
44-45	2.602	1.94	1.66	2.544	1.72262	2.56	7.16	2.391	1.83285	5.13	12.75	4.38235
48-6	2.652	1.72	1.00	2.486	1.66629	3.58	10.54	2.339	1.77101	6.16	15.83	4.14238
49-16	2.673	1.69	1.42	2.483	1.74661	4.35	11.30	2.384	1.81914	6.05	14.84	4.33684
59-65	2.574	1.97	1.67	2.471	1.84728	3.32	8.87	2.359	1.93499	5.28	13.00	4.56464
62-54	2.630	2.02	1.55	2.461	1.82711	4.21	11.40	2.340	1.92159	6.36	15.75	4.49653
63-54	2.637	1.42	0.98	2.510	1.58118	2.94	8.38	2.440	1.62655	4.11	10.94	3.96877
65-46	2.662	1.27	0.80	2.492	1.76335	3.42	9.55	2.390	1.83860	5.17	13.25	4.39426
71-6	2.640	1.27	0.90	2.509	1.60909	2.92	8.15	2.390	1.68921	4.95	12.50	4.03722
79-77	2.552	2.27	1.65	2.445	1.73900	3.40	9.74	2.313	1.83824	5.79	14.62	4.25185
80-45	2.606	2.33	1.84	2.488	1.71535	3.70	10.33	2.392	1.78420	5.35	13.79	4.26780
81-21	2.589	1.77	1.52	2.514	1.74971	2.69	7.35	2.440	1.80278	3.93	10.07	4.39877
Average	2.620	1.79	1.38	2.489	1.73889	3.42	9.43	2.380	1.81906	5.32	13.41	4.32726

TABLE 10

EXPERIMENTAL MEASUREMENTS OF #3-#4 FRACTIONS

Aggregate Blend	Bulk Specific Gravity (G_{bl})	Percent Water Absorption	Percent Asphalt Lost by Absorption (B_{ag})	Wax Coating Method				Pouring Method				Average Particle Weight, gr
				Packing Specific Gravity (G_p)	Packing Volume, cm^3 (V_p)	Percent Asphalt Lost by Rugosity (B_{rw})	Percent Specific Rugosity (S_{rv})	Packing Specific Gravity (G_p)	Packing Volume, cm^3 (V_p)	Percent Asphalt Lost by Rugosity (B_{rw})	Percent Specific Rugosity (S_{rv})	
2-34	2.580	2.20	1.89	2.459	0.10841	3.84	10.10	2.423	0.11002	4.46	11.42	0.26658
21-58	2.573	2.68	2.11	2.452	0.11157	4.07	11.27	2.388	0.11456	5.19	13.59	0.27356
30-58	2.608	2.12	1.69	2.475	0.10495	3.80	10.35	2.340	0.11101	6.18	15.24	0.25976
44-45	2.578	2.22	1.95	2.459	0.10852	3.87	10.07	2.434	0.10963	4.30	10.99	0.26685
48-6	2.606	2.30	1.98	2.421	0.10360	4.98	12.67	2.240	0.11197	8.39	19.20	0.25082
49-16	2.612	2.62	2.26	2.489	0.10791	4.20	11.23	2.324	0.11557	7.11	17.11	0.26859
59-65	2.523	2.83	2.36	2.401	0.10841	4.42	11.63	2.384	0.10918	4.73	12.26	0.26029
62-54	2.577	2.67	2.53	2.413	0.10983	5.23	12.81	2.404	0.11025	5.38	13.13	0.26503
63-54	2.623	1.59	1.69	2.469	0.10983	4.12	9.80	2.476	0.10952	4.01	9.54	0.27116
65-46	2.597	1.97	1.71	2.478	0.10806	3.60	9.46	2.352	0.11385	5.80	14.07	0.26777
71-6	2.584	2.07	1.81	2.449	0.10551	3.99	10.29	2.349	0.11000	5.77	13.96	0.25839
79-77	2.524	2.78	2.45	2.405	0.10395	4.45	11.40	2.316	0.10794	6.09	14.68	0.25000
80-45	2.544	3.12	2.84	2.461	0.11133	4.20	10.94	2.403	0.11402	5.20	13.04	0.27399
81-21	2.570	2.06	1.91	2.461	0.11002	3.67	9.31	2.465	0.10984	3.60	9.16	0.27075
Average	2.578	2.37	2.08	2.449	0.10799	4.17	10.81	2.378	0.11124	5.44	13.38	0.26454

TABLE 11

EXPERIMENTAL MEASUREMENTS OF #8-#10 FRACTIONS

				Wax Coating Method				Pouring Method				
Aggregate Blend	Bulk Specific Gravity (G_{bl})	Percent Water Absorption	Percent Asphalt Lost by Absorption (B_{ag})	Packing Specific Gravity (G_p)	Packing Volume, cm^3 (V_p)	Percent Asphalt Lost by Rugosity (B_{rw})	Percent Specific Rugosity (S_{rv})	Packing Specific Gravity (G_p)	Packing Volume, cm^3 (V_p)	Percent Asphalt Lost by Rugosity (B_{rw})	Percent Specific Rugosity (S_{rv})	Average Particle Weight, gr
2-34	2.573	2.52	1.70	2.415	0.00736	4.30	12.23	2.378	0.00747	4.96	13.57	0.01777
21-58	2.560	2.80	1.98	2.410	0.00744	4.47	12.61	2.320	0.00773	6.11	15.87	0.01793
30-58	2.555	3.00	2.33	2.392	0.00685	5.06	13.56	2.277	0.00719	7.21	17.71	0.01638
44-45	2.573	2.52	1.92	2.410	0.00690	4.61	12.41	2.401	0.00693	4.77	12.74	0.01664
48-6	2.570	2.90	2.28	2.404	0.00717	5.03	13.43	2.195	0.00786	9.08	20.96	0.01725
49-16	2.582	2.90	2.56	2.392	0.00764	5.70	14.30	2.228	0.00820	8.84	20.17	0.01828
59-65	2.531	3.00	2.28	2.381	0.00733	4.83	13.07	2.352	0.00742	5.36	14.13	0.01745
62-54	2.565	3.09	2.27	2.381	0.00752	5.35	14.53	2.318	0.00772	6.52	16.79	0.01790
63-54	2.614	1.66	1.07	2.401	0.00784	4.54	12.13	2.483	0.00758	3.14	9.13	0.01882
65-46	2.601	2.14	1.43	2.410	0.00735	4.54	12.50	2.299	0.00771	6.59	16.53	0.01772
71-6	2.587	2.23	1.58	2.404	0.00722	4.59	12.43	2.348	0.00740	5.60	14.47	0.01737
79-77	2.512	3.29	2.47	2.350	0.00744	5.27	14.18	2.254	0.00775	7.12	17.69	0.01747
80-45	2.555	3.00	2.24	2.381	0.00730	5.16	13.95	2.307	0.00753	6.54	16.63	0.01738
81-21	2.577	2.14	1.45	2.410	0.00753	4.20	11.64	2.428	0.00748	3.89	10.98	0.01815
Average	2.568	2.66	1.97	2.396	0.00735	4.83	13.07	2.328	0.00757	6.12	15.53	0.01761

TABLE 12

EXPERIMENTAL MEASUREMENTS OF #20-#30 FRACTIONS

Aggregate Blend	Bulk Specific Gravity (G_{bl})	Percent Water Absorption	Percent Asphalt Lost by Absorption (B_{ag})	Pouring Method: Packing Specific Gravity (G_p)	Pouring Method: Packing Volume, cm^3 (V_p)	Pouring Method: Percent Asphalt Lost by Rugosity (B_{rw})	Pouring Method: Percent Specific Rugosity (S_{rv})	Average Particle Weight, gr
2-34	2.630	0.52	-.09	2.336	0.00026	4.80	12.39	0.00060
21-58	2.634	0.88	0.50	2.242	0.00029	7.28	16.86	0.00064
30-58	2.604	1.53	1.33	2.190	0.00023	8.75	19.25	0.00051
44-45	2.608	1.40	1.19	2.260	0.00025	7.22	16.51	0.00056
48- 6	2.617	1.03	0.58	2.246	0.00024	7.03	16.49	0.00055
49-16	2.615	1.11	0.84	2.232	0.00026	7.55	17.12	0.00057
59-65	2.597	1.10	0.92	2.275	0.00025	6.49	14.90	0.00058
62-54	2.603	0.88	0.85	2.282	0.00025	6.38	14.34	0.00056
63-54	2.626	1.18	0.71	2.276	0.00026	6.69	16.01	0.00059
65-46	2.603	1.09	0.79	2.261	0.00025	6.73	15.60	0.00058
71- 6	2.631	0.97	0.57	2.297	0.00025	6.22	14.92	0.00056
79-77	2.589	1.64	1.01	2.195	0.00027	8.10	18.82	0.00059
80-45	2.608	1.39	1.12	2.282	0.00026	6.72	15.67	0.00060
81-21	2.609	1.34	1.05	2.264	0.00025	7.02	16.26	0.00057
Average	2.612	1.15	0.82	2.260	0.00025	6.93	16.08	0.00058

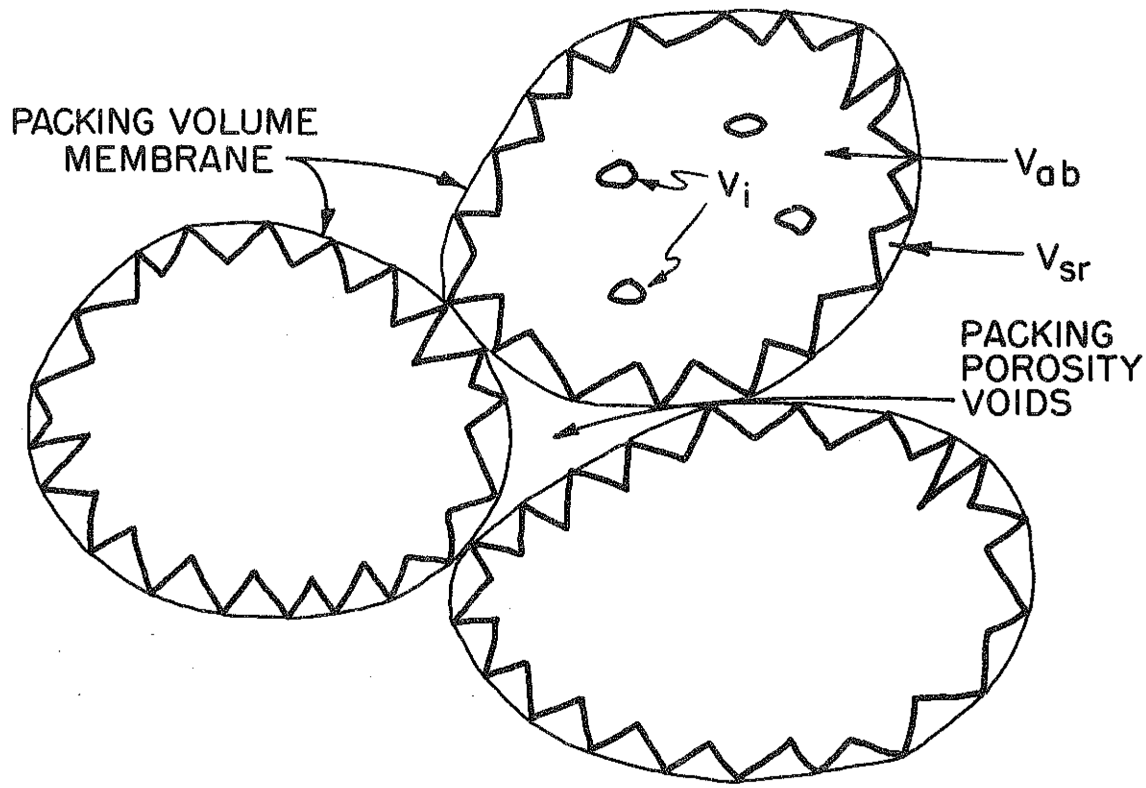


Figure 1. Packing volume definition for irregular particles.

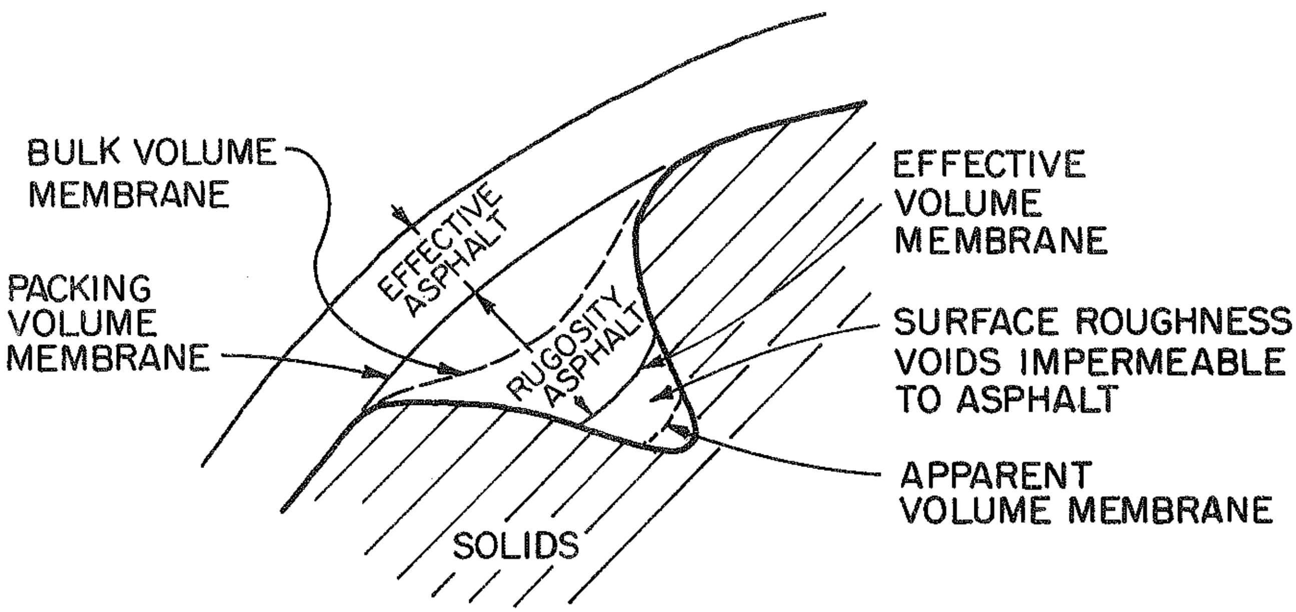


Figure 2. Rugosity asphalt in a surface pore.

