A new aggregate gradation modulus
by Roger Ward Surdahl

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering
Montana State University

Abstract:
Many things contribute to a pavement's response to traffic or loading. This response is evident as rutting, cracking, stability, or a lack of these. When selecting a pavement design, one strives to minimize costs of materials and to maximize the pavement's performance. Usually several mix designs are produced and tested. The best of these trial mixes is selected for use.

After a pavement has been placed in service, it begins to respond to traffic loads. Researchers may then evaluate the actual pavement composition and the external conditions to determine the cause of the pavement response. Many models have been empirically developed to predict pavement performance based on its characteristics, but these usually only apply regionally.

There is a need for a good general model which predicts pavement behavior and which would apply to all pavements. First, however, a good method needs to be established to incorporate an aggregate gradation into the model. When developing models, researchers usually disregard the majority of the aggregate, which may constitute approximately 94 to 96 percent of an asphalt pavement. A rigorous examination should utilize all components of the pavement, including the whole of the aggregate. To do this, a method is proposed here that incorporates the entire aggregate gradation into one number, called the R-modulus. This R-modulus can then be used to statistically analyze a pavement's performance.

This new gradation modulus is computed by inverting the sum of the inverses of the percent material passing selected standard sieves.

Relating the R-modulus to pavement performance, some trends seem evident. One is that a larger R-modulus predicts a lower mix stability. A smaller R-modulus predicts a higher mix stability. Statistical proof is still needed to verify these trends.

In conclusion, the R-modulus is an attempt to quantify aggregate gradations into a single value which may explain or predict pavement performance.

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APPROVAL

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Roger Ward Surdahl

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

7/2/90	Joe D. Armijo
Date	Chairperson, Graduate Committee

Approved for the Civil Engineering Department

9 July '90	Theodore E. Lang
Date	Head, Civil Engineering Department

Approved for the College of Graduate Studies

July 23, 1990	Henry L Parsons
Date	Graduate Dean

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ABSTRACT

Many things contribute to a pavement's response to traffic or loading. This response is evident as rutting, cracking, stability, or a lack of these. When selecting a pavement design, one strives to minimize costs of materials and to maximize the pavement's performance. Usually several mix designs are produced and tested. The best of these trial mixes is selected for use.

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There is a need for a good general model which predicts pavement behavior and which would apply to all pavements. First, however, a good method needs to be established to incorporate an aggregate gradation into the model. When developing models, researchers usually disregard the majority of the aggregate, which may constitute approximately 94 to 96 percent of an asphalt pavement. A rigorous examination should utilize all components of the pavement, including the whole of the aggregate. To do this, a method is proposed here that incorporates the entire aggregate gradation into one number, called the R-modulus. This R-modulus can then be used to statistically analyze a pavement's performance.

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CHAPTER 1

INTRODUCTION

Background

Designing flexible pavements is still a trial and error method. An aggregate gradation is selected from specifications which give permissible amounts and tolerances of material which pass certain selected sieves. With this gradation, various amounts of asphalt cement are combined with the aggregate, and the mixture is compacted into small 4-inch diameter by 2-1/2 inch high samples. These are then tested in the laboratory for air voids content, specific gravity, and Marshall stability and flow. Curves are obtained for each of these tests by plotting the several characteristics of each mixture versus percent asphalt content. From these curves the optimum asphalt content is selected for the particular gradation.

A mix thus designed becomes the target, or standard, for the many tons of asphalt mixture placed on a roadway. The performance of the pavement may be monitored to determine if it is indeed holding up as it was designed.

When a new pavement does not hold up, it may be examined to see what caused the failure.

Sometimes it is easy to point a finger at an item of design or construction that caused the failure, other times it is not. A failure could be due to too much variation (in one, or several characteristics of the target mix design) in the actual mixture. If proper construction methods have been employed, the physical and chemical properties of an asphalt mixture may be questioned as a possible cause of the failure. Some researchers(4,8,33,39,45,48,55,57) have attempted to develop models which predict pavement performance based on these physical and chemical properties of the asphalt mixture. These models, which have met with limited success, usually only apply regionally, or are specific only to the materials used in developing the models, and therefore cannot be extended to all pavements in general.

A research project this author participated in at Montana State University, during the period of September 1986 to September 1987, had a goal of developing a model for flexible pavements in Montana. The project, sponsored by the Montana Department of Highways and the Federal Highway Administration, was conducted by Jennings et al(33). The project examined a statistically significant number of asphalt pavements from highways in Montana and correlated pavement composition to pavement performance.

The scope of the project included collecting six four-inch diameter core samples, at each of one hundred eighty five locations randomly selected from the three Interstate freeways that traverse the state. Of these six cores, three were taken from a wheel path and three were taken from the shoulder. Each core was then cut by a diamond blade saw into its individual construction lifts. Overall, about seven hundred thirty samples of pavement were collected for analysis. Eighty samples were later discarded from the analysis for want of sufficient or accurate data.

For each location, historical information including data from design and construction of the pavement was collected. Site surveys also were conducted to evaluate pavement conditions such as rutting, cracking, bleeding, stripping, et cetera. Other data collected in the laboratory consisted of the following:

Information from the core samples:

1. Bulk Specific Gravity
2. Rice Specific Gravity
3. Marshall Stability and Flow
4. Percent Asphalt Content

Information from the extracted aggregate:

5. Aggregate Gradation

6. Percent Fractured Faces

Information from the extracted asphalt:

7. Ductility at 77^0 F

8. Penetration at 40^0, 70^0, and 90^0 F

9. Viscosity at 140^0 and 275^0 F

10. High Pressure - Gel Permutation Chromatography (HP-GPC)

From measured values of the above testing procedures, the air void content and the penetration-viscosity number were calculated.

Computer analysis of the data consisted of correlating individual, and combinations of individual values, with the measured pavement performance.

During this analysis, the research team felt dissatisfaction with the method used to correlate aggregate gradations to the pavement performance. Individual amounts of percent passing or percent retained on each sieve were used in the analysis. It was recognized that this did not accurately portray the aggregate's overall contribution to the pavement's performance. However, no other method for dealing with aggregate gradations was known at that time. This thesis was selected for study because of this issue.

Description of Proposal

An aggregate gradation is determined by obtaining discrete measurements of material which has been separated by a series of sieves which are nested in successively smaller sizes. A value, or modulus (consisting of one number if possible), is needed to represent the role aggregate gradation plays in asphalt pavement performance.

Various researchers[1,8,12,24,57,61,63] have suggested that the finer portions of the aggregate gradation affect the pavement performance more than the coarser material; their published test results tend to substantiate this.

Therefore, since the finer material is more important, it should be given more weight in quantifying aggregate gradations. To accomplish this type of weighted analysis, it is proposed that the inverse of the sum of the inverses of the percent material (by weight) passing each sieve of a standard set will result in a single number. This number might represent the influence of aggregate gradation on pavement performance better than partial aggregate gradation values or other gradation moduli.

This number can then be used as one of many variables in a statistical analysis in which pavement materials and properties are correlated to pavement performance.

Scope of Proposal

To test the above hypothesis, a variation in the modulus should be established as being the result of variation of aggregate gradation. Then, for actual mix designs of various gradations, a comparison with performance should be conducted to verify or invalidate the hypothesis.

Anticipated Results

Due to the nature of the computation of this proposed gradation modulus, as an aggregate gradation gets finer (having a higher percentage of smaller material), the gradation modulus value will increase. Conversely, as the aggregate gradation gets coarser (having a higher percentage of larger material), the gradation modulus value will decrease. Therefore, the thought is advanced that a finer aggregate gradation with a corresponding larger modulus will predict a lower stability. The coarser aggregate gradation with the smaller modulus will predict a higher stability.

CHAPTER 2

REVIEW OF LITERATURE

A review of material[10,20,22,27,36,44,46,54,64,70,80] pertaining to aggregates and aggregate gradations revealed that an aggregate sample possesses many characteristics. Some of these qualities are listed below.

1.	Abrasion Resistance	9.	Porosity
2.	Absorption	10.	Sand Equivalent
3.	Alkali-Silica Reactivity	11.	Shape
4.	Freeze-Thaw Durability	12.	Specific Gravity
5.	Gradation	13.	Specific Volume
6.	Liquid & Plastic Limit	14.	Surface Area
7.	Mineral Composition	15.	Texture
8.	Percent Fractures	16.	Voids

This thesis examines only the gradation in depth.

Methods of Representing an Aggregate Gradation

Abrams' Fineness Modulus

In 1919, Duff Abrams[1] proposed a fineness modulus for use in designing Portland Cement Concrete mixtures.

He initially defined two moduli, the first an overall modulus, and the second a fineness modulus. Each modulus was calculated by summing the cumulative percent of material retained, also referred to as percent retained, on each sieve of a standard set, and dividing the result by 100. Abrams selected a series of sieves in which the opening of each smaller sieve size was approximately one half of the preceding size. In 1919 these sieves were called the Tyler standard sieves, and were numbered 1-1/2, 3/4, 3/8, #4, #8, #14, #28, #48, and #100. These sieves were later updated to the numbers 1-1/2, 3/4, 3/8, #4, #8, #16, #30, #50, and #100.

Abrams computed his fineness modulus by summing the percents retained on the #4 through #100 sieves and dividing by 100. No record could be found of Abrams' thought process as to why he selected this method. Abrams also similarly computed an overall modulus, with the 1-1/2 inch sieve as the initial starting point. This overall modulus is no longer in use. An example of the computation of the accepted fineness modulus is presented in Table 1.

Table 1. Calculation of Abrams' Fineness Modulus

Sieve Size	Percent Passing	Percent Retained	Cumulative Percent Retained
1-1/2	100.0	0.0	
3/4	73.8	26.2	
3/8	45.8	28.0	
#4	40.3	5.5	5.5
#8	34.3	6.0	11.5
#16	27.2	7.1	18.6
#30	20.2	7.0	25.6
#50	12.3	7.9	33.5
#100	8.3	4.0	37.5
#200	6.5	1.8	
Pan	0.0	6.5	
		Total	132.2

FM = 132.2 / 100 = 1.32

Turnbull's Soil Classification

In 1948, Turnbull[76] proposed a way to classify soils based on their particle size distribution curves. His classification consisted of two components, the maximum particle size in a mix, and the area enclosed by the plot of the gradation curve of the largest to the smallest particle. Turnbull's particle distribution curve was plotted as percent coarser on the y-axis versus particle size in millimeters on a logarithmic scale on the x-axis. Table 2 shows a sample gradation with its soil classification.

Table 2. Calculation of Turnbull's Soil Classification.

Sieve Size	Sediment Size (inches)	Cumulative Percent Retained
3/8	----	0.0
#4	----	20.7
#8	----	34.9
#16	----	38.6
#30	----	42.1
#50	----	44.1
#100	----	45.4
#200	----	46.7
----	0.0460000	51.0
----	0.0230000	58.0
----	0.0115000	65.5
----	0.0057500	72.0
----	0.0028700	77.7
----	0.0014400	83.0
----	0.0007200	88.8
----	0.0003600	94.6
----	0.0001800	100.0
----	0.0000900	100.0
----	0.0000450	100.0
----	0.0000225	100.0
----	0.0000112	100.0
	Total	1363.4

Area = (13.634) X $(\log 2)^*$ = 4.104

Classification D/A = 3/8 in. / 4.104 sq. in.

* multiplication factor based on the sieves spaced at intervals of log 2

Surface Area

Another method to represent an aggregate gradation uses the equivalent surface area of the particles. The surface area of an aggregate mix may be calculated, assuming spherical particles, as demonstrated by the Asphalt Institute Manual[53]. An example is presented in Table 3.

Table 3. Calculation of Equivalent Surface Area.

Sieve Size	Percent Passing	S.A. Factor sq. ft. / lb.	Surface Area
3/8	100.0	2	2.0
#4	75.0	2	1.5
#8	60.0	4	2.4
#16	45.0	8	3.6
#30	35.0	14	4.9
#50	25.0	30	7.5
#100	18.0	60	10.8
#200	10.0	160	16.0
		Total	48.7

Surface Area = 48.7 sq. ft. / lb.

F. Field[20] points out however, that this surface area method is not realistic, since the surface area is dependent on particle shape. He illustrates that a cubical particle has 1.9 times more surface area than a sphere of the same outer dimensions.

FHWA's 0.45 Power Gradation Chart

In 1962, Goode and Lufsey[24] reported on a way to represent aggregate gradations. They proposed plotting the percent material passing each sieve versus the sieve opening measurement raised to the 0.45 power. This was similar to the Fuller chart[53] which also plotted percent passing each sieve versus the sieve size raised to a power, except that Fuller recommended a power of 0.50 instead of 0.45. The aggregate gradation from Table 1 is plotted on this 0.45 power chart in Figure 1. It is recognized that a logarithmic scale cannot have zero for an origin. However, this 0.45 power gradation chart utilizes a zero origin for the sake of simplicity and may be considered to be reasonably accurate due to the small size of particle represented near this origin.

> "The selection of this exponent was based on research performed by L. W. Nijboer of Holland and published in 1948[61]. Nijboer employed a double logarithmic gradation chart in a study of the influence of aggregate gradation on mineral voids. All gradations used in his study produced straight lines with various slopes when plotted on his chart. This variation in slope resulted from his use of several different gradations of the same maximum size (3/4 inch). He made two series of tests on compacted bituminous mixtures and determined the mineral voids for all of them. Mineral voids were plotted against the slopes of the straight line gradation curves. A rounded gravel was used for the coarse aggregate in one series of tests and an angular crushed stone in the other. In both instances minimum mineral voids, or maximum aggregate density, occurred for a gradation having a slope of 0.45 on the double log chart."[24]

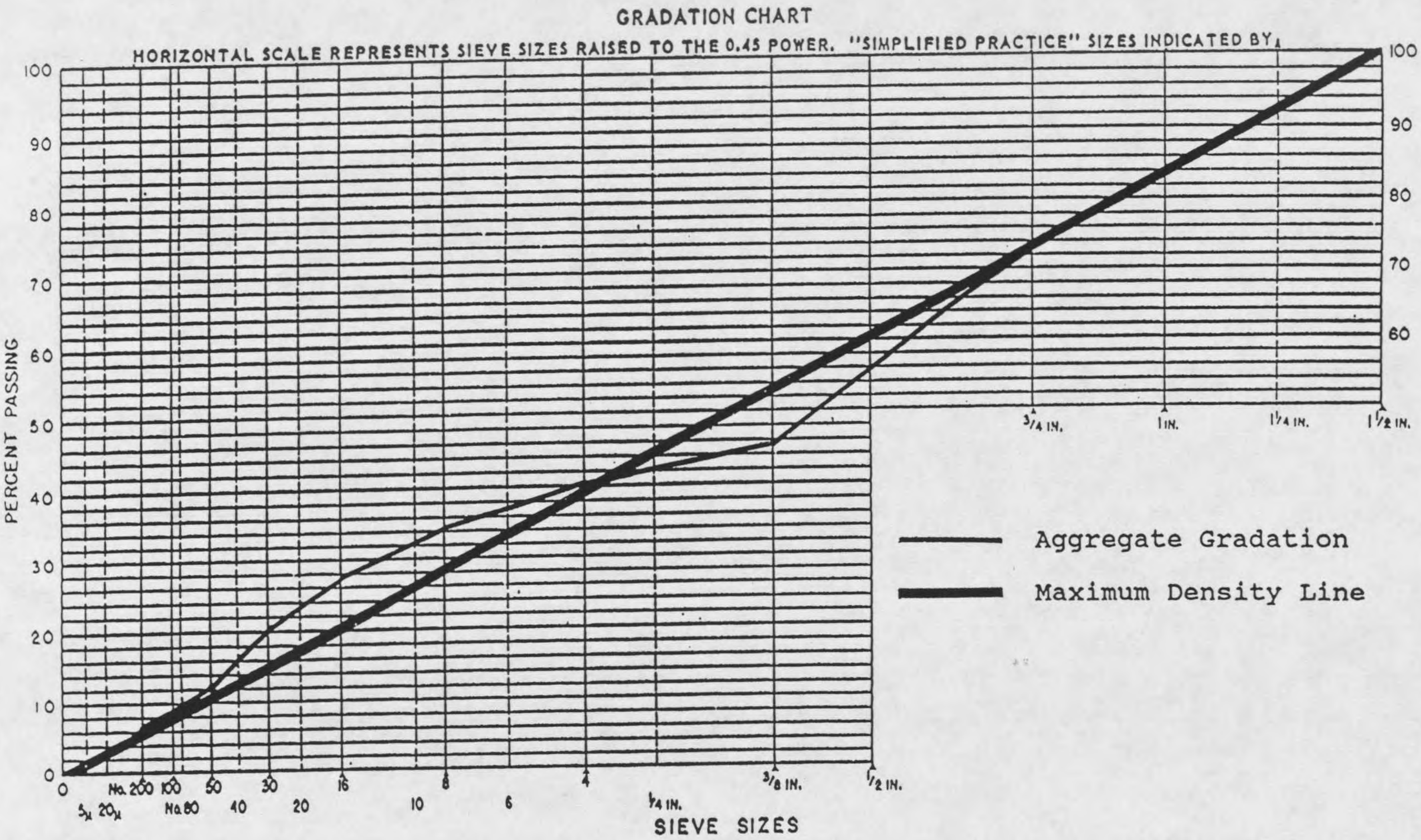

Figure 1. Aggregate Gradation as Listed in Table 1.

The slope, k = 0.45, was obtained with the following equation:

$$P = (S / M)^k \qquad \text{Eq. 1}$$

where

P = percent material passing the sieve having an opening of "S" microns
M = maximum size in microns of all particles
k = slope of the gradation curve

Goode and Lufsey, by experimental procedures, found that a mixture's maximum density, defined as that mix having minimum voids, occurred where k equalled 0.435. Since this was considered not a significant deviation from Nijboer's slope of 0.45, the Federal Highway Administration (FHWA) adopted 0.45 as a standard in the chart for plotting gradations.

Hudson's-A

In 1969, S. B. Hudson[31] proposed another gradation modulus to be used with bituminous mixtures. Hudson suggested summing the percent material passing the 1-1/2, 3/4, 3/8, #4, #8, #16, #30, #50, #100, and #200 sieves and dividing by 100. This method uses sieve sizes similar to Abrams' method, in which each sieve has an opening approximately one half that of the preceding sieve. Hudson pointed out that Abrams' fineness modulus was used mainly for design with Portland Cement Concrete, and it intentionally excluded the material passing the #100 sieve. It is not known why Abrams did this and others have not commented on it. Hudson's-A however, took into account the material smaller than the #100 sieve.

Hudson indicated that his modulus was related to the surface area of the aggregate and was a measure of its relative coarseness. Based on his research, he found that for the usual range of his gradation modulus (which varied from 4.00 to 6.00 in typical gradations), a change in his modulus of approximately 0.5 would affect, by one percent, the asphalt demand of an aggregate. This asphalt demand is the optimum amount of asphalt required to coat and bind the aggregate together. Hudson's-A is shown in Table 4.

Table 4. Calculation of Hudson's-A.

Sieve Size		Percent Passing
1-1/2		100.0
3/4		73.8
3/8		45.8
#4		40.3
#8		34.3
#16		27.2
#30		20.2
#50		12.3
#100		8.3
#200		6.5
	Total	368.7

Hudson's-A = 368.7 / 100 = 3.69.

Grading Modulus

In 1975, Lelievre et al[41], utilized a modification of Hudson's-A in what they termed the grading modulus. Computing their grading modulus for several mix designs, they developed an equation which could then be used for design purposes. They found that the asphalt demand of a particular aggregate mixture could be closely approximated with the following equation:

$$b = (Tg + 120) / 100 \qquad \text{Eq. 2}$$

where
 b = percent asphalt content
 Tg = grading modulus

The grading modulus was calculated by adding the percent passing the sieves 3/4, 1/2, 3/8, #4, #8, #16, #30, #50, #100, and #200. Note that this sequence is slightly different from the one proposed by Hudson in that the 1-1/2 inch sieve is not used and the 1/2 inch sieve is included in the set.

CHAPTER 3

AGGREGATE GRADATION RELIABILITY

Introduction

To compute a gradation modulus, one must rely on the actual reported gradation. Depending on the size of a sample, the gradation may or may not reflect the actual conditions in the field. As the size of the sample gets smaller, or as the frequency of the sampling decreases, the results will less accurately reflect average field conditions.

An example may be seen in relating the average aggregate gradation from the Jennings et al[33] data, discussed previously, to the allowable gradation band found in the Montana Department of Highways (MDOH) Standard Specifications[71]. The average gradation, consisting of the average of the percents passing similar sieves measured by Jennings et al, deviated outside the Montana standard allowances for the aggregate gradation. The average gradation indicated a higher percentage of fines (material passing the #4 sieve) than would normally be allowed by Montana specifications. Assuming that these gradations met the specifications at the time of construction, an assumption not always correct, explanations can be advanced as to why the average gradations tended to be more fine than required by the specifications. The reasons may apply not only to this particular project, but to all projects in general, and may be due to the fact that aggregates degrade with handling. Below are descriptions of the ways an aggregate is handled and how this may affect the reported aggregate gradation.

Handling and Test Procedures

As mentioned in Chapter 1, numerous tests were conducted on the pavement samples. Only those tests which contribute to aggregate degradation are outlined. These tests were run on core samples of pavements which had been in service for several months to many years.

Construction

During placement of the aggregate-asphalt mixture, a steel wheel roller is usually used to compact the asphalt mix into a solid, flexible mat. Some mixes compact easily, others require more weight and more intense vibrations, which may cause some aggregates to break down. The amount of breakage also depends on the type of aggregate.

Obtaining Core Samples

Samples were cored from in-service pavements by MDOH work teams. A 4-inch core barrel saw was used to extract the sample. This method shaved off pieces of the aggregates that were in the vertical plane of the cut. There is no method of predicting the absolute effect this had on the aggregate gradations, but it can be generalized that the gradations of the cut cores had less coarse material (retained above the #4 sieve) than the actual gradations of the pavements in service, due to the reduction in size of some of the aggregates.