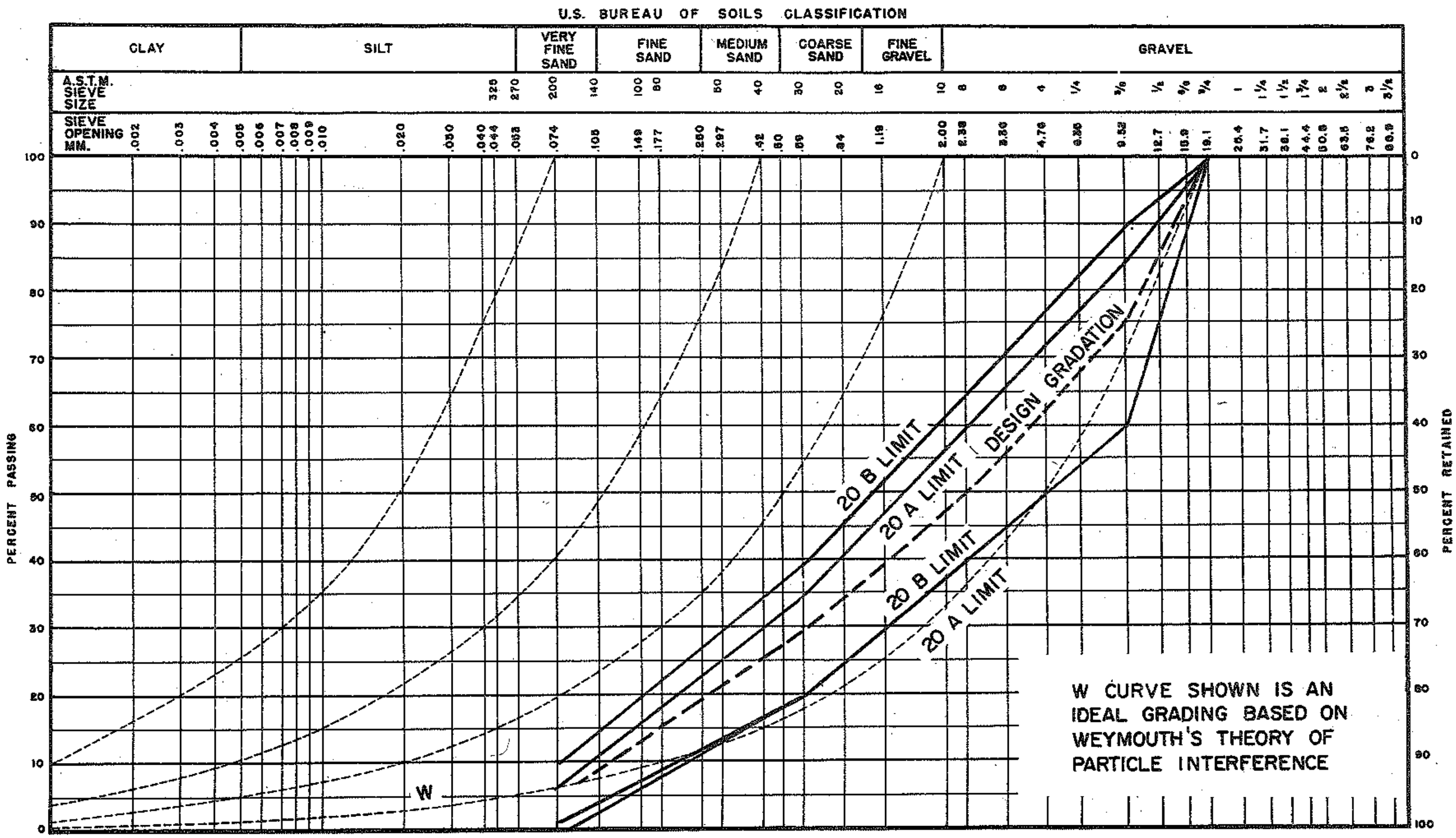


Figure 3. Average design gradation and specification limits for gravel type 20A and 20B.

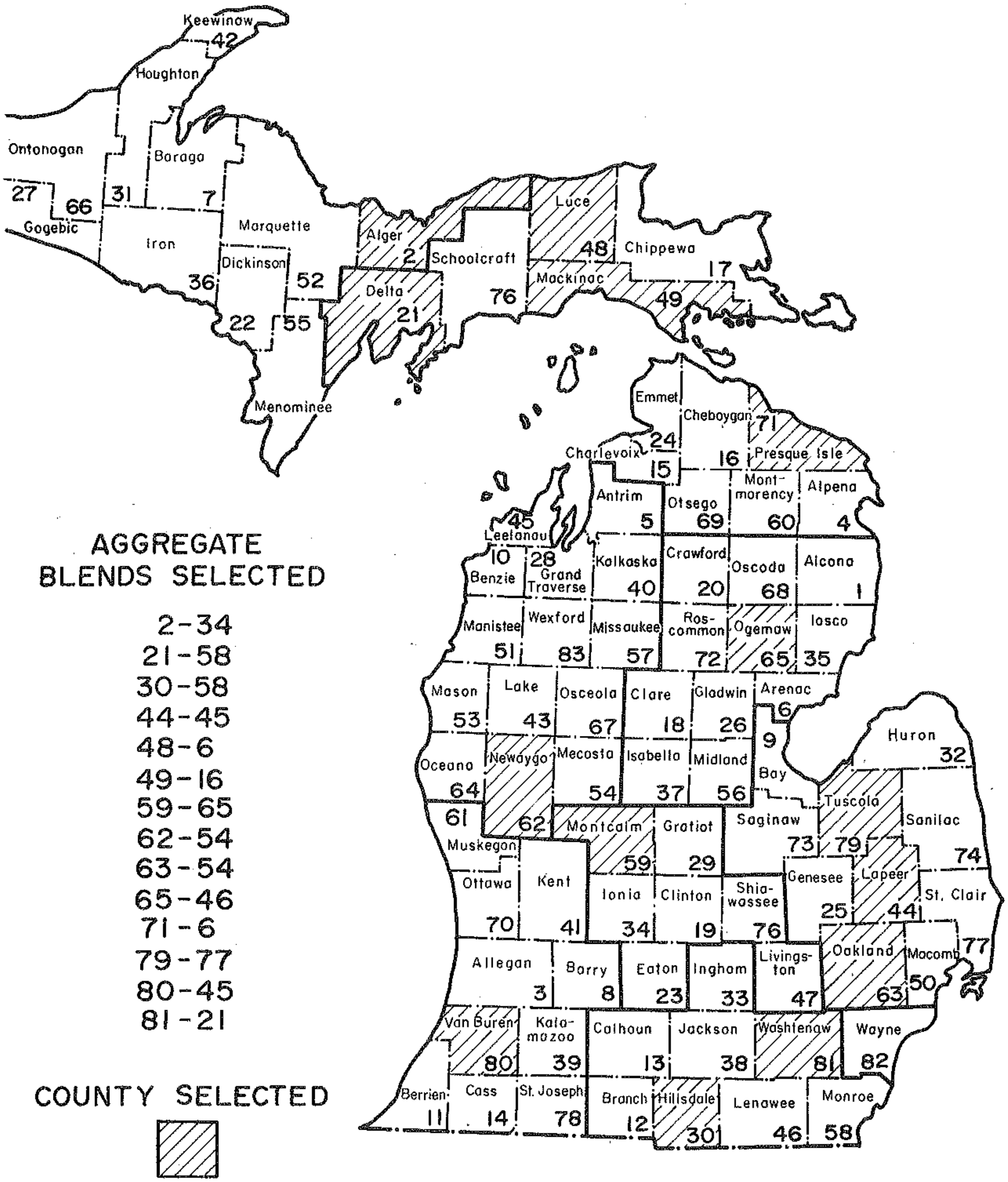


Figure 4. Geographic distribution of counties selected.

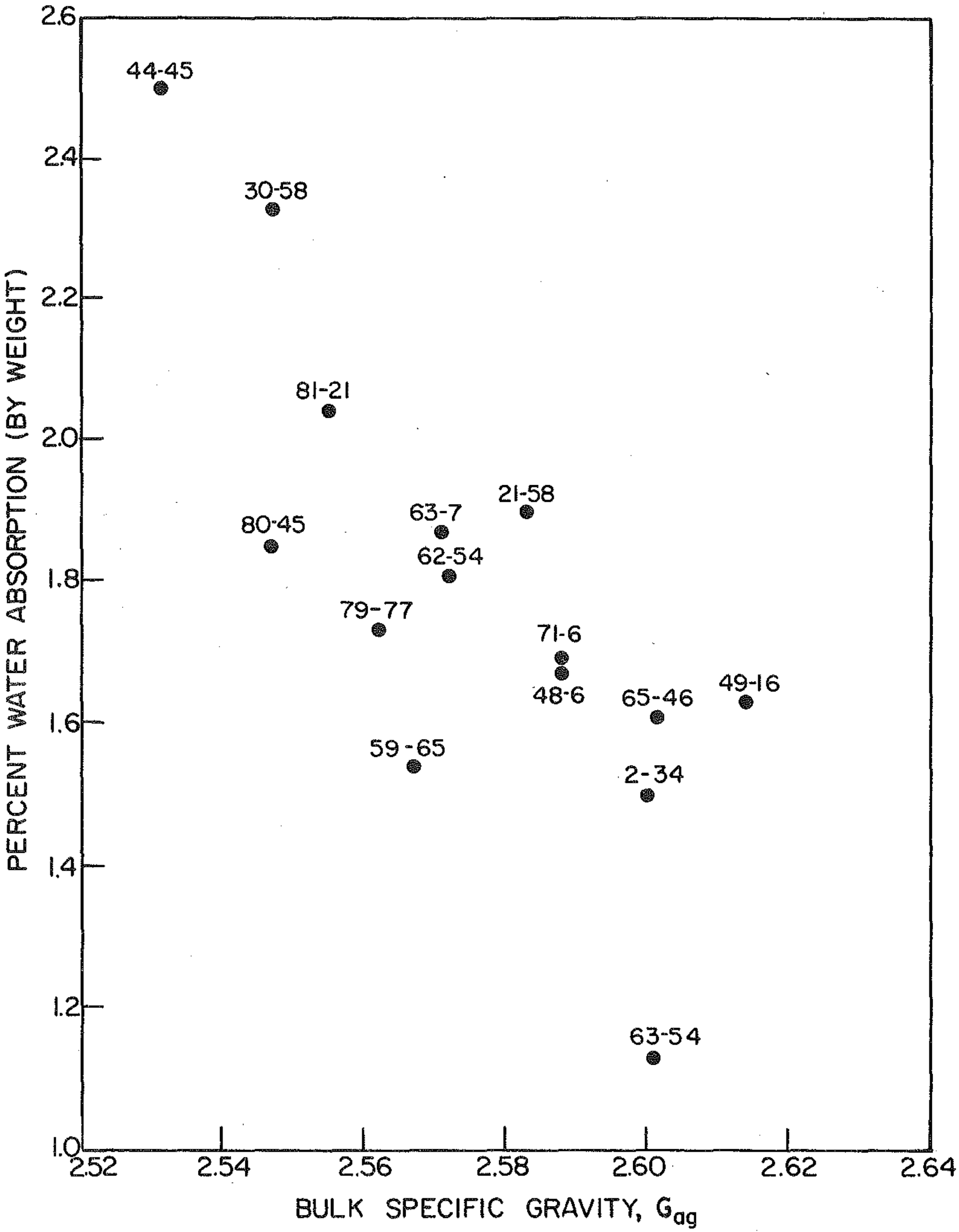


Figure 5. Relationship between water absorption and bulk specific gravity for graded aggregate blends (fines: -#4).

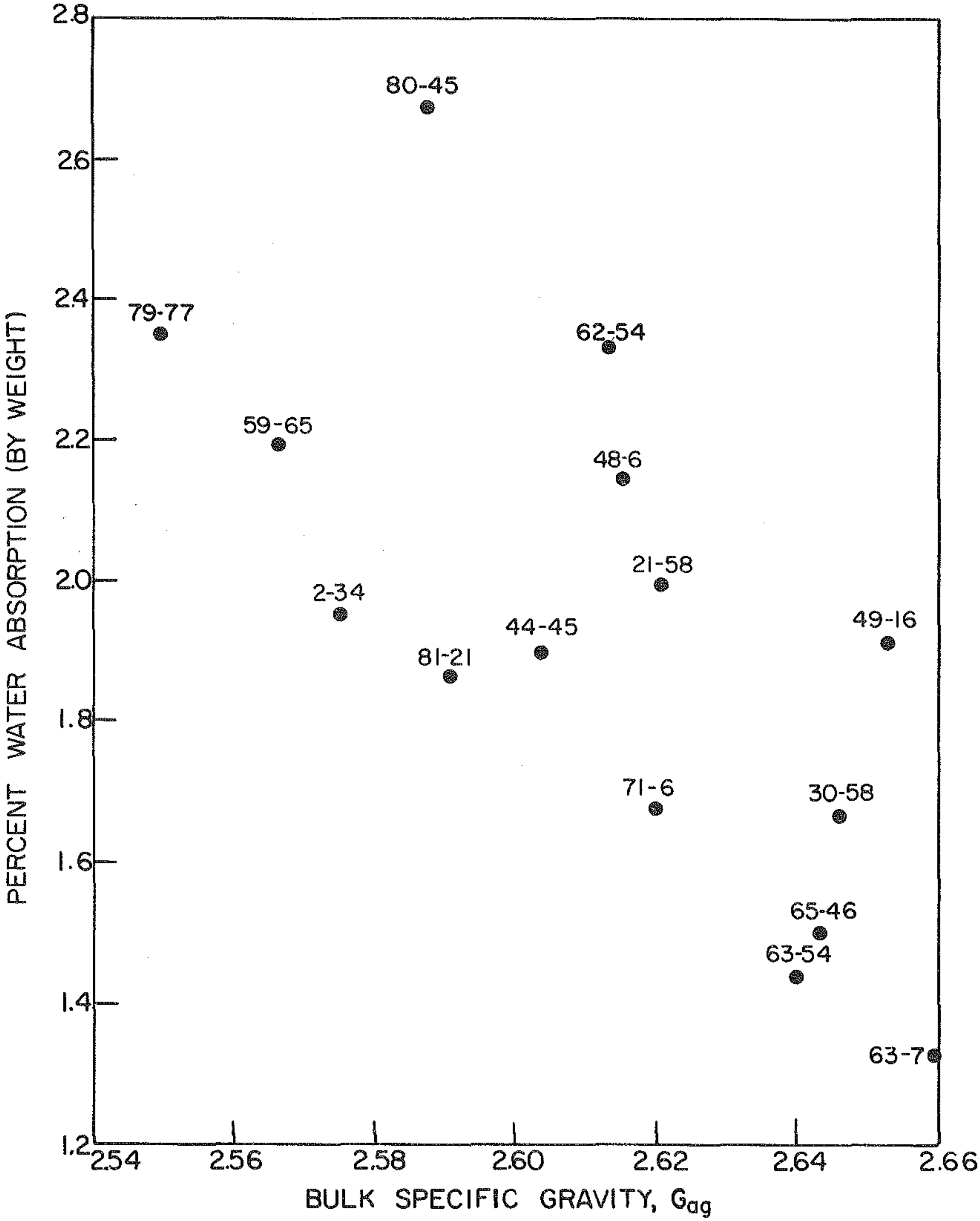


Figure 6. Relationship between water absorption and bulk specific gravity for graded aggregate blends (coarse: #4-3/4 in.).

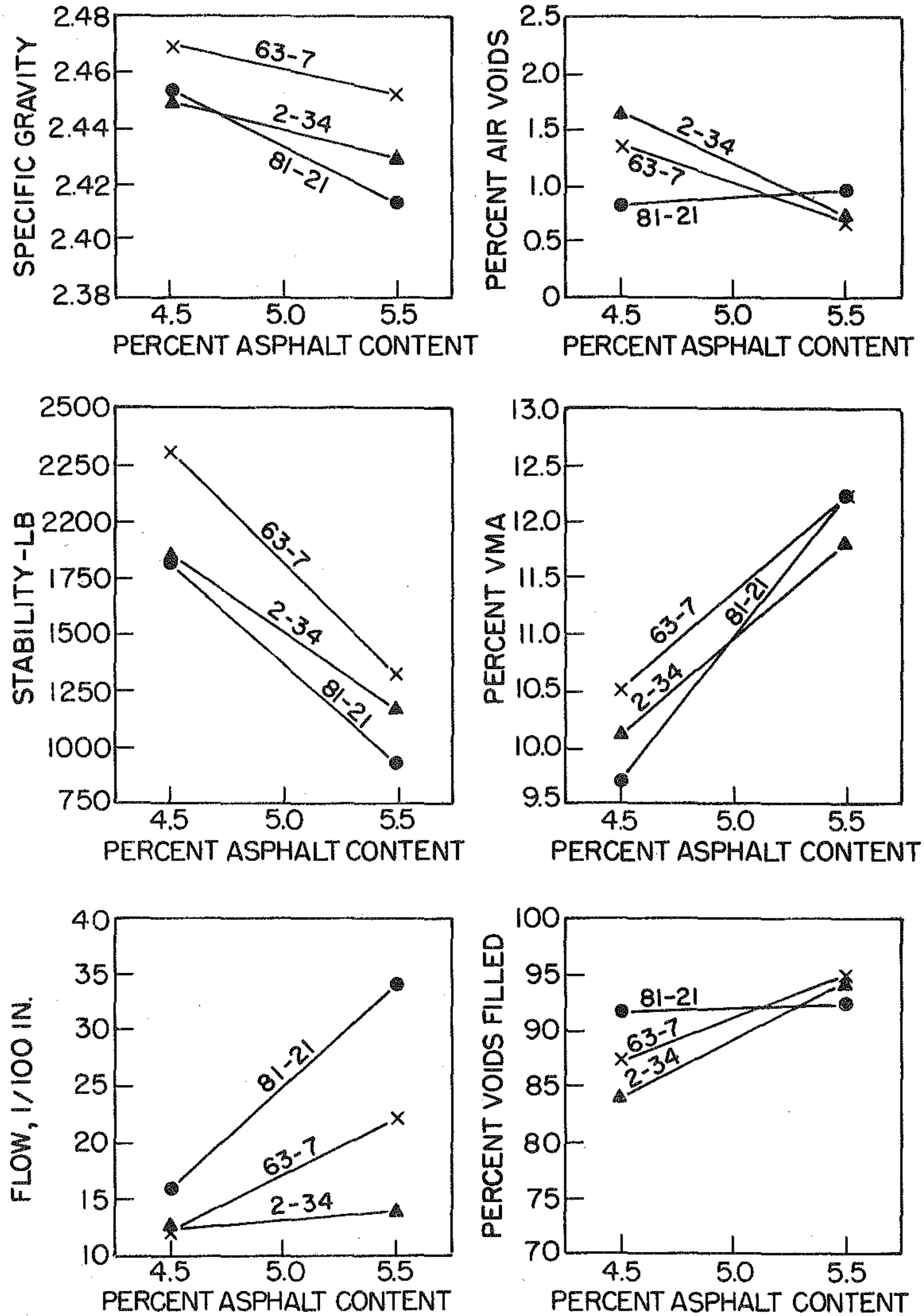


Figure 7. Marshall data for mixtures 81-21, 63-7, and 2-34 (unwashed).

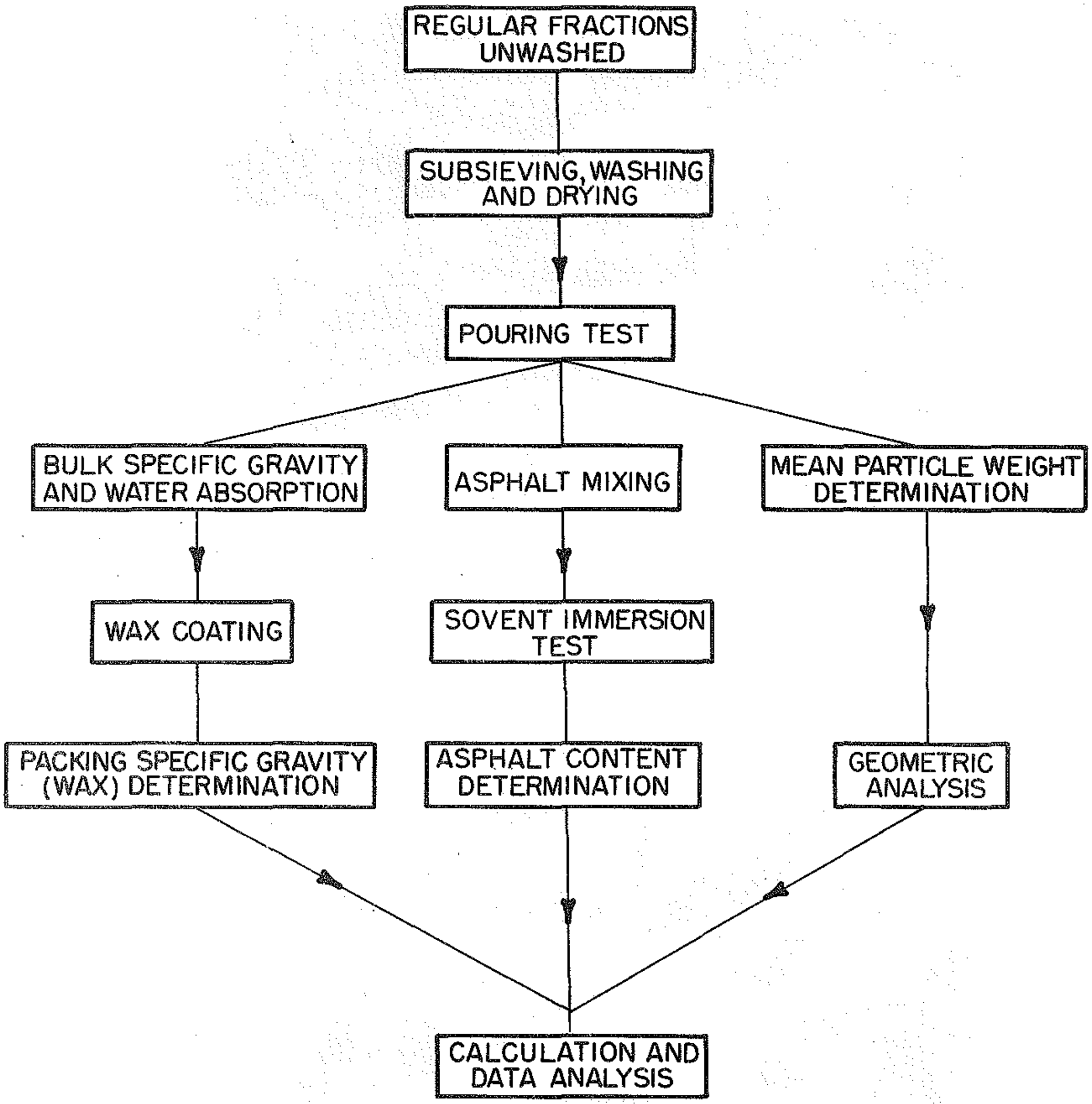
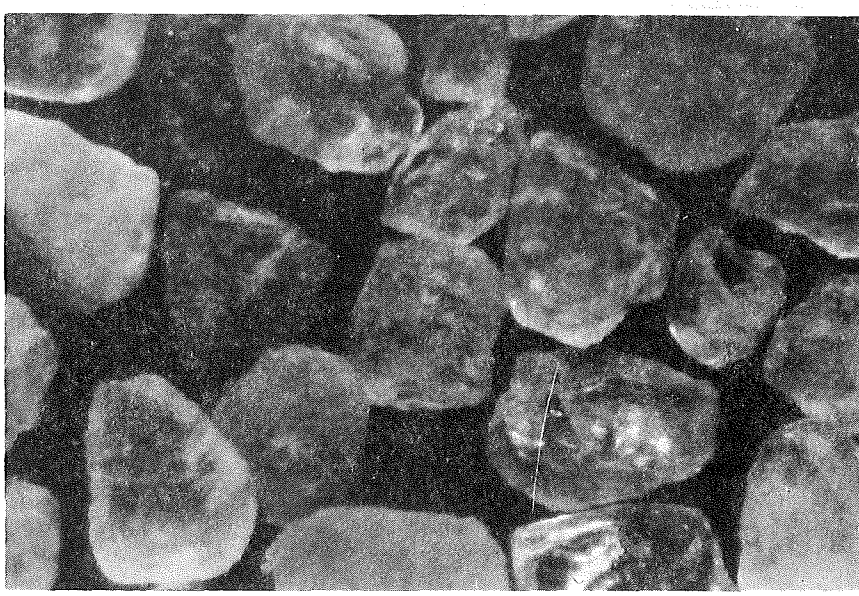


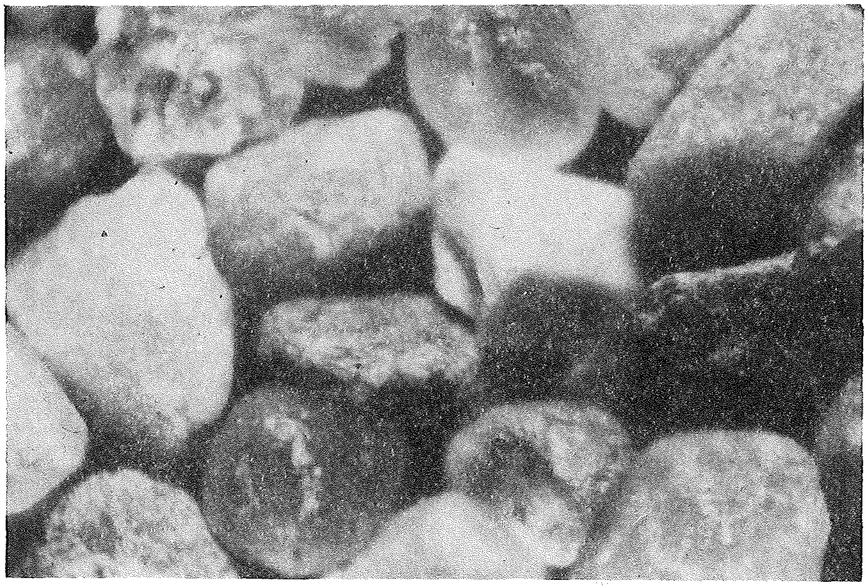
Figure 8. Method and order of testing program for each size of fractions. Flow chart.

Natural



Washed

Figure 9. Adhering fines to sand particles (#50-#100), aggregate 81-21.



81-21

2-34

Figure 10. Sand particles after washing, sieves #20-#30, aggregates 81-21 and 2-34.

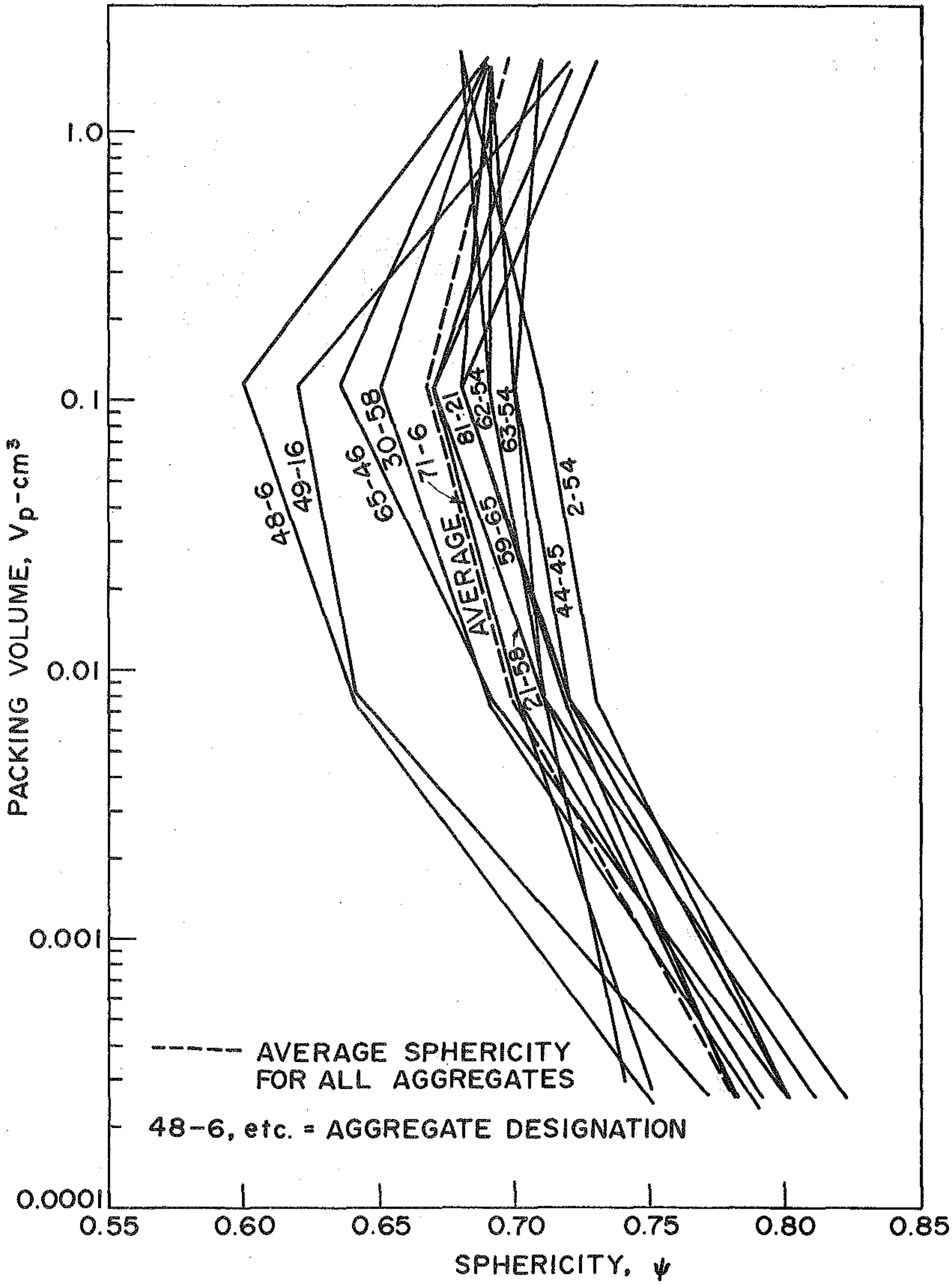


Figure 11. Relationship between packing volume and sphericity for different types of aggregates.