Cutting with Diamond Blade Saw

The MDOH sent the core samples to Jennings et al at Montana State University (MSU) who separated the cores into their individual construction lifts. These construction lifts were identified by observing where there was the least aggregate interlock, and then separated in the horizontal plane of the core. Some interlocking of the lifts did occur due to the thickness of the lifts, the amount of compaction, and aggregate shape. When the lifts were cut apart by a diamond-blade wet saw, more pieces of aggregate were reduced in size, giving each aggregate gradation more percentages of smaller particles. To distinguish the cut faces of the aggregate particles from the natural fractured faces each core was dyed. After removing the asphalt from the aggregate with solvents, the dye remained on the cut faces of the particles. This helped in identifying the true percentages of fractured faces, but no attempt was made to use the dyed faces for a correction to the percentages of the different sizes in the aggregate gradation. If such a method of correction exists the author is unaware of it.

Marshall Stability and Flow

Some research[61,74] has been conducted which indicates that a Marshall sample behaves as a uniform, homogenous mass, regardless of the direction of testing. It may be that at the Marshall Stability test temperature (77^0.F), the asphalt allows for easy slippage and flow of the aggregate, resulting in little crushing or fracturing. Conceivably, however, a condition could exist in which the aggregates interlock, are unusually soft or fracture easily, or, the aggregate matrix lines up in such a way that the aggregates are crushed.

This latter condition could result in an extremely high initial stability with low flow. The possibility is small of this type of damage occurring during the Marshall stability test, yet it still remains a possibility. The sample would probably be excluded from the data as a questionable value.

Preparing Extraction Samples

The pavement samples were prepared for the extraction of the asphalt by physically breaking them apart. This was done by heating them in a microwave oven until the asphalt began to soften. A spoon or spatula was used to break apart the heated mixture. As carefully as each sample was handled, there were still pieces of aggregate which, due to their flat shape or previous fractures, were broken further apart into smaller particles.

Extraction

The aggregates and the asphalt were separated from each other by dissolving the asphalt with trichloroethylene (TCE), and spinning the solution off of the aggregate in a centrifuge. A filter in the centrifuge retained the majority of the fines with the aggregate sample, but some material still escaped with the asphalt/TCE solution. These lost fines were recovered by filtering the solution through millipore filters. Some extremely fine particles could have penetrated even the millipore filters and remained in the extracted asphalt, but the effect on the final gradation would have been minimal.

Sieve Analysis

The laboratory at MSU was not equipped to perform a wet sieve analysis. To modify the procedure, it was allowed that the aggregate would be sieved dry, but shaken for a longer period of time. It is recognized that increased shaking time may not substitute for wet sieve analysis. An accurate percentage of material passing the #200 sieve may be obtained only with the wet sieve analysis. In this case the aggregate gradation may have had small particles that clung to the larger particles and skewed the results. Conversely, the longer time of fifteen minutes spent in shaking may have caused any remaining unstable aggregates to break down. Softer materials would degrade to smaller particles. A study[23] however, has shown that the Montana aggregates from gravel pits had Los Angeles (L.A.) abrasion wear values from 16 to 31 percent, with a statewide average of 21.75 percent, well within the maximum acceptable value of 50 percent. It is reasonable to assume that the aggregates, on the whole, were relatively resistant to degradation.

Since the sieve method was dry, some minute particles escaped as airborne dust through the pans and settled throughout the laboratory. With the specified accuracy of tenths of a gram to which the samples were weighed, this loss was probably undiscernible.

Other Changes to the Gradation

Careless behavior in the laboratory in performing the tests could have resulted in some material being lost. If a hole existed undetected in a plastic bag containing the sample, some fines could have leaked out. Care was taken at all times to ensure that this did not happen.

Another way to lose a portion of the sample would have been not to place all of the material from the bag into the set of sieves. Care was taken here also to make sure all of the material which clung to the inside of the plastic bags was placed in the sieves.

One final place where the gradations could have been affected was the transfer of the gradation values measured in the laboratory to a computer data file. This human error of entering wrong numbers was recognized as a possibility and every number was checked and rechecked for correctness.

CHAPTER 4

DEVELOPMENT OF THE R-MODULUS

Standard Sieves

If aggregate gradation moduli are to be used to describe aggregate, it is mandatory that all the moduli be based on the use of one set of standard sieves. A direct comparison between moduli from two dissimilar sets of sieves would be meaningless. It is possible that a constant value exists which would convert a gradation modulus calculated from a set of original sieves into the same value as a gradation modulus calculated from a set of standardized sieves, but development of this factor is not considered here.

The suggested sieves, hereafter to be referred to as the standard sieves, are those in which the sieve openings of the smaller sizes are approximately one-half the dimension of the preceding size. For the development of the R-modulus, these sieves are defined as the sizes 1-1/2, 3/4, 3/8, #4, #8, #16, #30, #50, #100, and #200.

It is noted that the Federal Highway Administration has adopted a series of standard sieves for use in their

0.45 Power Gradation Chart which includes two other sizes, the 1 inch, and the 1/2 inch sieves. It is not disputed that these sizes are valuable, but they do not fit the requirements of the series described for use with the R-modulus. If a set of non-standard sieves is used, the original gradation could be plotted, and the values for the standard sieves picked off the chart. The values for the standard sieves may also be mathematically interpolated, as explained later.

Theory for R-Modulus

Goode and Lufsey[24], among others, emphasized that a higher percentage of fine material passing the #4 sieve affected the pavement performance. Varying the percentages of this fine material influenced the stability of an asphalt mix more than varying the percentages of the coarse aggregates. They showed that a higher percentage of aggregate material passing the #4 sieve lowered a mixture's stability. Since this smaller material has a greater influence, it should be allowed more consideration in an analysis.

The aggregate particles may be dependent on each other and interlock, or slide around each other, when subjected to loads. Loads may be easier to bear if fewer small particles are present and the larger particles are allowed to interlock with each other. Larger particles would have less tendency to rotate under a load because of their larger moments of inertia. As the amounts of smaller particles increase, the larger particles may displace more readily under load (due to a ball-bearing behavior of the smaller particles) and permit slippage.

Loads may be transferred in a mix to all the particles at the same time. This would mean the load is supported in a parallel action rather than a series action as it would be if each particle sustained the load individually. Based on these ideas an equation can be borrowed from electrical circuitry[69] for finding the equivalent resistance of a circuit of resistors in parallel.

$$R_{eq} = 1 / (\mathrm{SUM} (1 / R)) \qquad \text{Eq. 3}$$

where
R_{eq} = equivalent resistance
R = resistance in ohms.

By inverting the sum of the inverses of the percent passing each sieve, a number, now defined as the R-modulus, may be obtained that indicates the relative coarseness of an aggregate gradation.

$$\text{R-modulus} = 1 / (\mathrm{SUM} (1 / P_i)) \qquad \text{Eq. 4}$$

where
R-modulus = Gradation Modulus
P_i = Percent Material Passing Each Standard Sieve

The R-modulus takes into account the entire aggregate gradation but places more emphasis on the finer materials. Hudson's-A also looks at the entire gradation but places equal weight on both fine and coarse materials. Abrams' fineness modulus, however, is a measure of relative fineness because it is based on only the fine material sieves. The R-modulus is in a sense, also a fineness modulus, but it has the advantage over Abrams' fineness modulus and Hudson's-A in that it combines Hudson's idea of utilizing the whole set of standard sieves of 1-1/2 to #200 with Abrams' idea of concentrating on only the #4 to #100. An example of how to calculate the R-modulus is given in Table 5.

Table 5. Calculation of the R-modulus.

Sieve Size	Percent Passing	Inverse Percent Passing
1-1/2	100.0	0.010
3/4	73.8	0.014
3/8	45.8	0.022
#4	40.3	0.025
#8	34.3	0.029
#16	27.2	0.037
#30	20.2	0.050
#50	12.3	0.081
#100	8.3	0.120
#200	6.5	0.154
	Total	0.541

R-modulus = 1 / 0.541 = 1.848.

Variation of R-Modulus with Gradation

Simple gradations are listed in Table 6, along with their moduli, and are plotted in Figure 2. It can be pointed out that for these gradations, as each one becomes relatively more coarse than the preceding one, the R-Modulus decreases. Looking at another set of gradations which are listed in Table 7 and plotted in Figure 3, with each one having a smaller top end size than the preceding, as each aggregate gradation gets relatively finer, the R-Modulus gets larger.

Table 6. Well-Graded Aggregate Gradations.

	Percent Passing Each Sieve Size									
#	1-1/2	3/4	3/8	#4	#8	#16	#30	#50	#100	#200
1	100.0	100.0	90.0	73.0	58.6	47.3	38.0	30.8	24.8	20.0
2	100.0	100.0	88.0	68.0	52.0	39.9	30.6	23.6	18.1	13.9
3	100.0	100.0	86.0	63.0	46.0	33.7	24.6	18.0	13.2	9.7
4	100.0	100.0	84.0	59.0	40.8	28.5	19.8	13.8	9.7	6.7
5	100.0	100.0	82.0	55.0	36.2	24.0	15.9	10.6	7.1	4.7
6	100.0	100.0	80.0	51.0	32.1	20.3	12.8	8.1	5.2	3.2

R-modulus For Each Numbered Gradation	
1	4.502
2	3.538
3	2.747
4	2.111
5	1.612
6	1.206