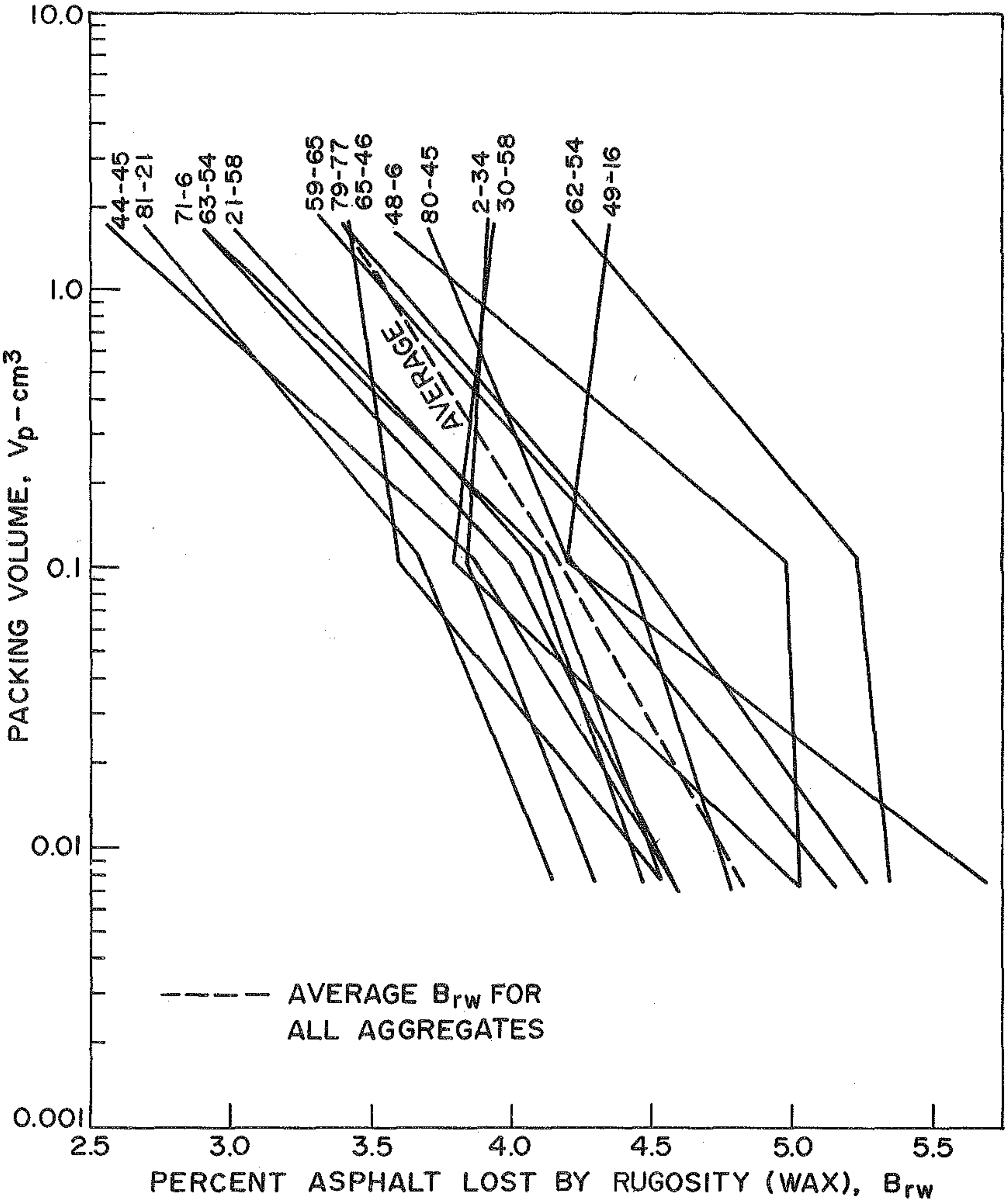


Figure 12. Relationship between packing volume and asphalt lost by rugosity for different types of aggregates (wax method).

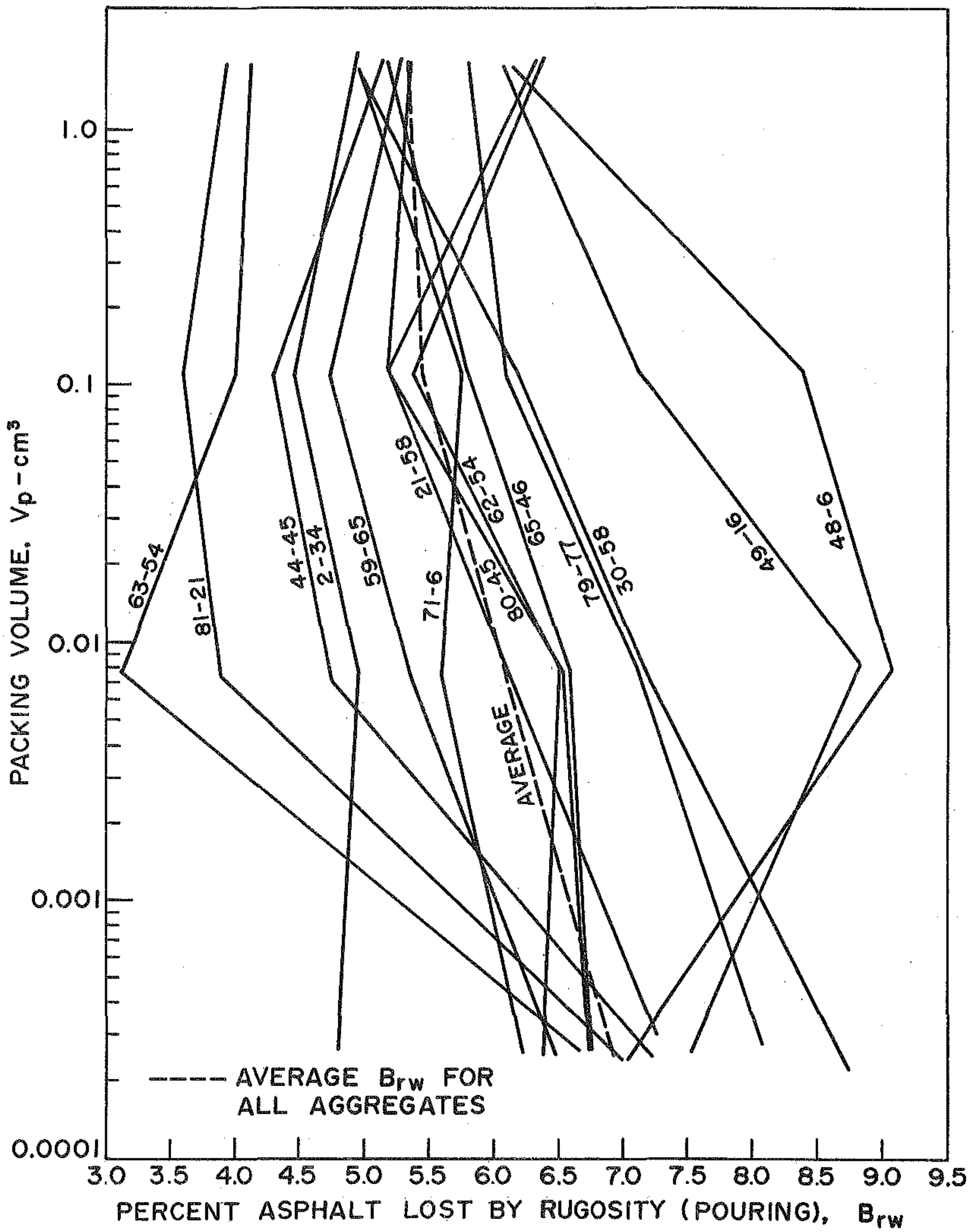


Figure 13. Relationship between packing volume and asphalt lost by rugosity for different types of aggregates (pouring method).

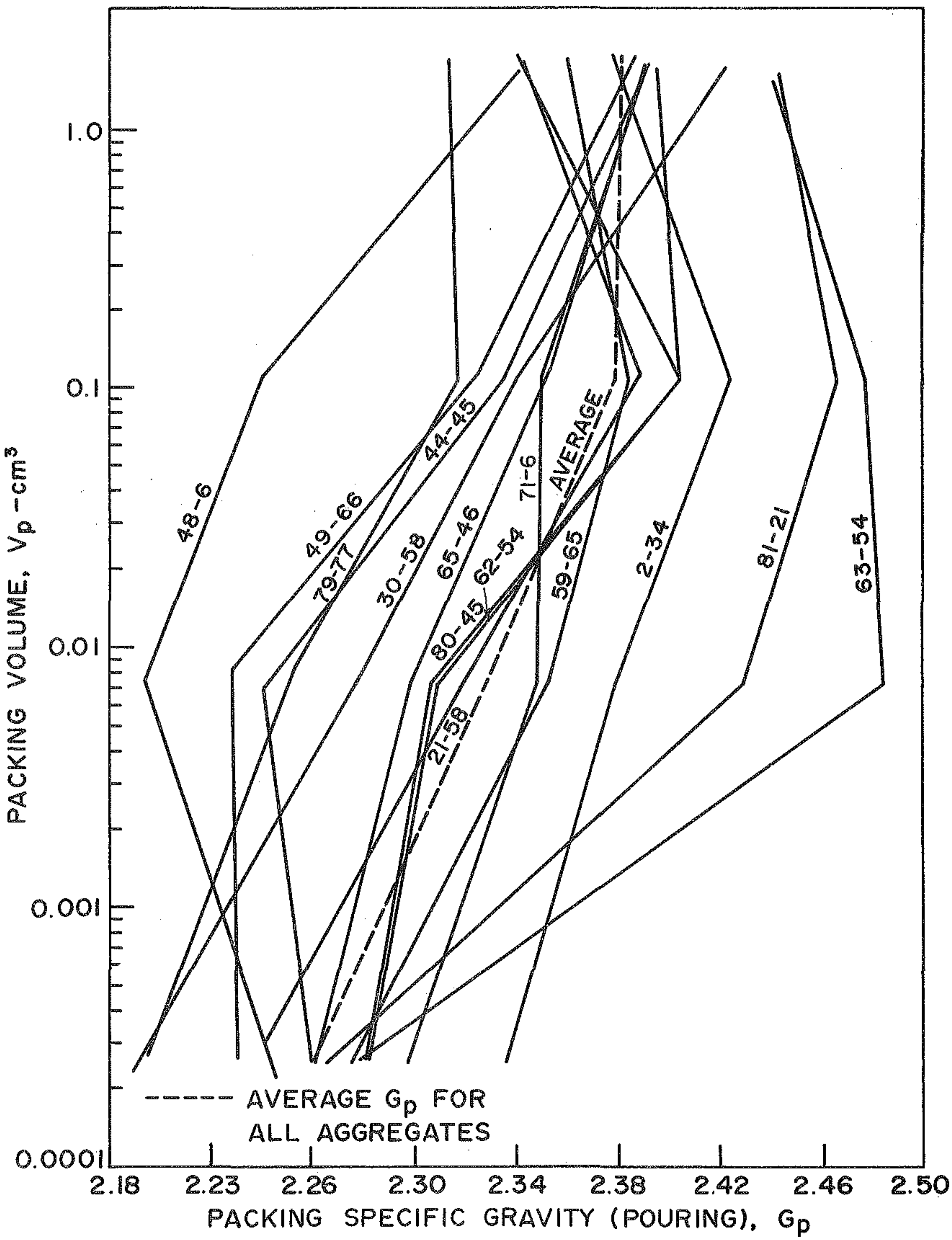


Figure 14. Relationship between packing volume and packing specific gravity (pouring) for different types of aggregates.

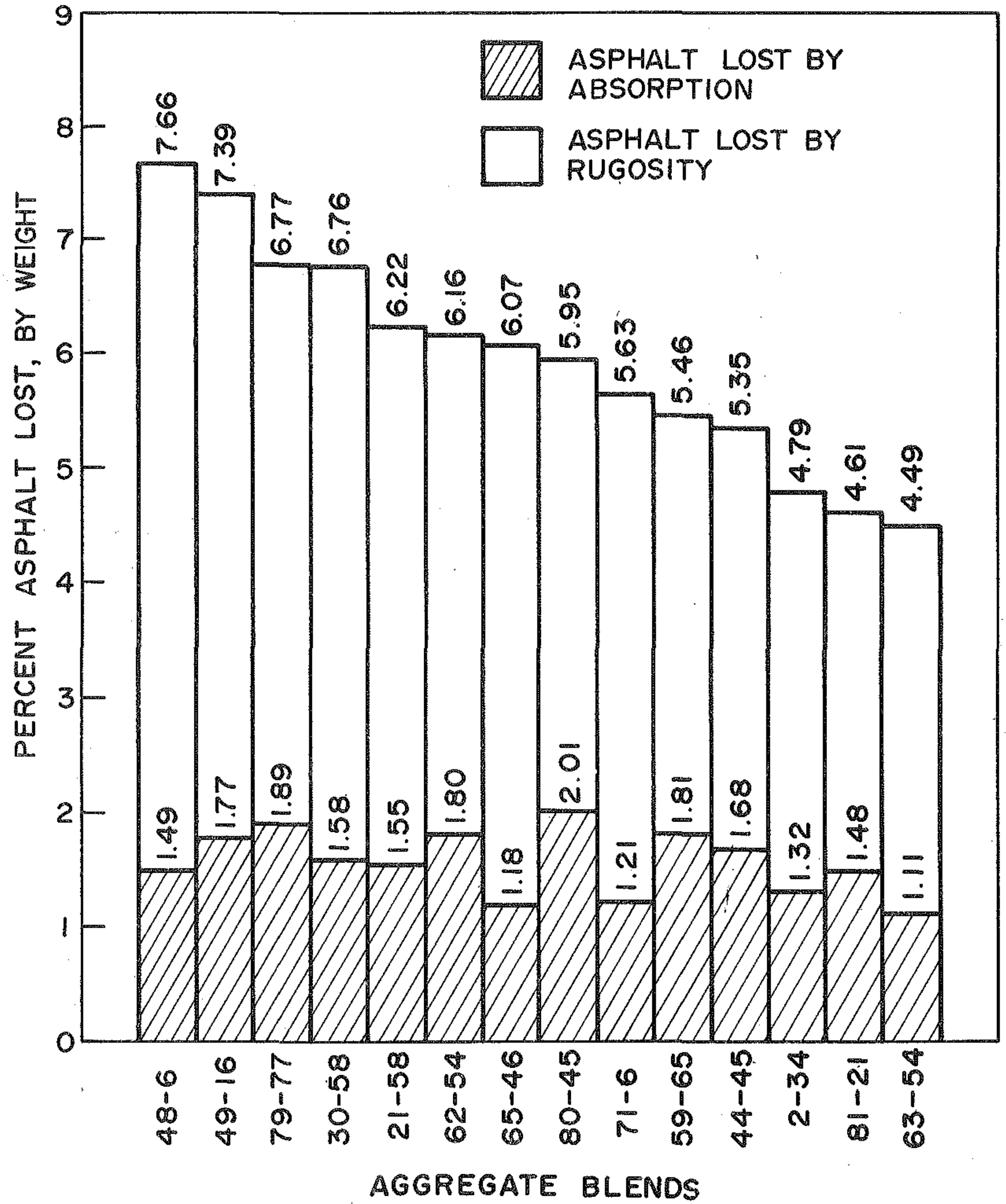


Figure 15. Average asphalt lost by rugosity and asphalt lost by absorption for different types of aggregates.