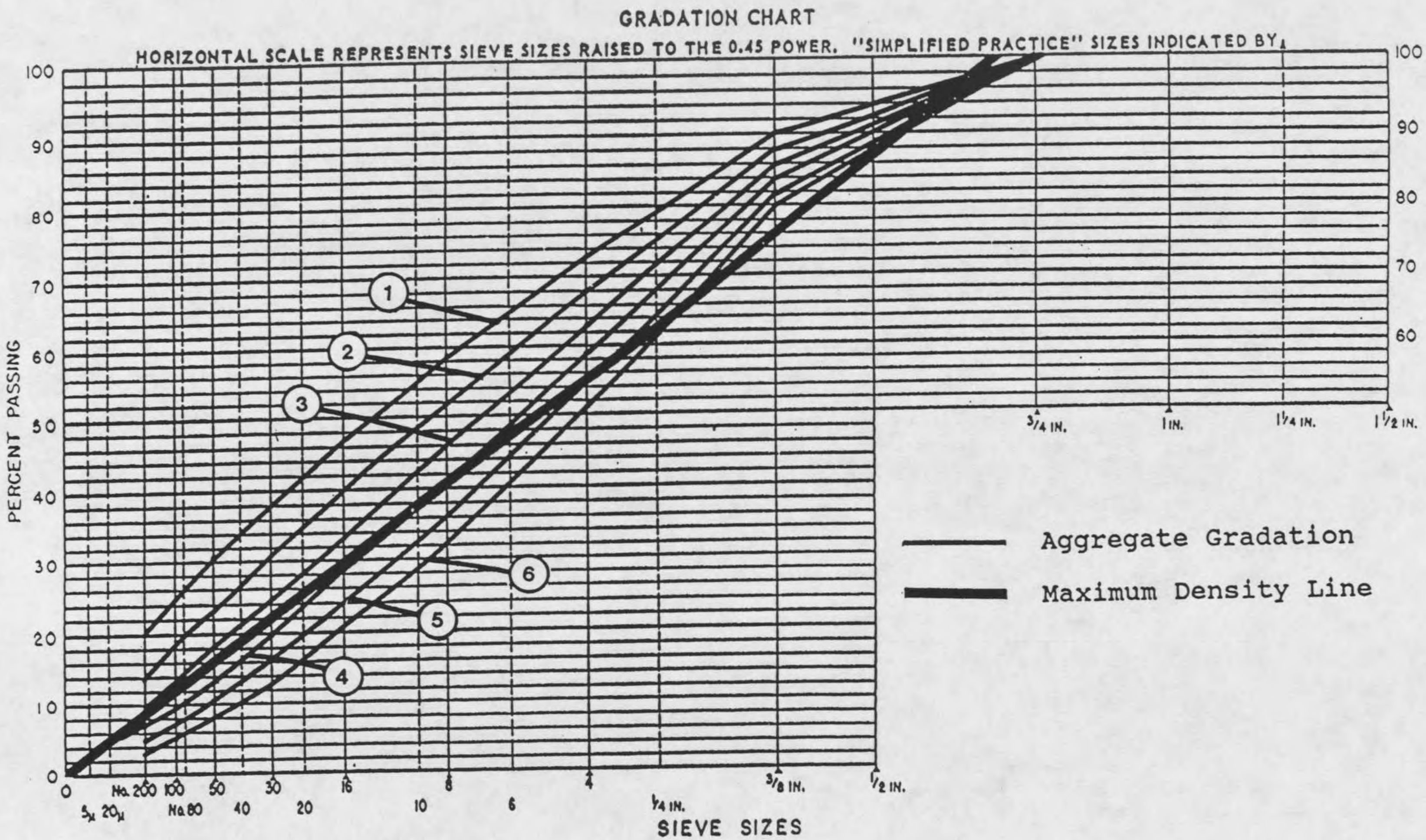

Figure 2. Well-Graded Aggregate Gradations as Listed in Table 6.

Table 7. Aggregate Gradations With Decreasing Top End Sizes.

Percent Passing Each Sieve Size

#	1-1/2	3/4	3/8	#4	#8	#16	#30	#50	#100	#200
1	100.0	73.2	53.6	39.2	28.7	21.0	15.4	11.3	8.3	6.0
2		100.0	73.2	53.5	39.2	28.7	21.0	15.4	11.3	8.2
3			100.0	73.1	53.6	39.2	28.7	21.0	15.4	11.2
4				100.0	73.3	53.7	39.2	28.7	21.1	15.3
5					100.0	73.2	53.6	39.2	28.8	20.9
6						100.0	73.1	53.5	39.3	28.6
7							100.0	73.2	53.8	39.1
8								100.0	73.5	53.4
9									100.0	72.6
10										100.0

R-modulus For Each Numbered Gradation

1	1.691
2	2.350
3	3.287
4	4.648
5	6.653
6	9.731
7	14.741
8	23.618
9	42.077
10	100.000

Examination of more complex gradations, listed by decreasing R-Modulus in Table 8 and plotted in Figure 4, shows that as expected, material percentage variation in the smaller sieve sizes affects the R-Modulus more than material percentage variation in the larger sieve sizes. After computation of the R-modulus, a hump in the plot of the gradation in the region of the smaller sieve sizes,

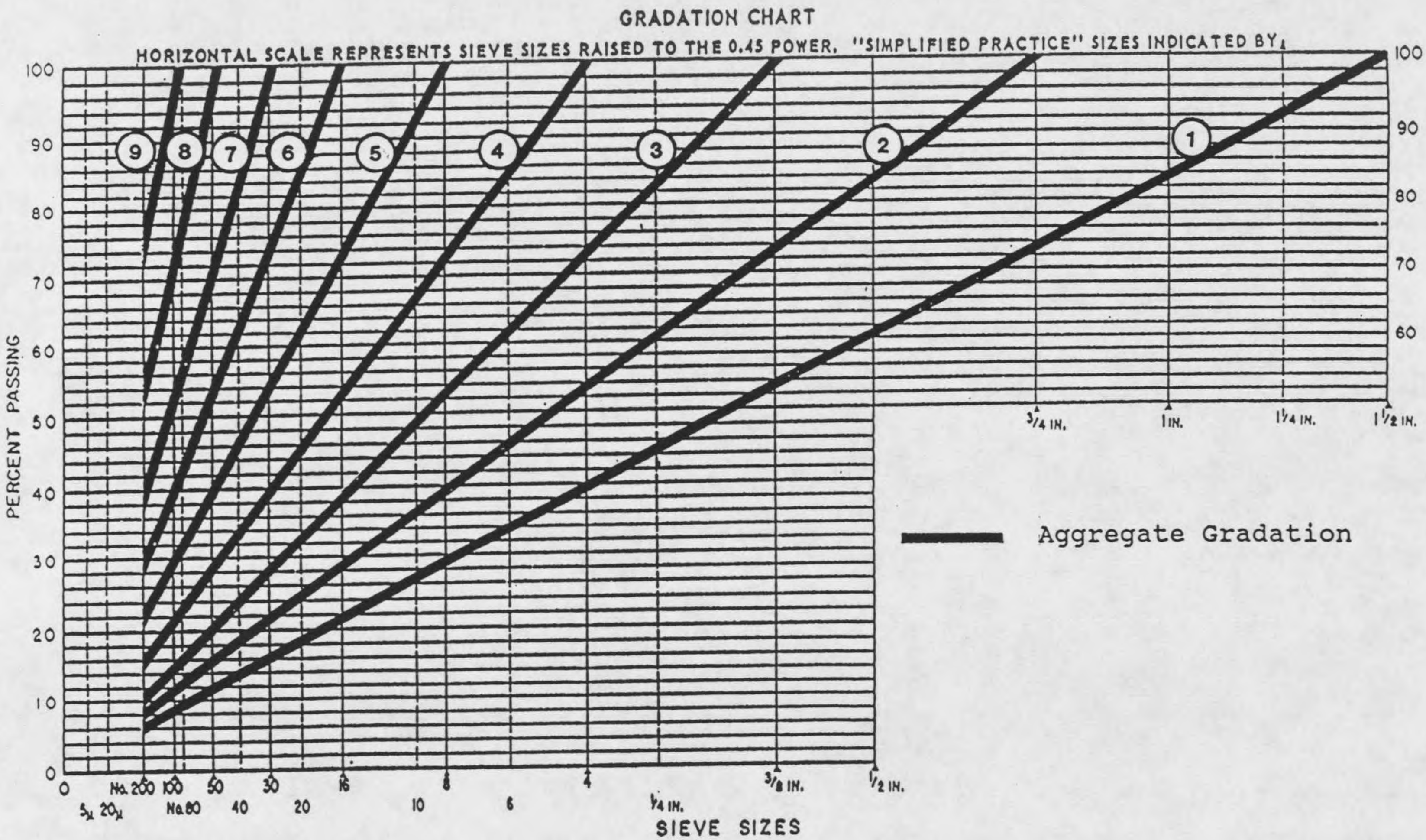

Figure 3. Aggregate Gradations of Decreasing Top End Sizes as Listed in Table 7.

Table 8. Aggregate Gradations of Various Shapes.

	Percent Passing Each Sieve Size									
#	1-1/2	3/4	3/8	#4	#8	#16	#30	#50	#100	#200
1	100.0	88.0	72.0	56.0	44.0	34.0	28.0	21.0	14.0	6.0
2	100.0	88.0	53.6	39.2	36.0	32.0	28.0	21.0	14.0	6.0
3	100.0	73.2	53.6	39.2	36.0	32.0	28.0	21.0	14.0	6.0
4	100.0	58.0	53.6	39.2	36.0	32.0	28.0	21.0	14.0	6.0
5	100.0	88.0	56.0	39.2	28.7	21.0	15.4	11.2	8.3	6.0
6	100.0	73.2	53.6	39.2	28.7	21.0	15.4	11.2	8.3	6.0
7	100.0	58.0	53.6	39.2	28.7	21.0	15.5	11.2	8.3	6.0
8	100.0	88.0	53.6	39.2	21.0	12.0	9.0	7.0	6.5	6.0
9	100.0	73.2	53.6	39.2	21.0	12.0	9.0	7.0	6.5	6.0
10	100.0	58.0	53.6	39.2	21.0	12.0	9.0	7.0	6.5	6.0
11	100.0	58.0	35.0	22.0	16.0	12.0	9.0	7.0	6.5	6.0

R-modulus and Description For Each Numbered Gradation

1	2.343	All hump	finer
2	2.242	3/4 and #30 humps	.
3	2.231	#30 hump	.
4	2.213	3/4 trough and #30 hump	.
5	1.697	3/4 hump	.
6	1.690	Maximum density	.
7	1.680	3/4 trough	.
8	1.297	3/4 hump and #30 trough	.
9	1.293	#30 trough	.
10	1.287	3/4 trough and #30 trough	.
11	1.217	All trough	coarser

which means relatively higher percentages of material passing the #4 sieve, is not balanced out by a trough in the region in the larger sieve sizes. Conversely, a trough in the smaller sieve size region is not balanced by a hump in the larger sieve size region. This means that a hump in the smaller sieves (more fine material) gives a