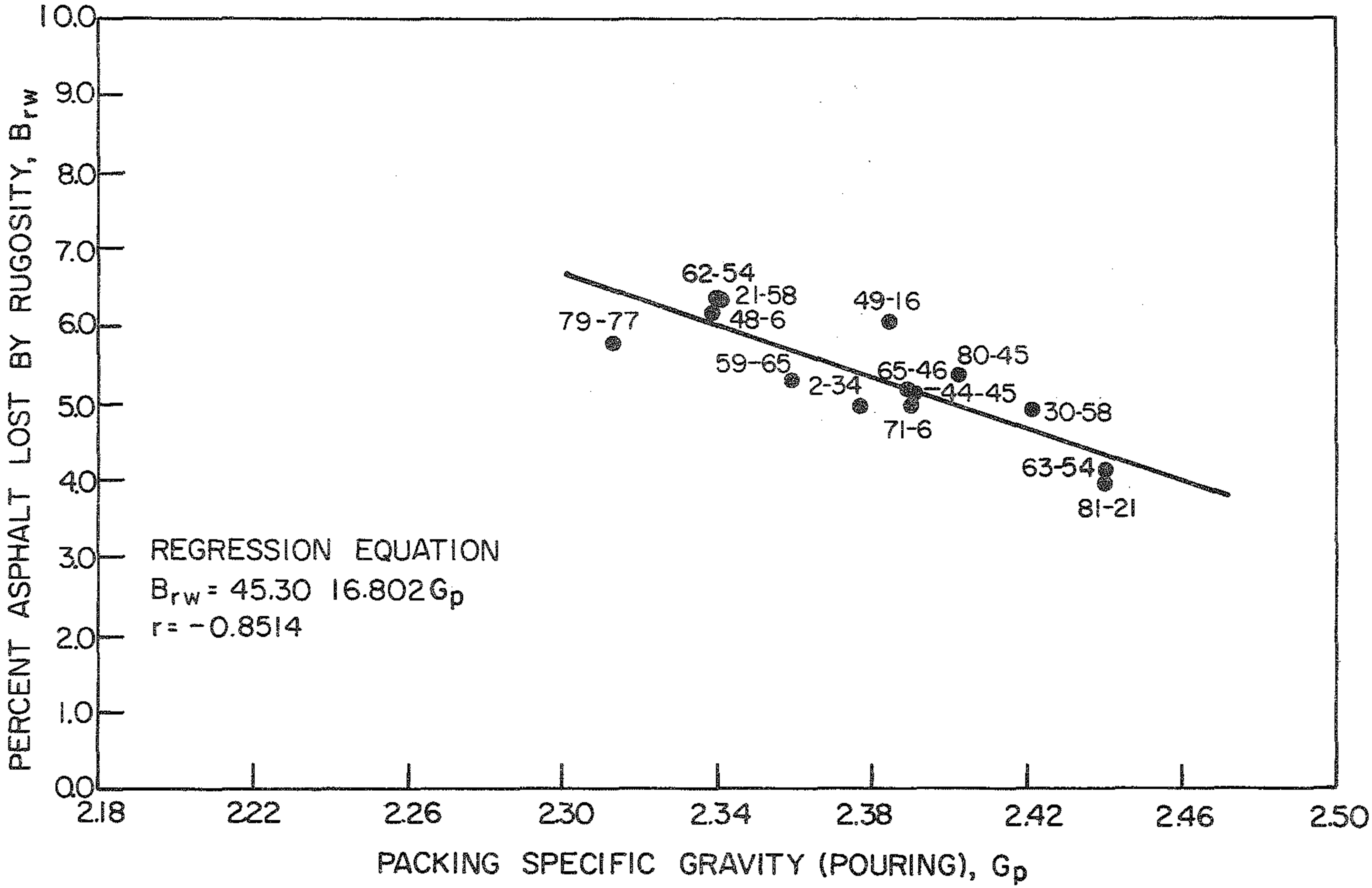


Figure 16. Asphalt lost by rugosity vs. packing specific gravity (pouring) for 1/2 in.-5/8 in. fractions.

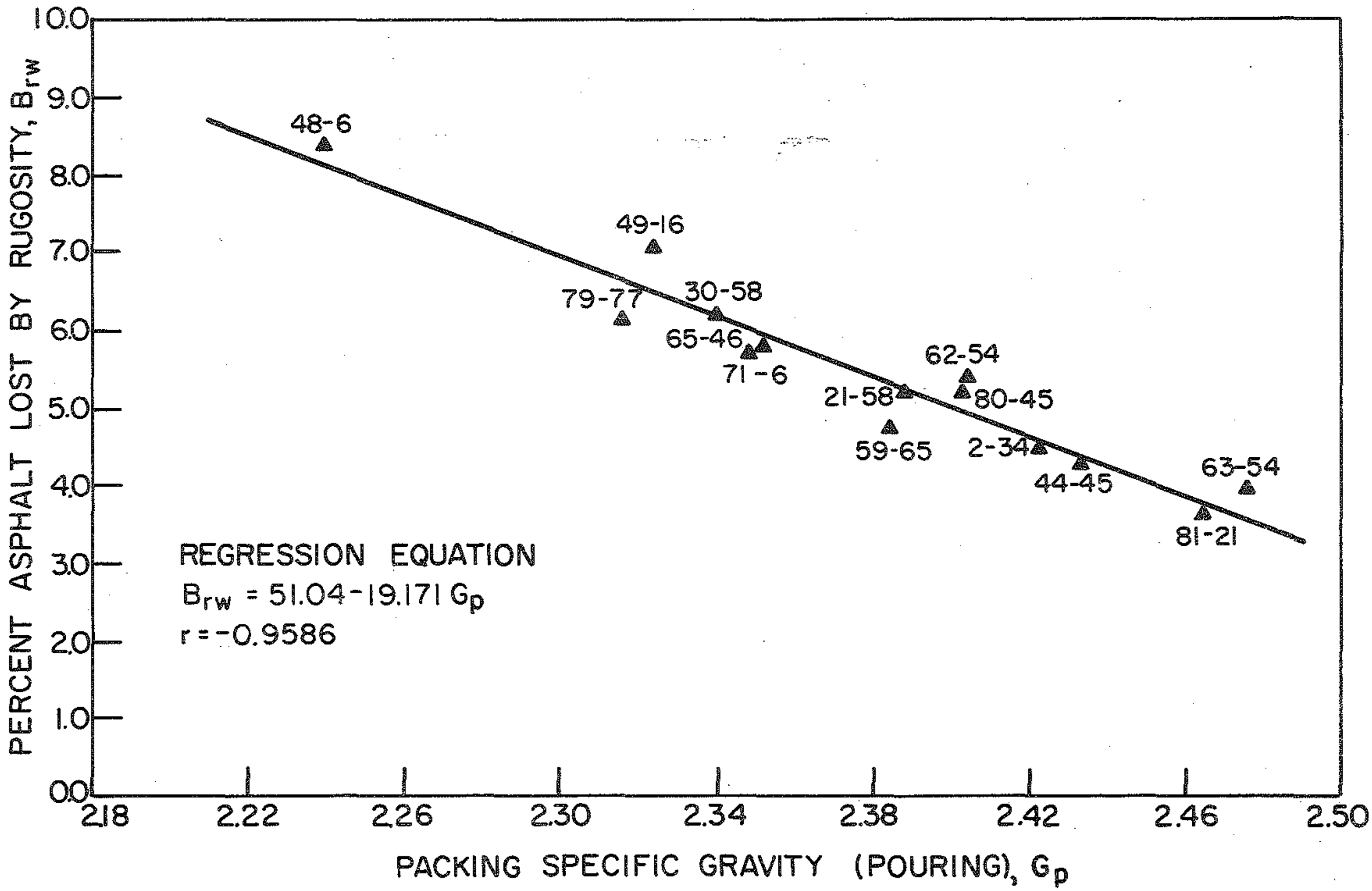


Figure 17. Asphalt lost by rugosity vs. packing specific gravity (pouring) for #3-#4 fractions.

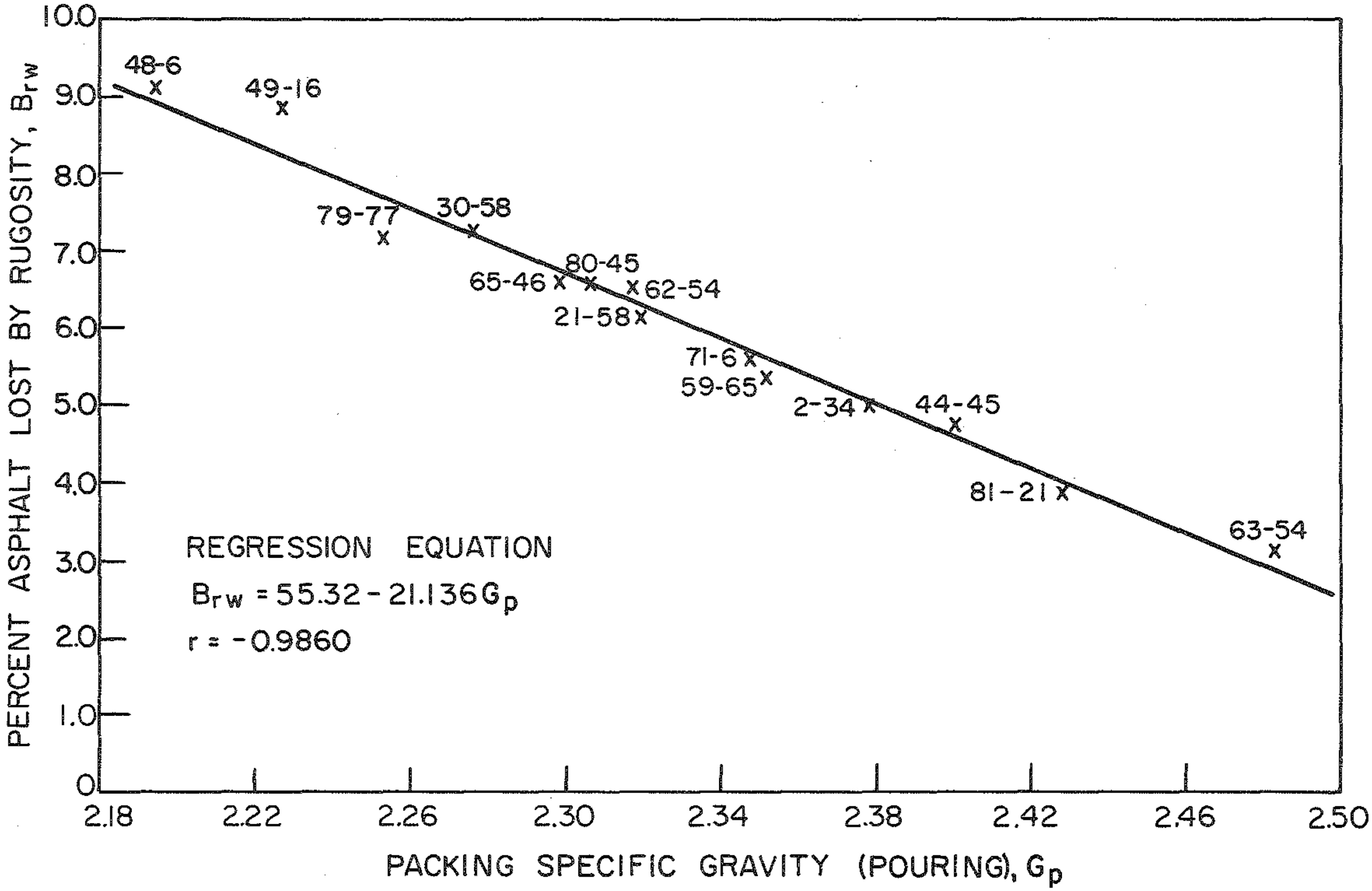


Figure 18. Asphalt lost by rugosity vs. packing specific gravity (pouring) for #8-#10 fractions.