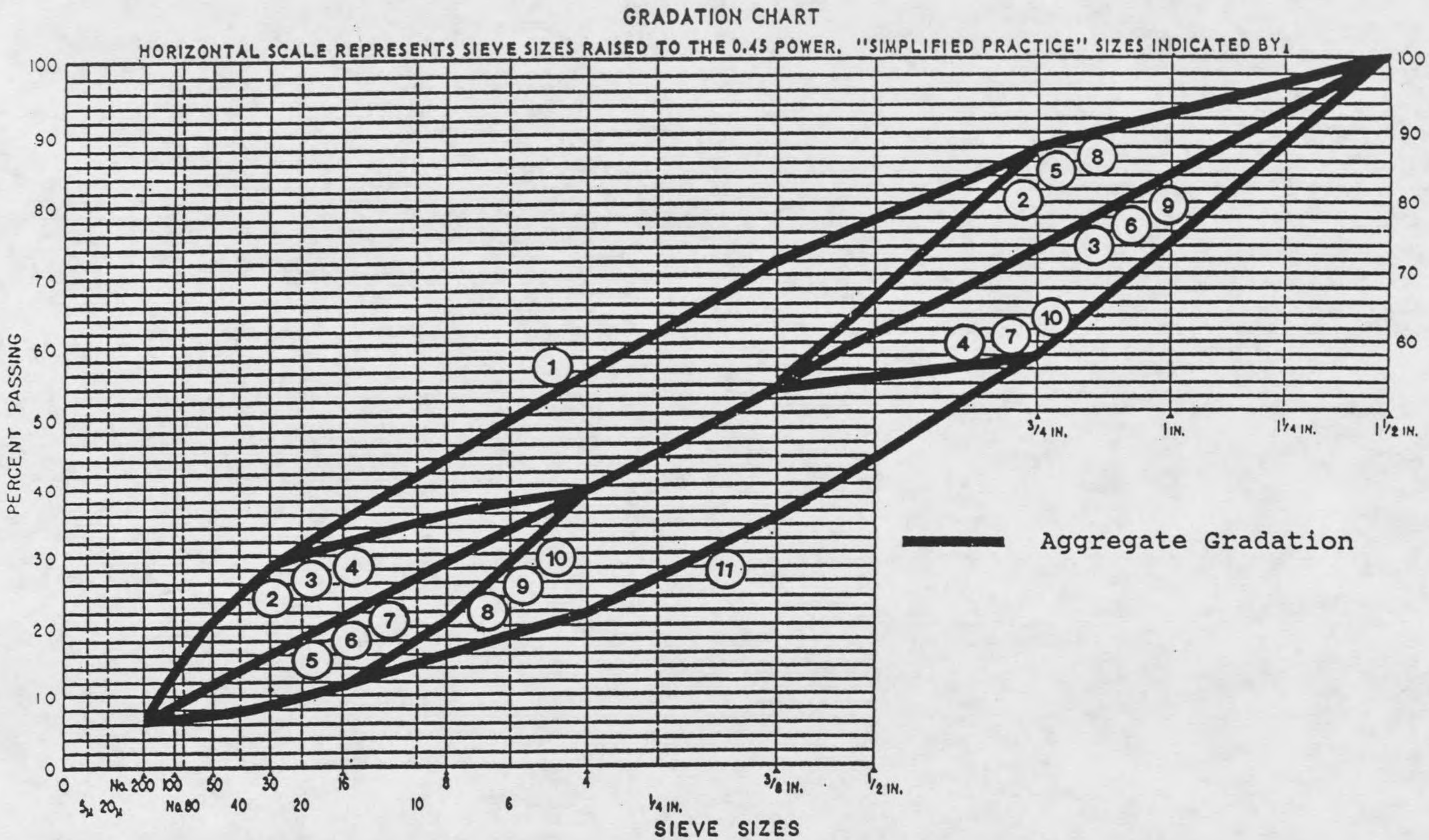

Figure 4. Aggregate Gradations of Various Shapes as Listed in Table 8.

R-modulus than if the hump is in fact that the smaller particle sizes are weighted more heavily, the finer an aggregate gradation is, the larger its R-modulus becomes.

<u>Gradation Analysis Using R-modulus</u>

Each aggregate gradation has a unique maximum density line to which it may be compared. This maximum density line is an empirical characteristic defined by Goode and Lufsey[24] as that combination of different sizes of material that has the least voids. The proper method for obtaining this figure is still being debated[37]. Those that dispute the calculation agree that the maximum density line is a straight line plotted on FHWA's 0.45 Power Gradation Chart, with its origin at zero. The dispute occurs in how the other point is selected for drawing the line. The three methods known are:

(A) Upper point is the maximum size particle, that is, the last sieve size that all the material will pass.

(B) Upper point is the first sieve size on which material is retained.

(C) Upper point is the intersection of the actual aggregate gradation curve with the 90 or 95 percent passing line.

To obtain the maximum density line, the percentages passing each sieve may be calculated mathematically, or obtained graphically by drawing a straight line from the origin to 100 percent passing through the point where the actual gradation crosses 95 percent passing as selected for this thesis.

If after plotting, a gradation curve is above the maximum density line, the gradation is said to be relatively fine. If it is below the maximum density line, it is said to relatively coarse. The R-Modulus for the actual gradation may be compared to the R-Modulus for the maximum density line to obtain a measure of the actual gradation's relative coarseness or fineness. Subtracting the maximum density line's R-Modulus from the actual gradation's R-modulus may give a positive or negative value. Depending on the magnitude of this difference, one can determine just how coarse or fine a gradation is. A large positive difference indicates a fine gradation relative to the maximum density line. A large negative difference indicates a coarse gradation, again relative to the maximum density line.

Referring to Table 7 for the aggregate gradations with decreasing top end sizes, one should notice that the calculations for summing the inverses begin at the smallest sieve that has 100 percent passing. It is meaningless to include all the sieves with 100 percent passing in the calculation of this modulus, since no material from those sizes contributes to the mixture's behavior.

Table 9 is an example of how to compute the R-Modulus from a series of non-standard sieves. To aid in this

Table 9. Standardizing an Original Aggregate Gradation

Original Sieves	Original Percent Passing	Standard Sieves	Sieve Size (inches)	Standard Percent Passing
1-1/2	100.0	1-1/2	1.5000	100.0
1	98.0	-----	1.0000	-----
3/4	92.0	3/4	0.7500	92.0
1/2	74.0	-----	0.5000	-----
3/8	68.0	3/8	0.3750	68.0
#4	40.0	#4	0.1870	40.0
-----	-----	#8	0.0937	31.7
#10	30.0	-----	0.0787	-----
-----	-----	#16	0.0469	28.4
-----	-----	#30	0.0234	26.7
#40	26.0	-----	0.0165	-----
-----	-----	#50	0.0117	23.3
#80	20.0	-----	0.0070	-----
-----	-----	#100	0.0059	17.3
#200	8.0	#200	0.0029	8.0

$$SPP = PP_L - \frac{(SS_L^{0.45} - SS^{0.45}) * (PP_L - PP_S)}{(SS_L^{0.45} - SS_S^{0.45})}$$

where

SSP = Standardized Percent Passing
PP_L = Percent Passing Original Larger Sieve
PP_S = Percent Passing Original Smaller Sieve
SS_L = Original Larger Sieve Size
SS_S = Original Smaller Sieve Size
SS = Standardized Sieve Size.

calculation, a list of sieves and their sizes are given in Table 10. Note that if one plotted the original non-standard gradation and replotted the interpolated standard gradation, the curves could be different, as Figure 5 illustrates. Some researchers[18,24,29,31,34,51] have suggested the standardizing of sieves and they have met with limited success. This author also recommends a uniform set of standard sieves. If other sieves are desired, they should be added to the standard set of sieves. (See this author's definition of "standard sieves" and the recommended sizes at the beginning of this chapter.)

In calculating the R-modulus, discrete sieve sizes are required. The maximum density line (found by Method C above) however, usually does not terminate at a discrete size and 100 percent passing. To obtain the R-modulus for this case it is suggested that an interpolation be drawn between the known R-moduli that represent the maximum density lines which terminate on discrete sieve sizes, and bracket the third maximum density line for which the R-modulus is being sought. To simplify this calculation, an equation has been developed in which all that is needed is the position on the x-axis where the actual gradation curve intersects with 100 percent passing, defined as the effective maximum size.

Table 10. Nominal Dimensions of Wire Cloth Sieves.

Sieve Designation	Nominal Sieve Opening (in)	Nominal Sieve Opening (mm)
3 in.	3.0	75
2-1/2 in.	2.5	63
2 in.	2.0	50
1-3/4 in.	1.75	45
1-1/2 in.	1.5	37.5
1-1/4 in.	1.25	31.5
1 in.	1.0	25.0
7/8 in.	0.875	22.4
3/4 in.	0.750	19.0
5/8 in.	0.625	16.0
0.530 in.	0.530	13.2
1/2 in.	0.500	12.5
7/16 in.	0.438	11.2
3/8 in.	0.375	9.5
5/16 in.	0.312	8.0
0.265 in.	0.265	6.7
1/4 in.	0.250	6.3
No. 3-1/2	0.223	5.6
No. 4	0.187	4.75
No. 5	0.157	4.00
No. 6	0.132	3.35
No. 7	0.111	2.80
No. 8	0.0937	2.36
No. 10	0.0787	2.00
No. 12	0.0661	1.70
No. 14	0.0555	1.40
No. 16	0.0469	1.18
No. 18	0.0394	1.00
No. 20	0.0331	0.85
No. 25	0.0278	0.71
No. 30	0.0234	0.60
No. 35	0.0197	0.50
No. 40	0.0165	0.425
No. 45	0.0139	0.355
No. 50	0.0117	0.300
No. 60	0.0098	0.250
No. 70	0.0083	0.212
No. 80	0.0070	0.180
No. 100	0.0059	0.150
No. 120	0.0049	0.125
No. 140	0.0041	0.106
No. 170	0.0035	0.090
No. 200	0.0029	0.075

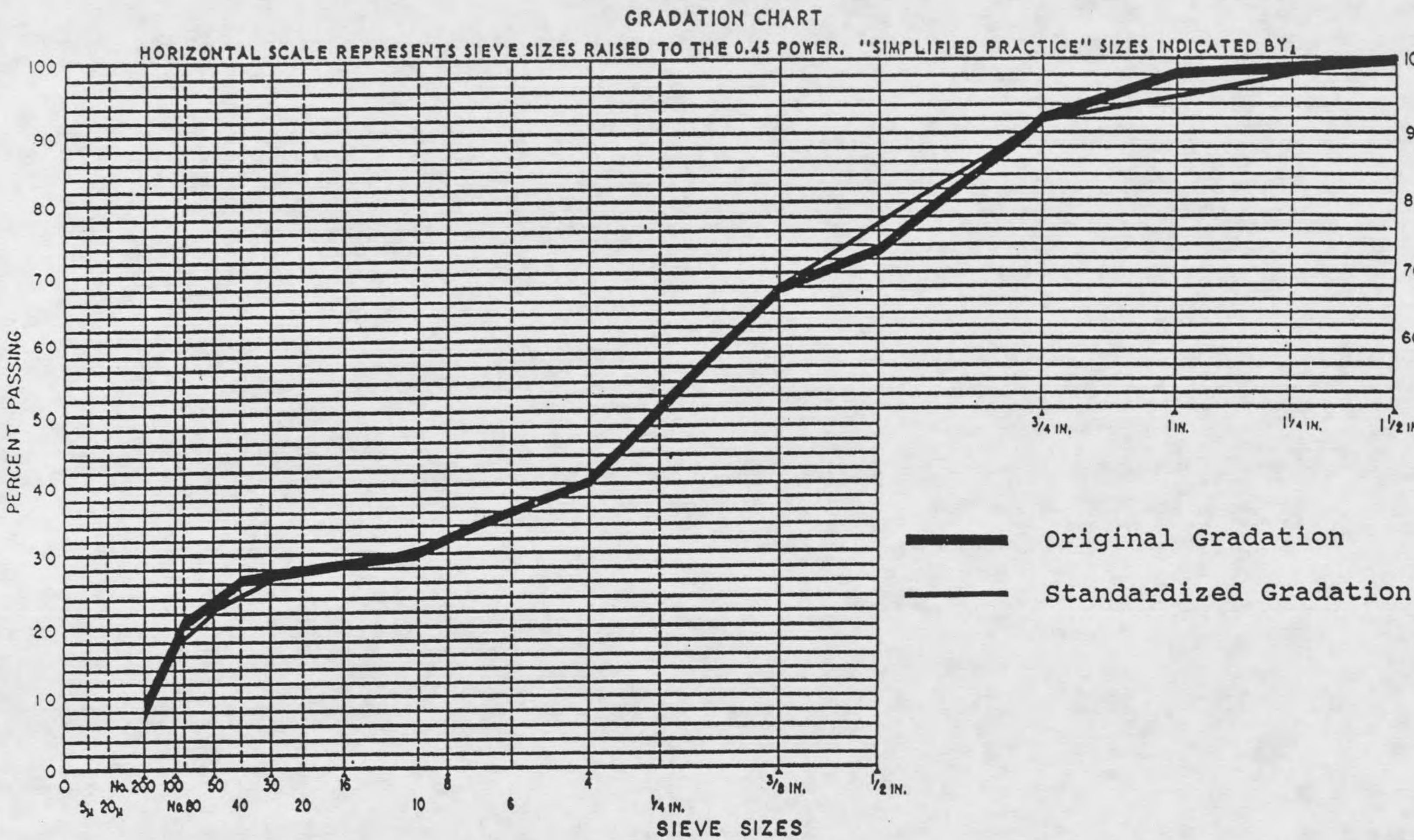

Figure 5. Original and Standardized Aggregate Gradations as Listed in Table 9.