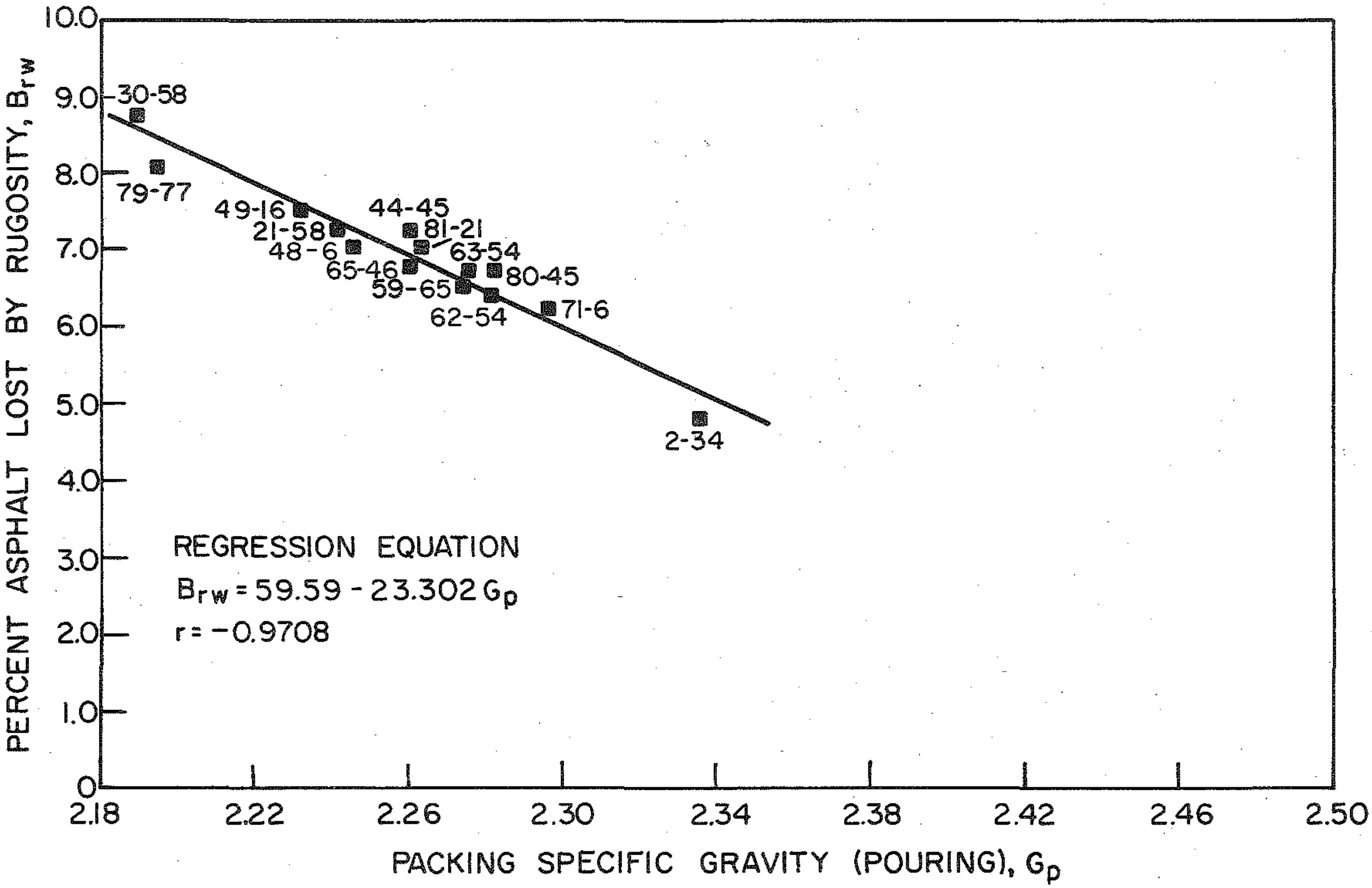


Figure 19. Asphalt lost by rugosity vs. packing specific gravity (pouring) for #20-#30 fractions.

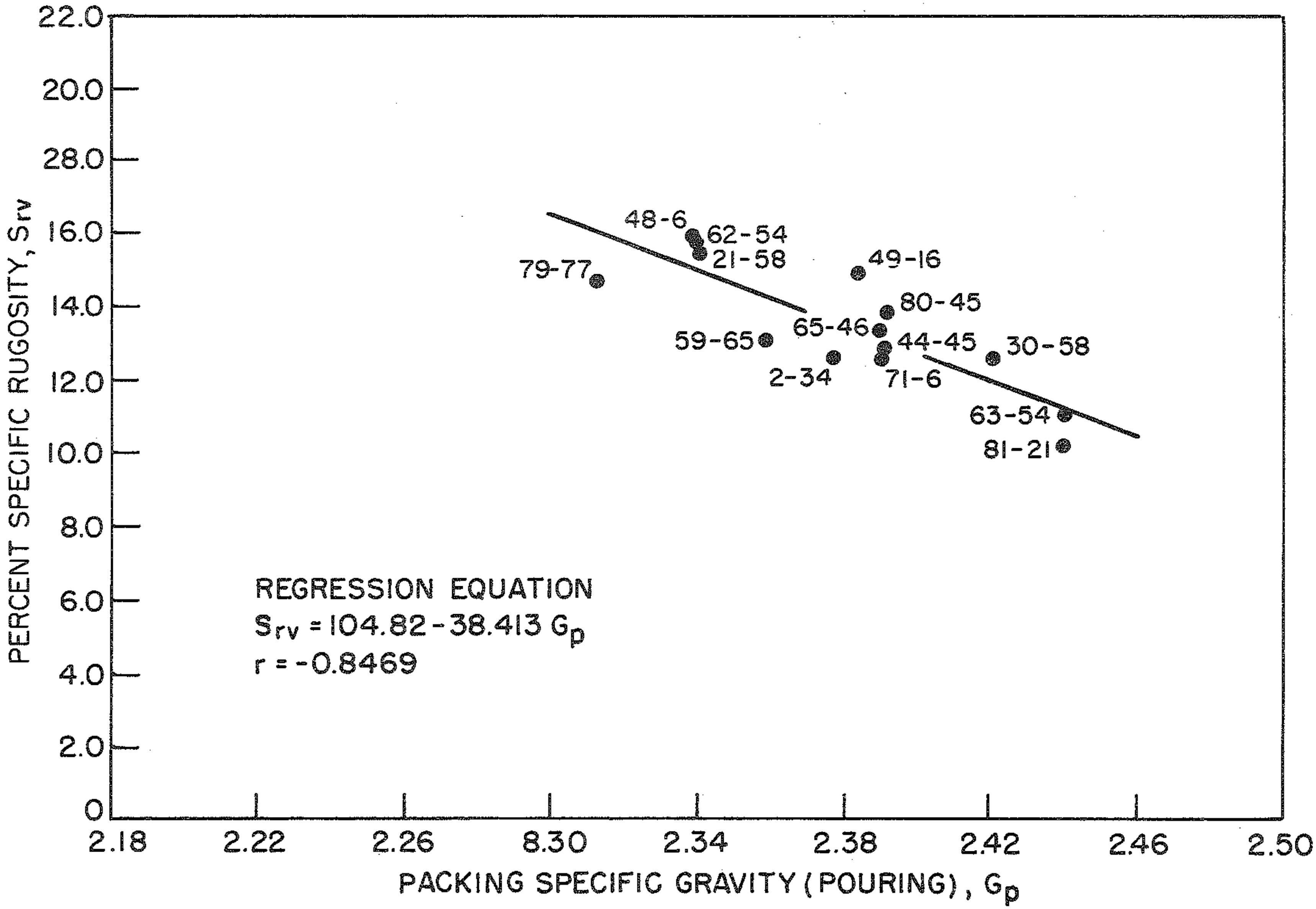


Figure 20. Specific rugosity vs. packing specific gravity (pouring) for 1/2 in.-5/8 in. fractions.

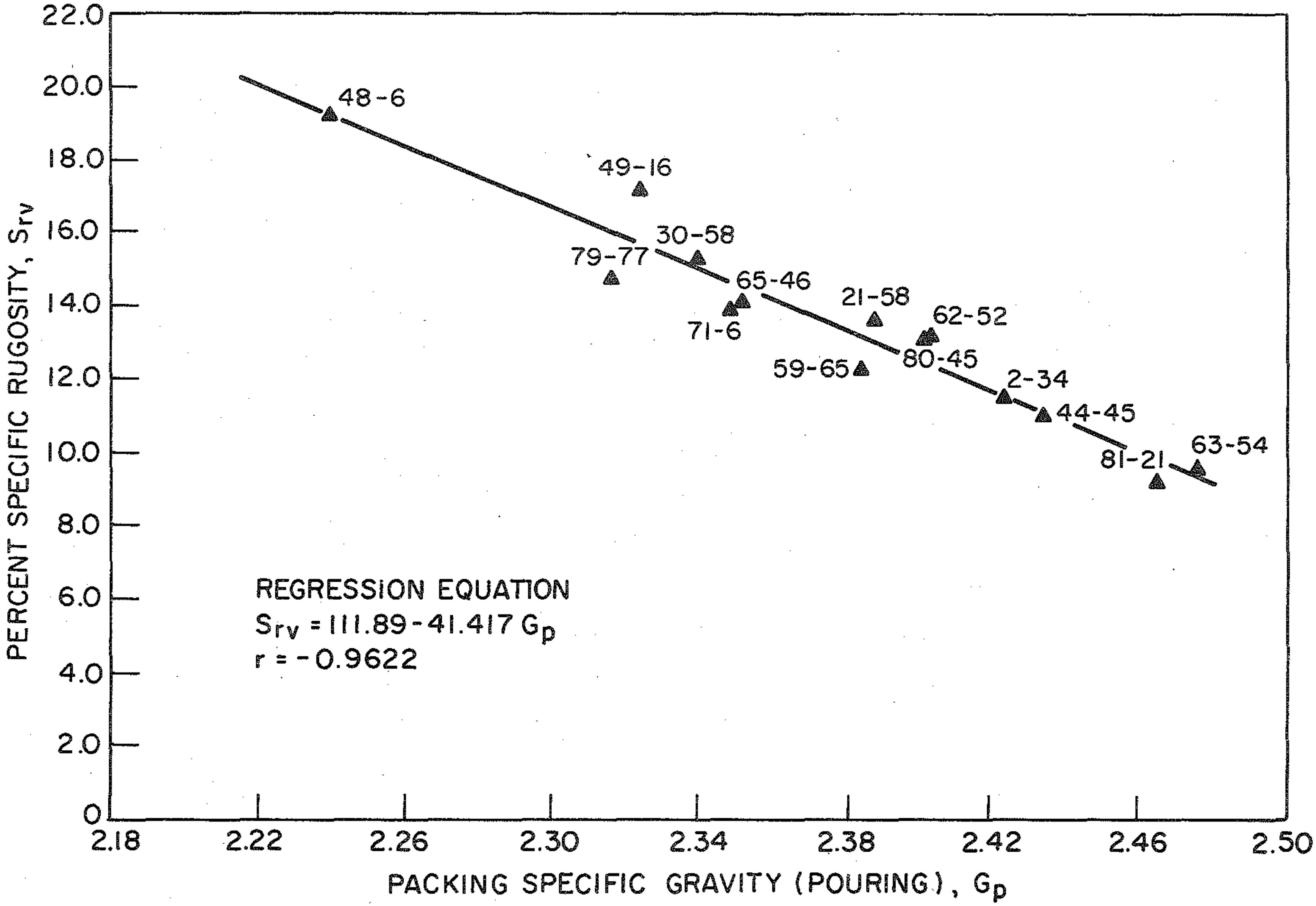


Figure 21. Specific rugosity vs. packing specific gravity (pouring) for #3-#4 fractions.

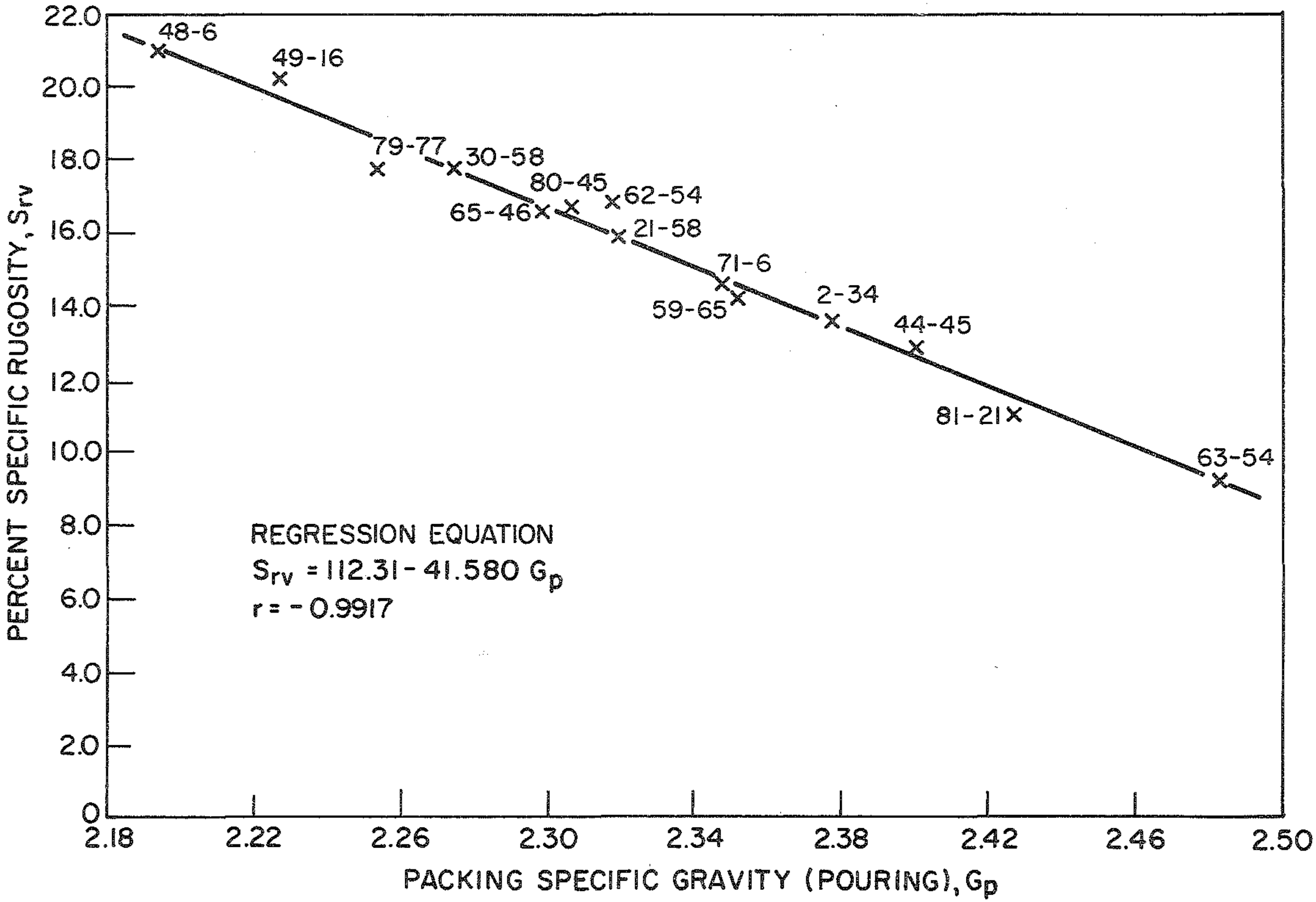


Figure 22. Specific rugosity vs. packing specific gravity (pouring) for #8-#10 fractions.