Each aggregate gradation, for which the effective maximum size of the maximum density line is sought, has several known values. These are the several sizes of sieves and the percent material passing them. These values usually bracket the effective maximum size. The maximum density line begins at the origin and intersects the actual gradation at 95 percent passing. The unknown is the horizontal coordinate where the maximum density lines intersects with the 100 percent passing.

Using the semi-log 0.45 power gradation chart the relationship between the two curves at the point of intersection may be given thus:

$$\frac{PP_L - 95}{PP_L - PP_S} = \frac{SS_L^{0.45} - x^{0.45}}{SS_L^{0.45} - SS_S^{0.45}} \qquad \text{Eq. 5}$$

where

EMS = Effective Maximum Sieve Size

x = Size of Particle at the 95% Intersection

SS_L = Larger Discrete Sieve Size

SS_S = Smaller Discrete Sieve Size

PP_L = Percent Material Passing the Larger Sieve

PP_S = Percent Material Passing the Smaller Sieve

One should note that PP_L may not be 100 percent in all cases.

Cross multiplying and solving for x gives:

$$x = SS_L^{0.45} - \frac{(SS_L^{0.45} - SS_S^{0.45}) * (PP_L - 95)}{(PP_L - PP_S)} \qquad \text{Eq. 6}$$

Since this x is only 95 percent of the effective maximum size the particle size at 100 percent passing may be obtained by multiplying x by the ratio of 100/95.

$$EMS = x * (20/19) \qquad \text{Eq. 7}$$

Substituting Equation 6 into Equation 7 then gives an effective maximum size of:

$$EMS^{0.45} = (SS_L^{0.45} - \frac{(SS_L^{0.45} - SS_S^{0.45}) * (PP_L - 95)}{(PP_L - PP_S)}) * \frac{20}{19} \qquad \text{Eq. 8}$$

With the maximum effective size defined, it may be used to find an unknown R-modulus for a maximum density line. Plotting each known R-Modulus from Table 7 versus its largest sieve size, raised to the 0.45 power, gives the shape shown in Figure 6. Plotting 1 / R-Modulus versus sieve size to 0.45 power gives a straight line as shown in Figure 7. The equation for this line is

$$1 / \text{R-Modulus} = 0.5155\ (EMS^{0.45}) - 0.0274 \qquad \text{Eq. 9}$$

where
R-modulus = Gradation Modulus
EMS = Effective Maximum Sieve Size

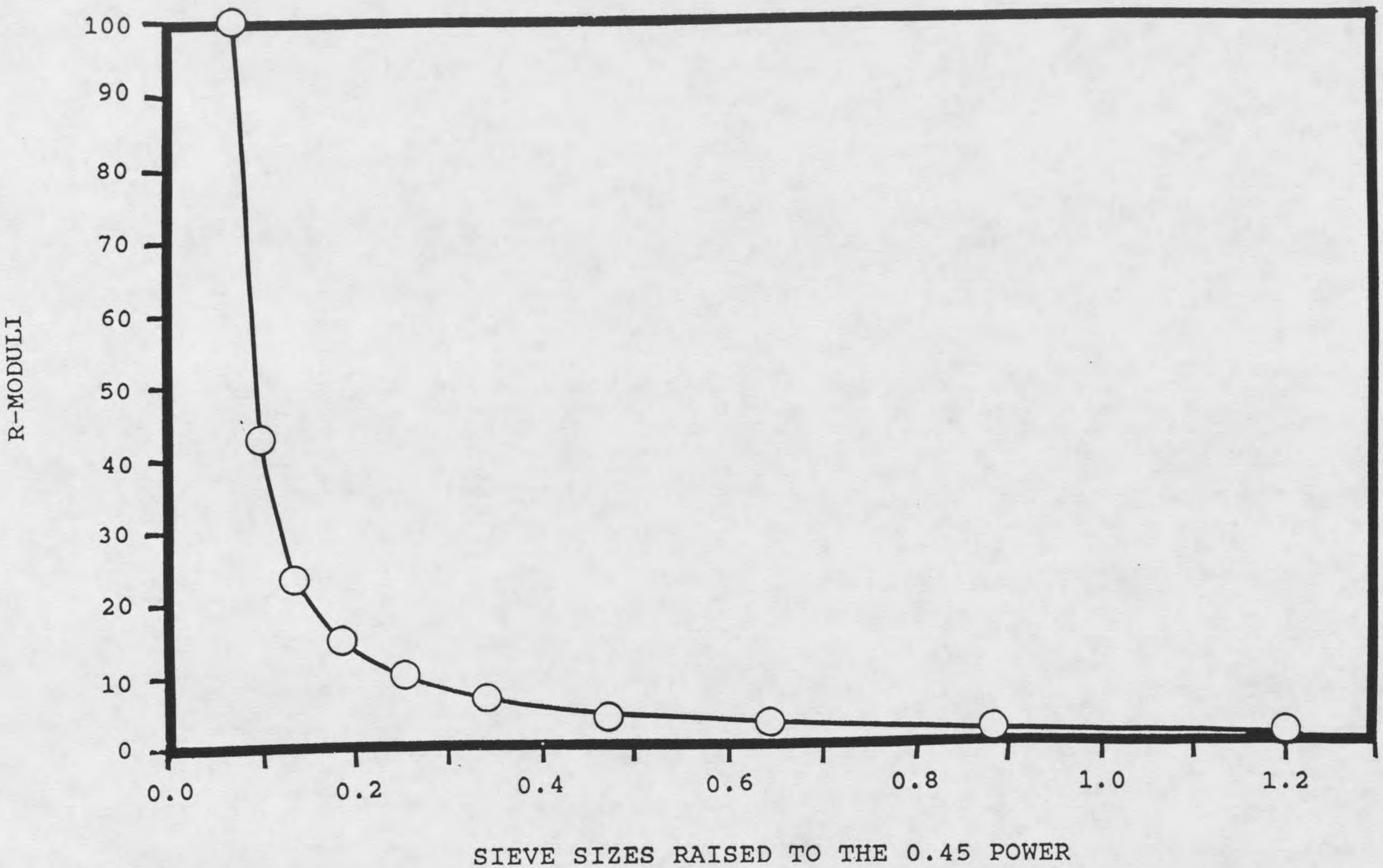

Figure 6. R-moduli Versus Sieve Sizes Raised to the 0.45 Power.

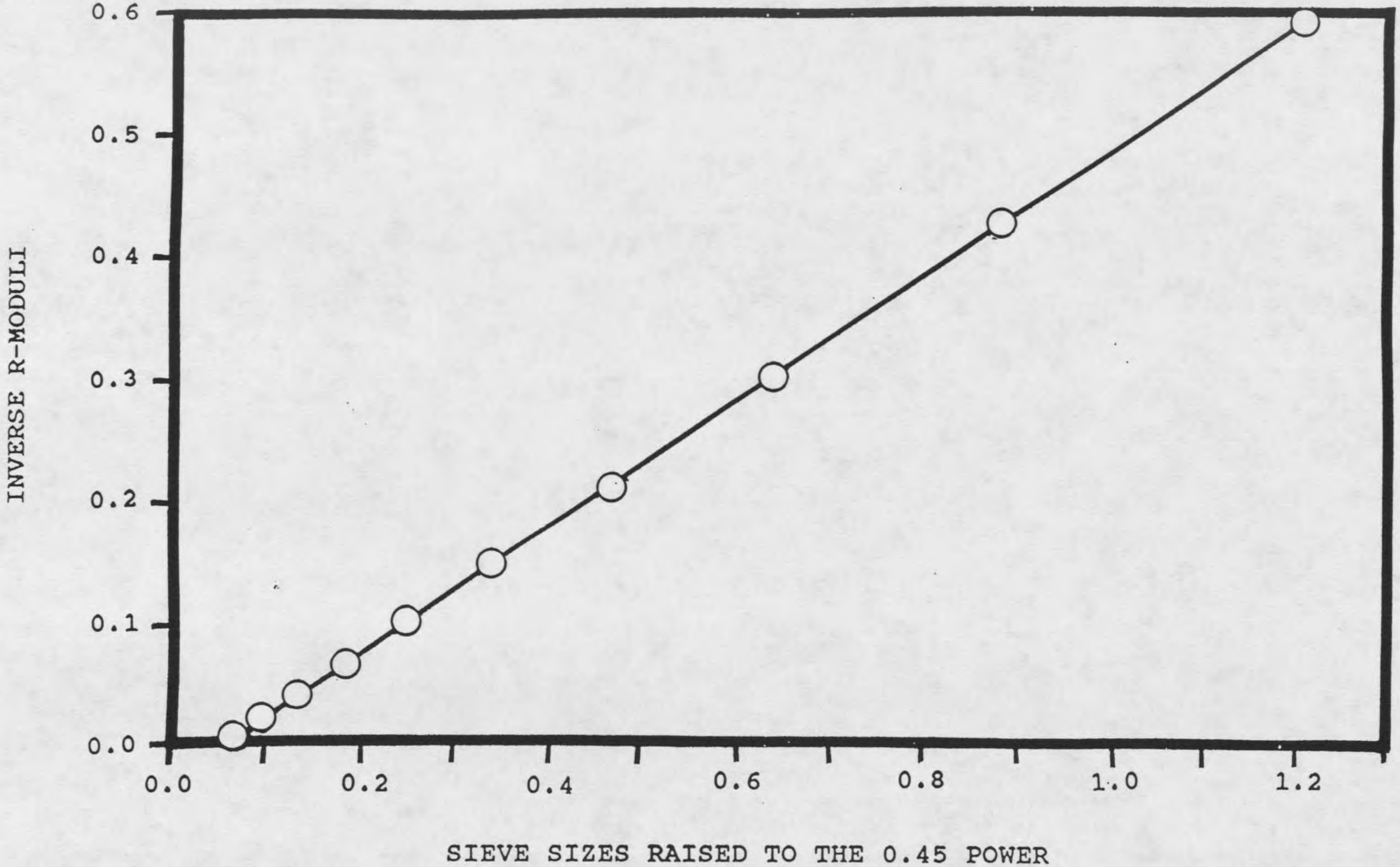

Figure 7. Inverse R-moduli Versus Sieve Sizes Raised to the 0.45 Power.