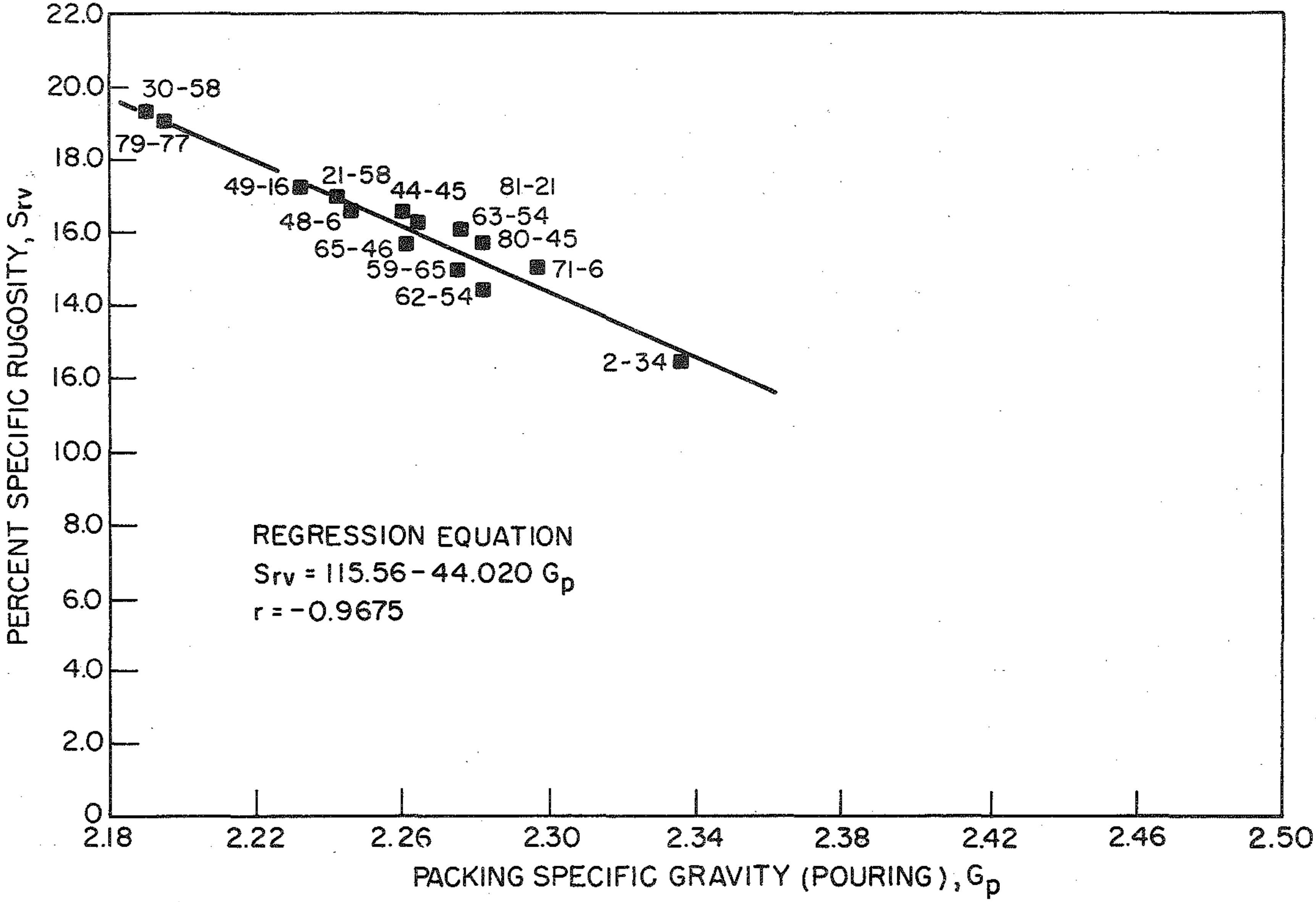


Figure 23. Specific rugosity vs. packing specific gravity (pouring) for #20-#30 fractions.

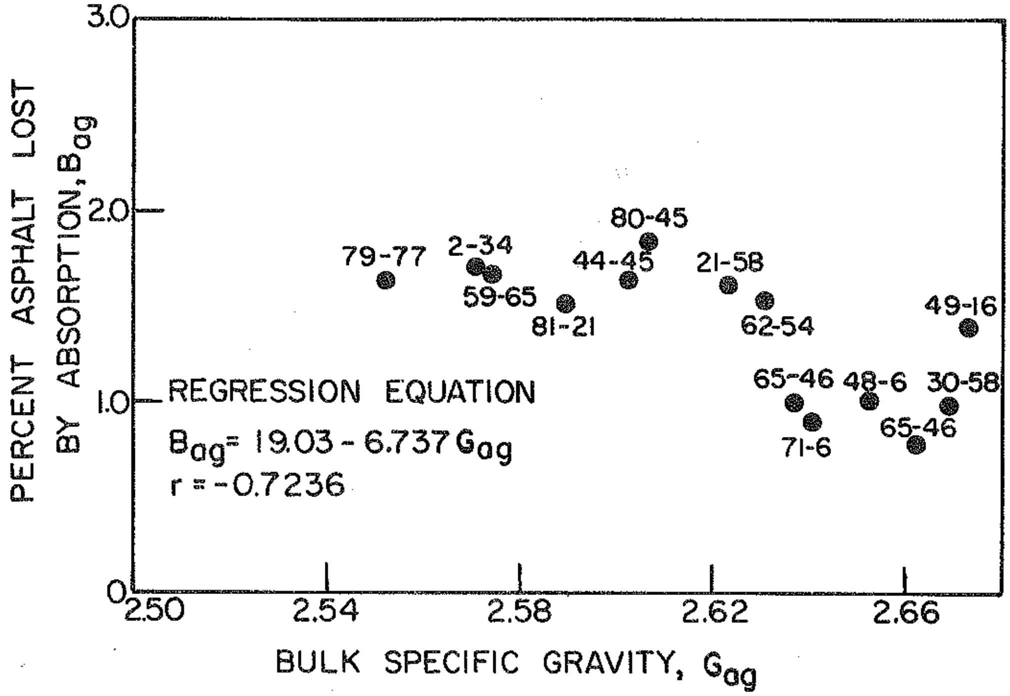


Figure 24. Asphalt lost by absorption vs. bulk specific gravity for 1/2 in.-5/8 in. fractions.

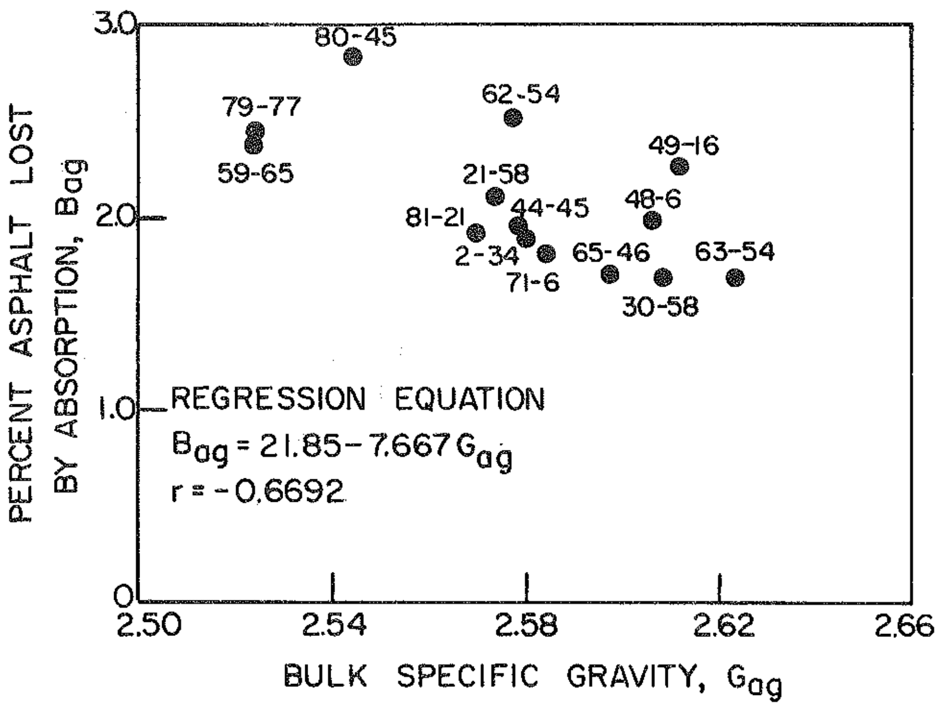


Figure 25. Asphalt lost by absorption vs. bulk specific gravity for #3-#4 fractions.

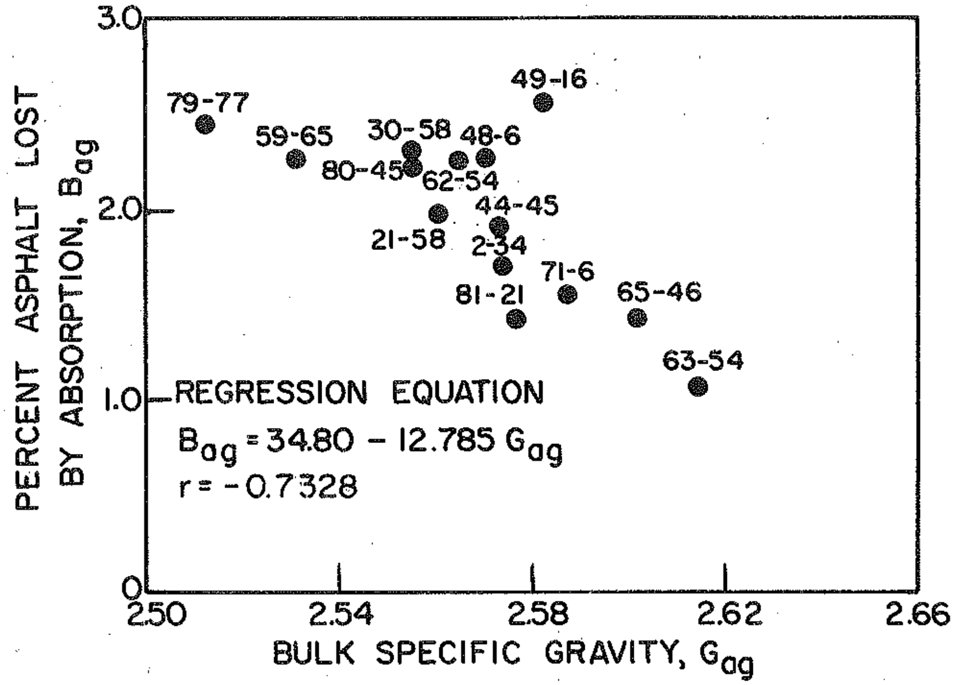


Figure 26. Asphalt lost by absorption vs. bulk specific gravity for #8-#10 fractions.

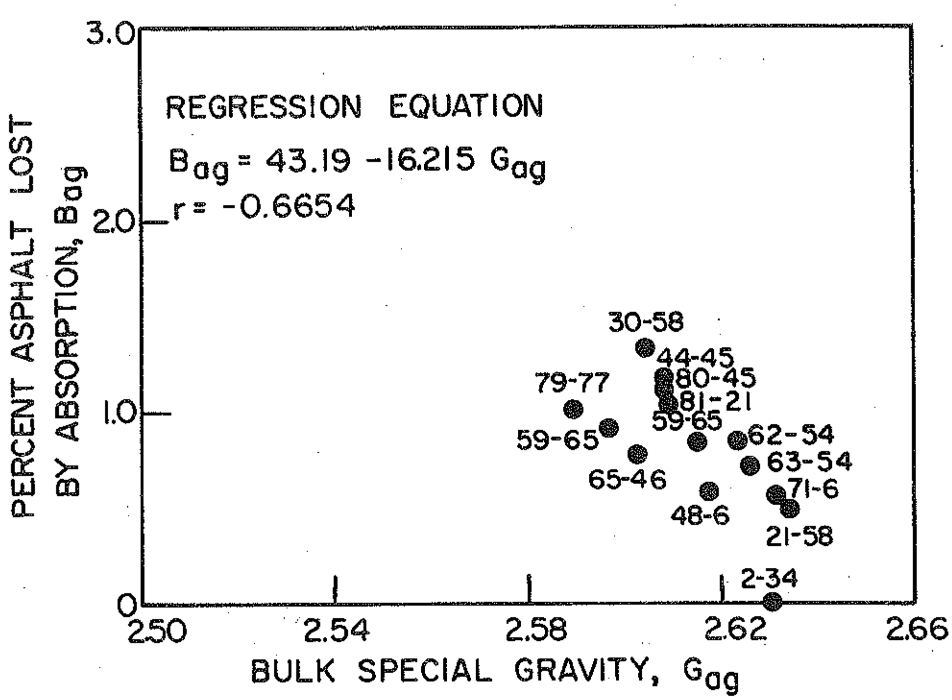


Figure 27. Asphalt lost by absorption vs. bulk specific gravity for #20-#30 fractions.