For example, using Eq. 8, and Gradation #6 from Table 6 the effective maximum size is:

$$EMS^{.45} = (.75^{.45} - \frac{(.75^{.45} - .375^{.45}) * (100 - 95)}{(100 - 80)} * \frac{20}{19} = .863$$

Using this value in Eq. 9, an R-Modulus is obtained of 2.395. Subtracting this maximum density R-Modulus from the actual R-Modulus of 1.206 shown in Table 6, gives a difference of -1.189. Since the difference is negative, the aggregate gradation is relatively coarse. This can be confirmed visually in Figure 2 by noting that the actual aggregate gradation falls mostly below the maximum density line.

CHAPTER 5

ANALYSIS OF SEVERAL DATA SETS

The purpose of this chapter is to show that the R-modulus may be valuable in interpreting the response of material to loading. The data sets examined consist of plain aggregates, Portland Cement concrete mixtures, or asphalt mixtures. The initial intended use of the R-modulus during development was for interpreting physical behavioral data of asphaltic mixtures, but there is no reason to limit its application to this. The R-modulus may be more useful with some materials than with others. This chapter also compares the R-modulus with the Abrams fineness modulus and Hudson's-A.

Five data sets were examined from five different researchers. The first data set from Barksdale[8] looked at rutting depths in the subgrade of various aggregate gradations that had no asphalt or Portland Cement binder. The second data set from Goode and Lufsey[24] examined the effect, on asphalt pavement's performance, of varying the aggregate gradations in an asphalt mixture, while maintaining a constant asphalt content. The third data set, from Abrams[1], showed that for different gradations, similar fineness moduli may be obtained and then related to compressive strengths of 28-day concrete. The fourth data set from Jennings et al[33] was a compilation of aggregate gradations from cores taken from the State of Montana's Interstate system pavements. The last data set is from the Accelerated Loading Facility (ALF)[11] at the Turner-Fairbank Highway Research Center of the Federal Highway Administration at McLean, Virginia. The gradations were from both asphalt mixes, and untreated bases.

Barksdale's Data

The ten gradations listed in Table 11 were Barksdale's original reported gradations. The standardized values from the original gradations are listed in Table 12. These ten gradations can be divided into five groups, with similar materials in each group. Table 13 lists the gradations numerically by group. It also lists the computed R-Modulus for the standardized gradation, the R-Modulus for each maximum density line, the difference between the two R-moduli, Hudson's-A, the fineness modulus, and Barksdale's rut index.

Barksdale placed his specimens in six inch diameter by twelve inch high triaxial cells and subjected them to 100,000 load repetitions. In his abstract Barksdale says,

Table 11. Barksdale's Original Aggregate Gradations

Gradation #	Description	Percent Passing 1-1/2	3/4	#10	#60	#200
1.	Orange-tan, slightly clayey, silty sand.	100.0	100.0	100.0	63.0	40.0
2.	40% silty fine sand and 60% crushed granite gneiss.	99.0	85.0	42.0	25.0	13.0
3.	40% silty fine sand and 60% crushed biotite gneiss.	100.0	72.0	39.0	23.0	11.0
4.	17% silty sand and 83% crushed biotite granite gneiss.	95.0	60.0	30.0	13.0	8.0
5.	21% sandy silty and 79% crushed biotite granite gneiss.	97.0	78.0	28.0	28.0	14.8
6.	Crushed prophyritic granite gneiss - 3% fines.	100.0	60.0	25.0	9.0	3.0
7.	Crushed prophyritic granite gneiss - 11.25% fines.	100.0	90.0	45.0	27.0	11.25
8.	Crushed biotite granite gneiss - 3% fines.	100.0	60.0	25.0	9.0	3.0
9.	Crushed biotite granite gneiss - 11.25% fines.	100.0	90.0	45.0	27.0	11.25
10.	Crushed biotite granite gneiss - 22% fines.	100.0	90.0	45.0	27.0	22.0

Table 12. Standardized Gradations of Barksdale's Data.

Gradation #	1-1/2	3/4	3/8	#4	#8	#16	#30	#50	#100	#200
	Percent Passing Each Sieve Size									
1	100.0	100.0	100.0	100.0	100.0	87.4	74.4	65.0	51.9	40.0
2	99.0	85.0	66.9	53.6	44.0	36.2	30.2	25.9	19.2	13.0
3	100.0	72.0	58.1	47.9	40.5	33.5	27.9	23.9	17.2	11.0
4	95.0	60.0	47.4	38.1	31.4	24.2	18.2	13.9	10.6	8.0
5	97.0	78.0	57.0	41.5	30.3	28.0	28.0	28.0	21.6	14.8
6	100.0	60.0	45.3	34.5	26.6	19.5	13.9	9.9	6.1	3.0
7	100.0	90.0	71.1	57.2	47.1	38.9	32.6	28.0	19.4	11.3
8	100.0	60.0	45.3	34.5	26.6	19.5	13.9	9.9	6.1	3.0
9	100.0	90.0	71.1	57.2	47.1	38.9	32.6	28.0	19.4	11.3
10	100.0	90.0	71.1	57.2	47.1	38.9	32.6	28.0	19.4	22.0

> "The concept of a rut index was proposed which can be calculated making use of the plastic stress-strain relationship, and is approximately proportional to the rut depth that will occur in the base after a desired number of load repetitions."[8]

No comparisons can be drawn from Group 1, Table 13, because the group contains only one sample. It can be noted that the gradation in this group has a very high R-Modulus. The difference between the actual R-modulus and the maximum density R-modulus indicates that Gradation #1 is very fine in relation to its maximum density. Barksdale did not report a rut index for this sample, but stated it was "very large". The theory of a high R-modulus for the actual gradation, in combination with the large positive difference between the actual and the maximum density R-moduli, would indicate a high rut index.

The calculated values of the R-moduli for Group 2, Table 13 show that a larger R-modulus corresponds to a higher rut index.

Table 13. Calculated and Measured Data of Barksdale.

	A	B	C	D	E	F	G
Group 1	1	10.576	7.150	3.426	8.19	1.21	----
Group 2	2	3.263	1.742	1.521	4.73	1.92	1050
	3	2.914	1.687	1.227	4.32	1.58	405
Group 3	4	2.025	1.603	0.422	3.47	1.48	332
	5	3.138	1.651	1.486	4.24	1.64	164
Group 4	6	1.195	1.661	-0.466	3.19	1.61	176
	7	3.261	1.863	1.398	4.95	2.03	298
Group 5	8	1.195	1.661	-0.466	3.19	1.61	258
	9	3.261	1.863	1.398	4.95	2.03	385
	10	3.964	1.863	2.101	5.11	1.98	419

Column A - Aggregate Gradation Number
Column B - Actual Aggregate Gradation R-modulus
Column C - Maximum Density Line's R-modulus
Column D - Difference Between Column B and C
Column E - Hudson's-A
Column F - Abrams' Fineness Modulus
Column G - Barksdale's Rut Index
---- data not available

Both gradations in Group 2 are relatively fine compared to their maximum density lines, as shown by the difference in the two R-moduli. This would seem to add some confirmation to the R-modulus theory. Group 3 however, seems to contradict it. The larger R-modulus in Group 3 corresponds to the lower rut index, rather than the higher rut index.

The values in Groups 4 and 5 however, correlate to the rut index as they did in Group 2. It is difficult to explain why the Group 3 values correspond poorly. One possible explanation is that the reported percent passing the #60 sieve in Gradation #5, Table 11, is in error, as it is the same as the value for the #10 sieve. This would indicate "gap grading" between the sieves. In such a case, no material would be represented for the sieves between the sizes of #60 and #10. Barksdale may, or may not have specifically wanted this condition.

Group 4 has only two gradations in it. Gradation #6 is a coarser material than Gradation #7 and is more coarse when compared to its maximum density. Gradation #7 is a finer material when compared to its maximum density. Gradation #7 has a higher rut index than Gradation #6 as would be predicted by the R-modulus theory.

The three gradations in Group 5 also behave as expected. Gradation #9 has a higher percentage of fine materials than does Gradation #8, while Gradation #10 has the highest percentage of fine material, as shown by their actual R-modulus. Compared to the R-modulus for maximum density, Gradation #8 is relatively coarse, while Gradations #9 and #10 are relatively fine. Gradation #8, which is the most coarse, has the lower rut index, while Gradations #9 and #10 have rut indices that increase with their fineness.

Hudson's-A and the fineness modulus compare similarly to the rut index, but because they lack maximum density moduli to compare to the actual moduli, no estimate of their gradations' relative fineness or relative coarseness is offered. Conceivably moduli could be calculated for maximum density lines, but this is not entered into here.

Goode and Lufsey's Data

The twenty-four gradations reported by Goode and Lufsey are listed in Table 14. Table 15 lists the standardized gradations. For a constant asphalt content of 5.5 percent and a variable air voids content, Goode and Lufsey measured the Marshall stability and flow of each mixture.

The twenty-four gradations can be divided into five gradation types as shown in Figures 8 through 12. Figure 8 shows "well-graded" gradations.

Table 14. Goode and Lufsey's Original Gradations.

Gradation #	Percent Passing Each Sieve Size: 0.525	1/2	3/8	#4	#8	#16	#30	#50	#100	#200
1	100.0	99.0	90.0	73.0	58.6	47.3	38.0	30.8	24.8	20.0
2	100.0	98.0	88.0	68.0	52.0	39.9	30.6	23.6	18.1	13.9
3	100.0	98.0	86.0	63.0	46.0	33.7	24.6	18.0	13.2	9.7
4	100.0	98.0	84.0	59.0	40.8	28.5	19.8	13.8	9.7	6.7
5	100.0	97.0	82.0	55.0	36.2	24.0	15.9	10.6	7.1	4.7
6	100.0	97.0	80.0	51.0	32.1	20.3	12.8	8.1	5.2	3.2
7	100.0	98.0	85.0	61.0	43.1	30.1	20.4	13.5	8.4	4.7
8	100.0	98.0	86.0	63.0	46.0	40.6	36.6	22.6	12.3	4.7
9	100.0	98.0	86.0	63.0	46.0	38.3	32.6	20.4	11.4	4.7
10	100.0	98.0	86.0	63.0	46.0	36.0	28.6	18.1	10.4	4.7
11	100.0	98.0	86.0	63.0	46.0	33.7	24.6	15.9	9.4	4.7
12	100.0	98.0	86.0	63.0	46.0	32.0	21.6	14.2	8.7	4.7
13	100.0	98.0	88.0	68.0	53.3	46.0	40.6	24.9	13.3	4.7
14	100.0	98.0	88.0	68.0	53.3	43.7	36.6	22.6	12.3	4.7
15	100.0	98.0	88.0	68.0	53.3	41.4	32.6	20.4	11.4	4.7
16	100.0	98.0	88.0	68.0	53.3	39.1	28.6	18.1	10.4	4.7
17	100.0	98.0	88.0	68.0	53.3	36.8	24.6	15.9	9.4	4.7
18	100.0	98.0	84.0	58.0	38.9	35.3	32.6	20.4	11.4	4.7
19	100.0	98.0	84.0	58.0	38.9	33.0	28.6	18.1	10.4	4.7
20	100.0	98.0	84.0	58.0	38.9	30.7	24.6	15.9	9.5	4.7
21	100.0	98.0	84.0	58.0	38.9	28.4	20.6	13.6	8.5	4.7
22	100.0	98.0	84.0	58.0	52.0	36.0	24.1	15.6	9.3	4.7
23	100.0	97.0	82.0	52.0	46.0	32.0	21.6	14.2	8.7	4.7
24	100.0	97.0	80.0	46.6	40.0	28.1	19.2	12.8	8.1	4.7

Figures 9 through 11 show "hump" gradations that have medium, high, and low sand contents, respectively.

Table 15. Standardized Gradations of Goode and Lufsey's.

Gradation #	1-1/2	3/4	3/8	#4	#8	#16	#30	#50	#100	#200
	Percent Passing Each Sieve Size									
1	100.0	100.0	90.0	73.0	58.6	47.3	38.0	30.8	24.8	20.0
2	100.0	100.0	88.0	68.0	52.0	39.9	30.6	23.6	18.1	13.9
3	100.0	100.0	86.0	63.0	46.0	33.7	24.6	18.0	13.2	9.7
4	100.0	100.0	84.0	59.0	40.8	28.5	19.8	13.8	9.7	6.7
5	100.0	100.0	82.0	55.0	36.2	24.0	15.9	10.6	7.1	4.7
6	100.0	100.0	80.0	51.0	32.1	20.3	12.8	8.1	5.2	3.2
7	100.0	100.0	85.0	61.0	43.1	30.1	20.4	13.5	8.4	4.7
8	100.0	100.0	86.0	63.0	46.0	40.6	36.6	22.6	12.3	4.7
9	100.0	100.0	86.0	63.0	46.0	38.3	32.6	20.4	11.4	4.7
10	100.0	100.0	86.0	63.0	46.0	36.0	28.6	18.1	10.4	4.7
11	100.0	100.0	86.0	63.0	46.0	33.7	24.6	15.9	9.4	4.7
12	100.0	100.0	86.0	63.0	46.0	32.0	21.6	14.2	8.7	4.7
13	100.0	100.0	88.0	68.0	53.3	46.0	40.6	24.9	13.3	4.7
14	100.0	100.0	88.0	68.0	53.3	43.7	36.6	22.6	12.3	4.7
15	100.0	100.0	88.0	68.0	53.3	41.4	32.6	20.4	11.4	4.7
16	100.0	100.0	88.0	68.0	53.3	39.1	28.6	18.1	10.4	4.7
17	100.0	100.0	88.0	68.0	53.3	36.8	24.6	15.9	9.4	4.7
18	100.0	100.0	84.0	58.0	38.9	35.3	32.6	20.4	11.4	4.7
19	100.0	100.0	84.0	58.0	38.9	33.0	28.6	18.1	10.4	4.7
20	100.0	100.0	84.0	58.0	38.9	30.7	24.6	15.9	9.5	4.7
21	100.0	100.0	84.0	58.0	38.9	28.4	20.6	13.6	8.5	4.7
22	100.0	100.0	84.0	58.0	52.0	36.0	24.1	15.6	9.3	4.7
23	100.0	100.0	82.0	52.0	46.0	32.0	21.6	14.2	8.7	4.7
24	100.0	100.0	80.0	46.0	40.0	28.1	19.2	12.8	8.1	4.7

Figure 12 illustrates "skip" gradations. Table 16 summarizes the calculated gradation moduli and the measured values for the mixtures of the twenty-four gradations.

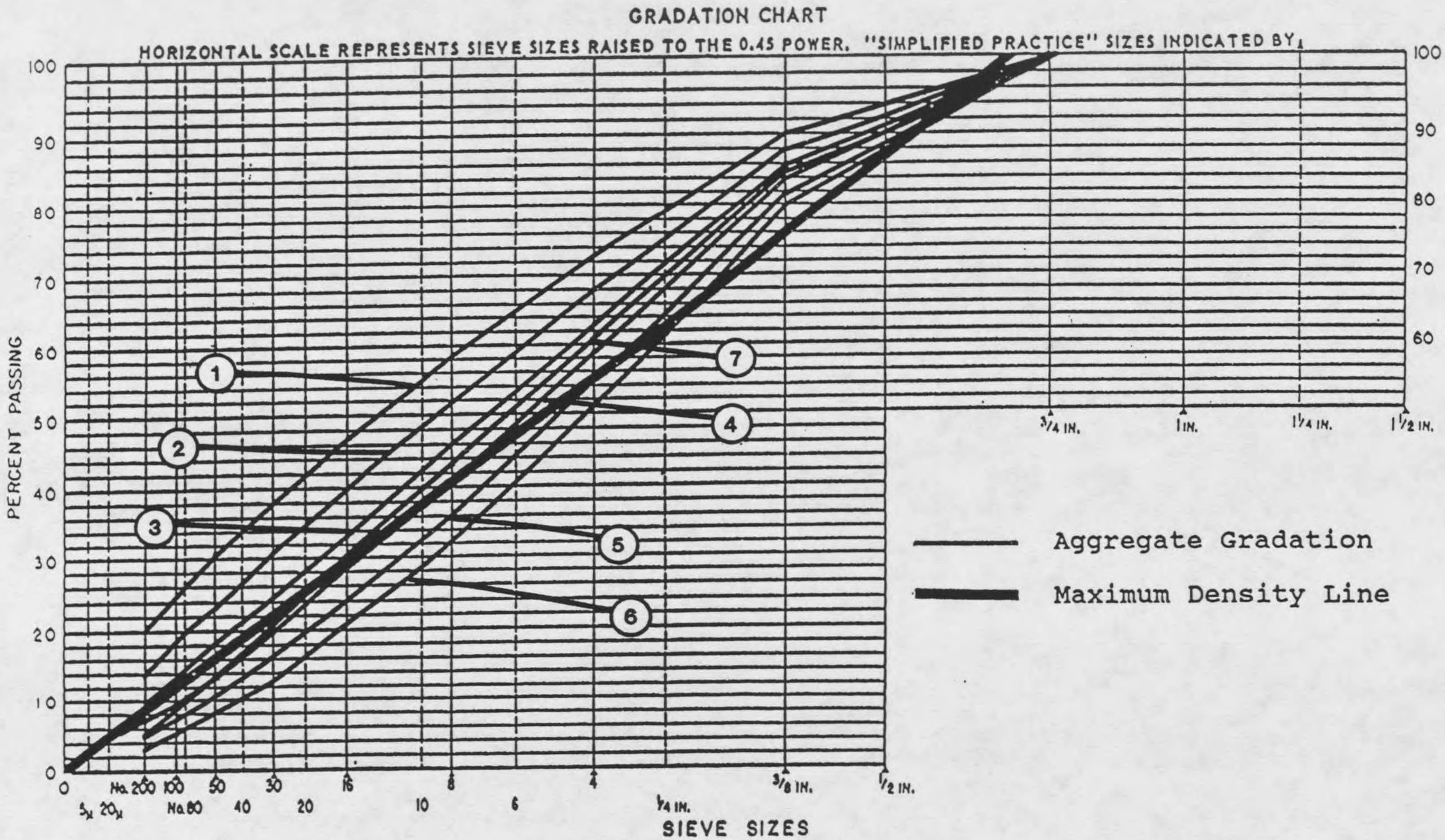

Figure 8. Well-Graded Aggregate Gradations as Listed in Table 15.

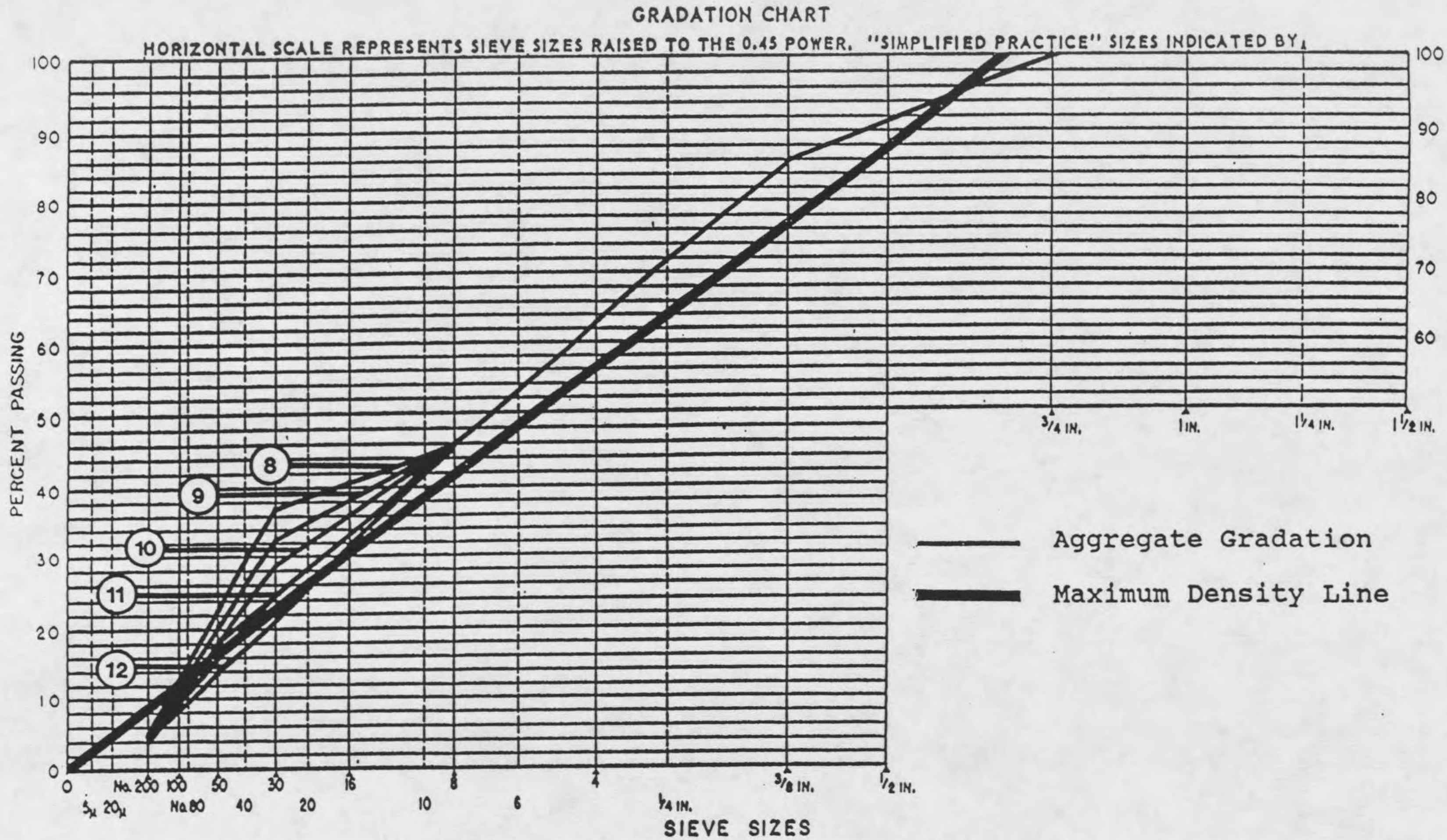

Figure 9. "Hump" Graded Aggregate Gradations, Medium Sand, as Listed in Table 15.