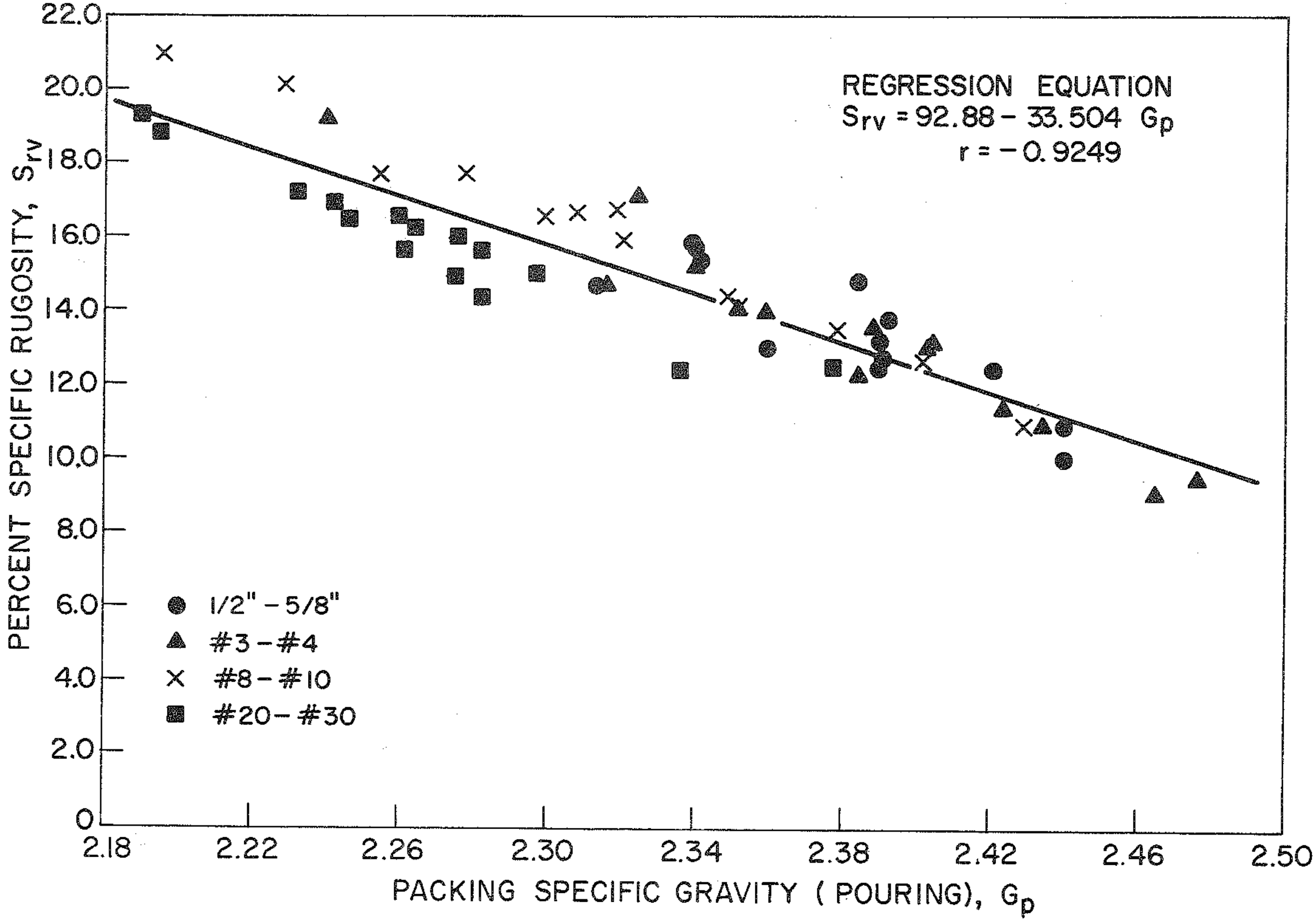


Figure 28. Specific rugosity vs. packing specific gravity (pouring) for all sizes.

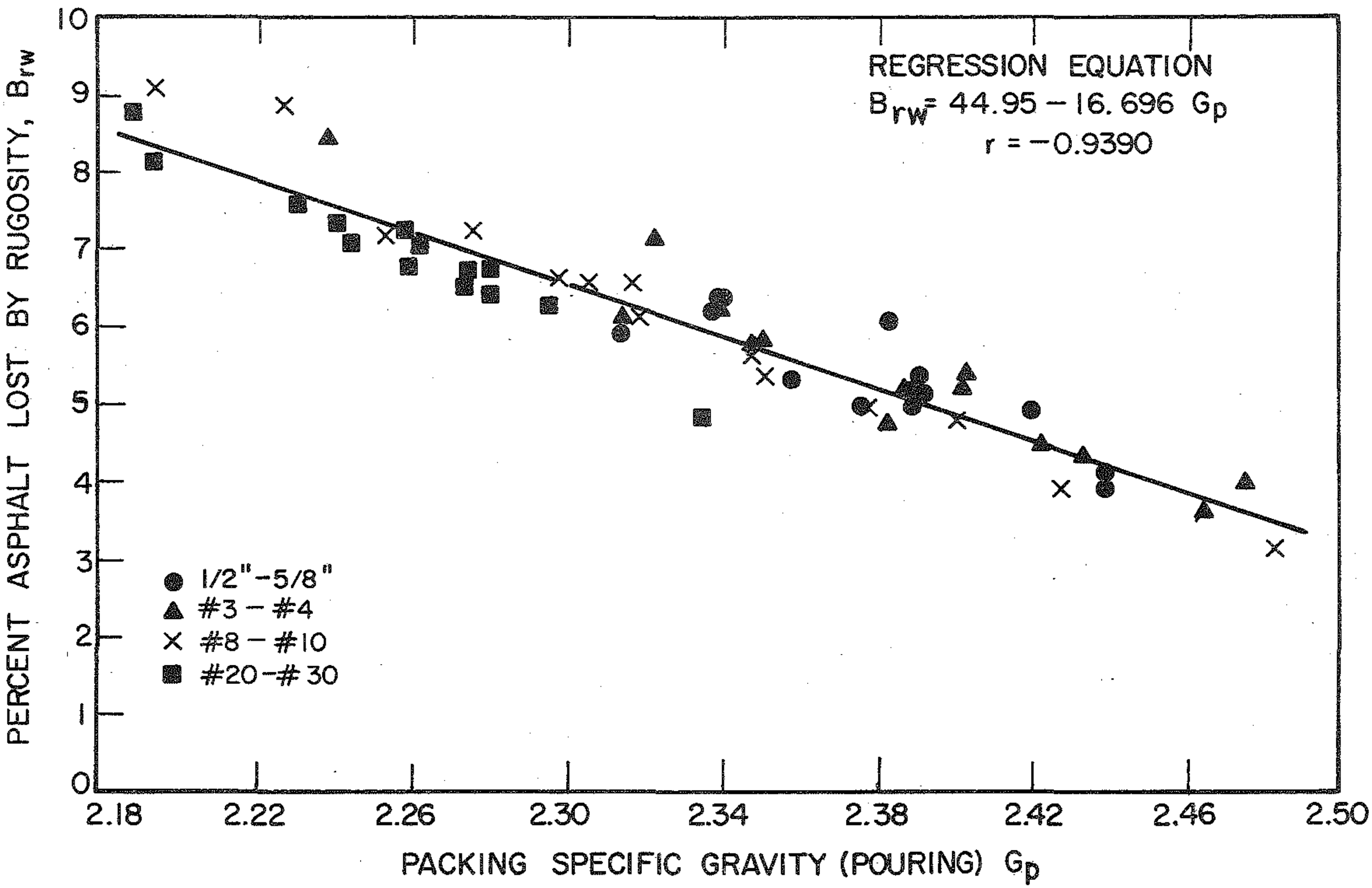


Figure 29. Asphalt lost by rugosity vs. packing specific gravity (pouring) for all sizes.

APPENDIX

THE POURING TEST METHOD

GENERAL

The pouring test was used for direct measurement of the Packing Specific Gravity of one-size aggregate fractions.

EQUIPMENT

The equipment and materials used were as follows:

1. Pouring device setup, which consists of (see Figure A-1):
   a. supported conical bin
   b. steel container
   c. pan for collecting particles.

The specific setups used for different aggregate fractions were as follows (see Figure A-1):

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

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 gr.

6. One-size clean, smooth glass beads (6 mm diameter for comparing with 1/2 in.-5/8 in.; #3-#4, and 3 mm diameter beads for #8-#10, and #20-#30 aggregate fractions).

TESTING PROCEDURE

The following procedure was used for each group of one-size fractions:

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

2. Open the bin shutter and allow all particles to come out.

3. Level the top of the pile down to the top of the container by applying gentle movements with the steel ruler.

4. Weigh the content and the container (test measurement).

5. Collect all particles and repeat the same procedure for the number of measurements desired. (In this investigations two samples were tested for each size of glass beads. For each sample 10 measurements were taken. The total average of the 20 measurements was used to calculate the packing specific gravity factor Q, see Table A-1).

6. Repeat the same procedure for all comparative aggregate fractions. (In this investigation four measurements have been taken for each type of aggregate, see Table A-1.)

CALCULATIONS

Based on the known specific gravity and packing specific gravity of the glass beads used, the packing specific gravity of a given fraction can be calculated by using Equation (8). An example and a working sheet, similar to those used, is given in Table A-1.

REMARKS

1. In the present testing program a 6.5 cm high container was used for measurements with 1/2 in.-5/8 in. fraction. The observations indicate that

this size of container may have introduced some boundary effects. This may be one of the reasons for the lower correlations obtained for the large size fractions compared to the finer fractions.

2. The rate of flow of particles was found to be a significant factor which influenced the test results. The factor has been considered and adjusted in the tests.

SUGGESTIONS FOR POURING EQUIPMENT

1. Based on the test experience so far the following minimum dimensions for the various parts of the pouring test equipment are recommended, depending on the size of the aggregate fraction (see Figure A-1 for symbols):

Dimensions \ Range of Fractions	3/8 in.-3/4 in.	#4-3/8 in.	#10-#4	passing #10
D (cm)	10.0	10.0	7.5	7.5
c (cm)	25.0	25.0	20.0	20.0
a (cm)	7.5	5.5	3.5	1.5
∅ (cm)	$\geq$ 12.5	$\geq$ 10.0	$\geq$ 7.5	$\geq$ 5.0
h (cm)	$\geq$ 10.0	$\geq$ ∅	$\geq$ ∅	$\geq$ ∅

2. The size of each sample (bulk volume) should be about 1.3-1.5 times the capacity of the receiving calibrated container.

3. The average diameter of the glass beads used for a comparison should be as close as possible to the average diameter of the aggregate fraction tested.

4. Further simplification and standardization of the equipment may be possible with additional experience and experimentation.

TABLE A-1

AN EXAMPLE OF A WORKING SHEET USED IN THE POURING TEST

Pouring Test Using #8-#10 Fractions

Container Diameter: 5.0 cm
Bin Diameter: 7.5 cm
Aggregate Head: 9.0 cm
Average Diameter of Glass Beads: 3 mm
Specific Gravity of Glass Beads: 2.213

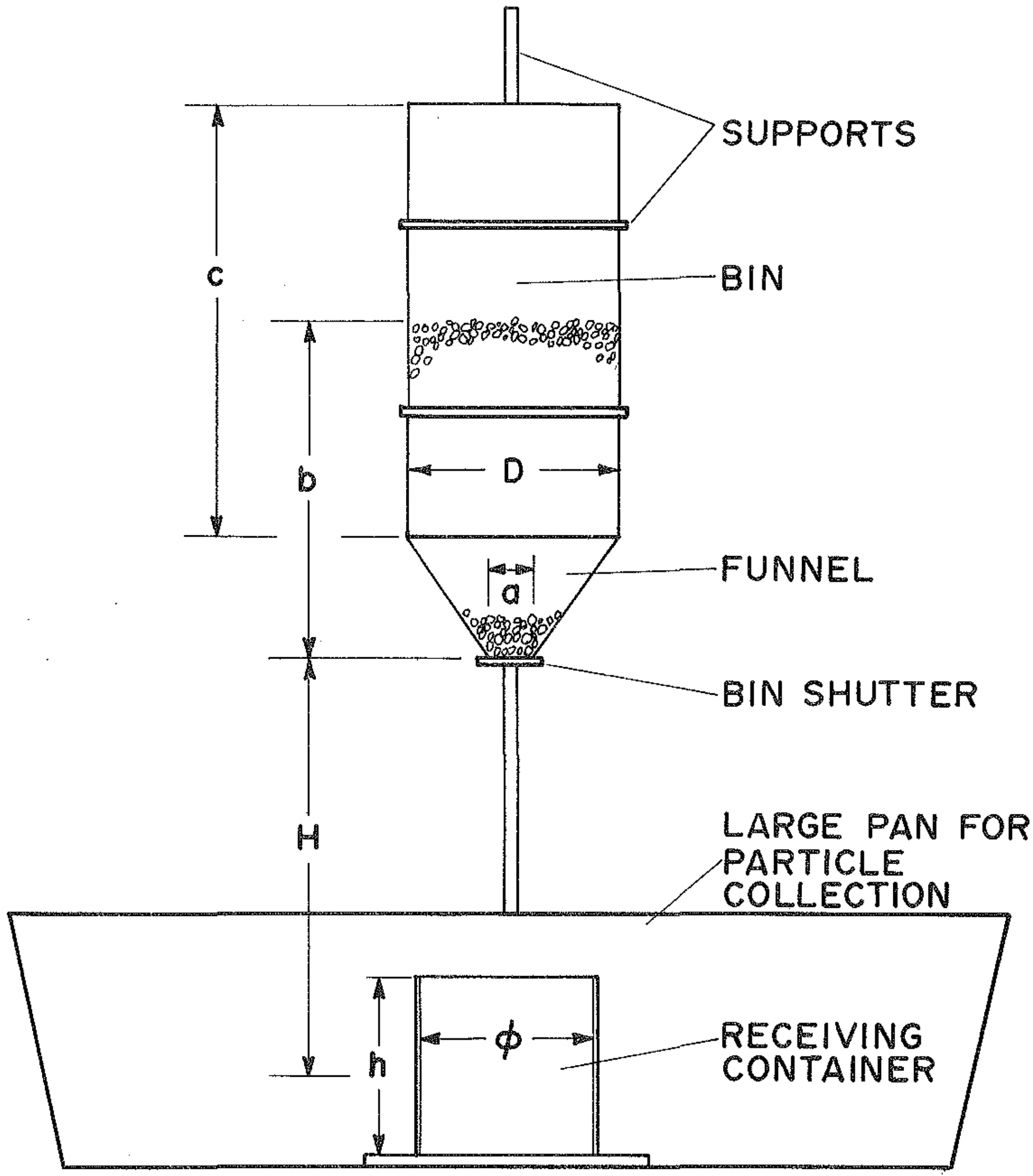
Container Height: 9.5 cm
Funnel Opening Diameter: 1.5 cm
Pouring Height: 20.0 cm

$$G_{px} = \frac{G_{ps}}{\Sigma W_s} \Sigma W_x = Q \Sigma W_x \text{ (see Equation (8))}$$

$$Q = \frac{G_{ps}}{\Sigma W_s} = \frac{2.213}{270.78} = 0.008173$$

Test Data

Sample	Weight in grams (Σ W)											Packing	Packing
	Test										$\Sigma W_s, \Sigma W_x$	Sp. Gr.	Specific
	1	2	3	4	5	6	7	8	9	10	Average	Factor-Q	G_{px}
G. Beads I	270.2	271.4	271.2	270.9	270.8	270.1	271.0	270.4	270.3	270.7	270.78	0.008173	
G. Beads II	271.5	270.9	270.8	270.9	270.7	270.7	271.0	270.7	270.6	270.8			
71-6	287.5	287.4	287.3	287.2							287.35	0.008173	2.348
44-45	294.4	293.2	294.1	293.2							293.72	0.008173	2.401
62-54	284.0	283.2	283.7	283.3							283.67	0.008173	2.318
81-21	297.6	297.2	296.4	297.2							297.10	0.008173	2.428
63-54	304.2	304.0	303.4	303.7							303.82	0.008173	2.483
80-45	282.7	282.1	282.3	282.1							282.10	0.008173	2.307



D = BIN DIAMETER
a = BIN OPENING DIAMETER
c = BIN HEIGHT
s = AGGREGATE HEAD
H = POURING HEIGHT
ϕ = CONTAINER DIAMETER
h = CONTAINER HEIGHT

Figure A-1. Schematic description of the pouring device setup.