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.

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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.

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.

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

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.

<u>FHWA's 0.45 Power Gradation Chart</u>

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]

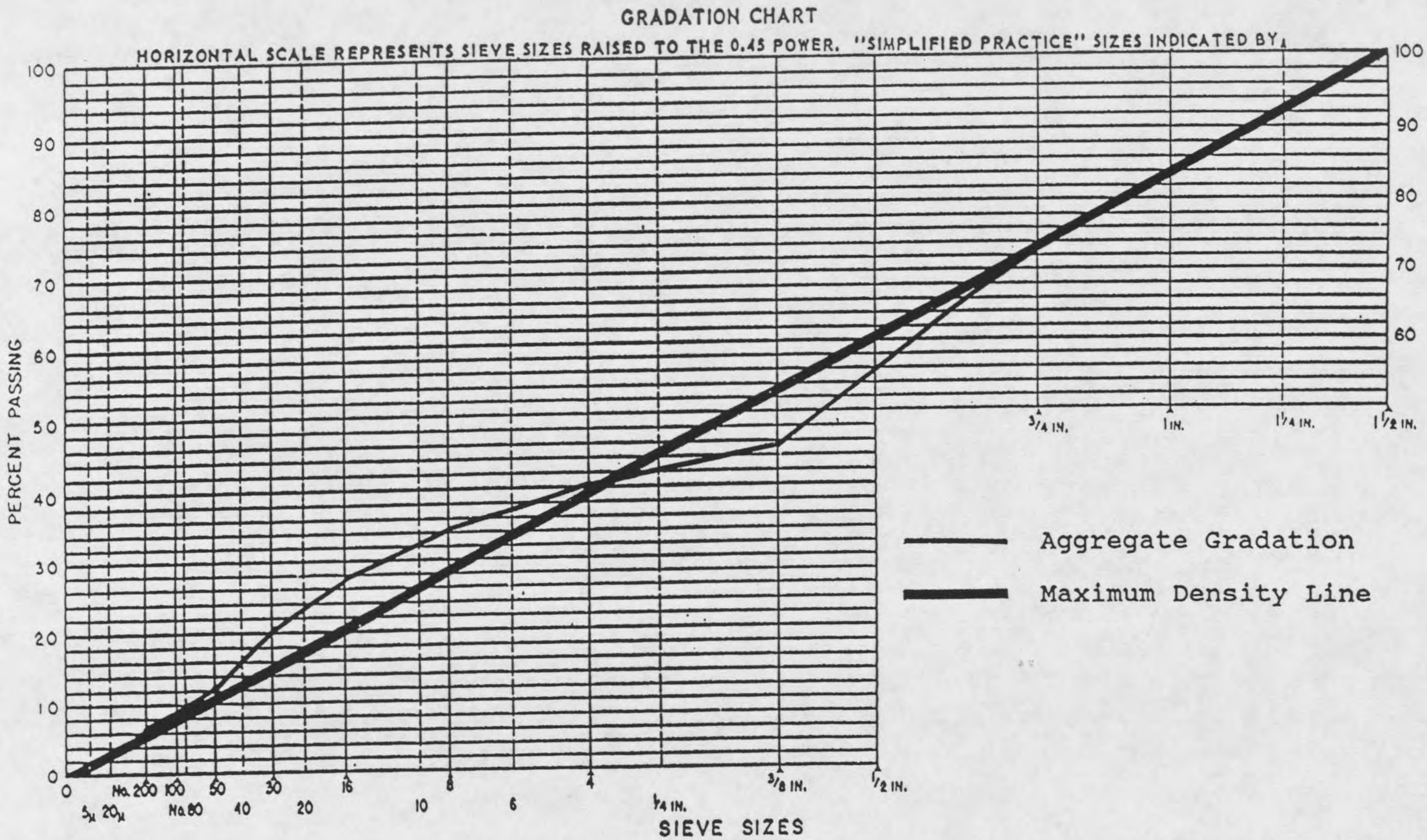

Figure 1. Aggregate Gradation as Listed in Table 1.

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.

<u>Hudson's-A</u>

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 tri-chloroethylene (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.

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

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.

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

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

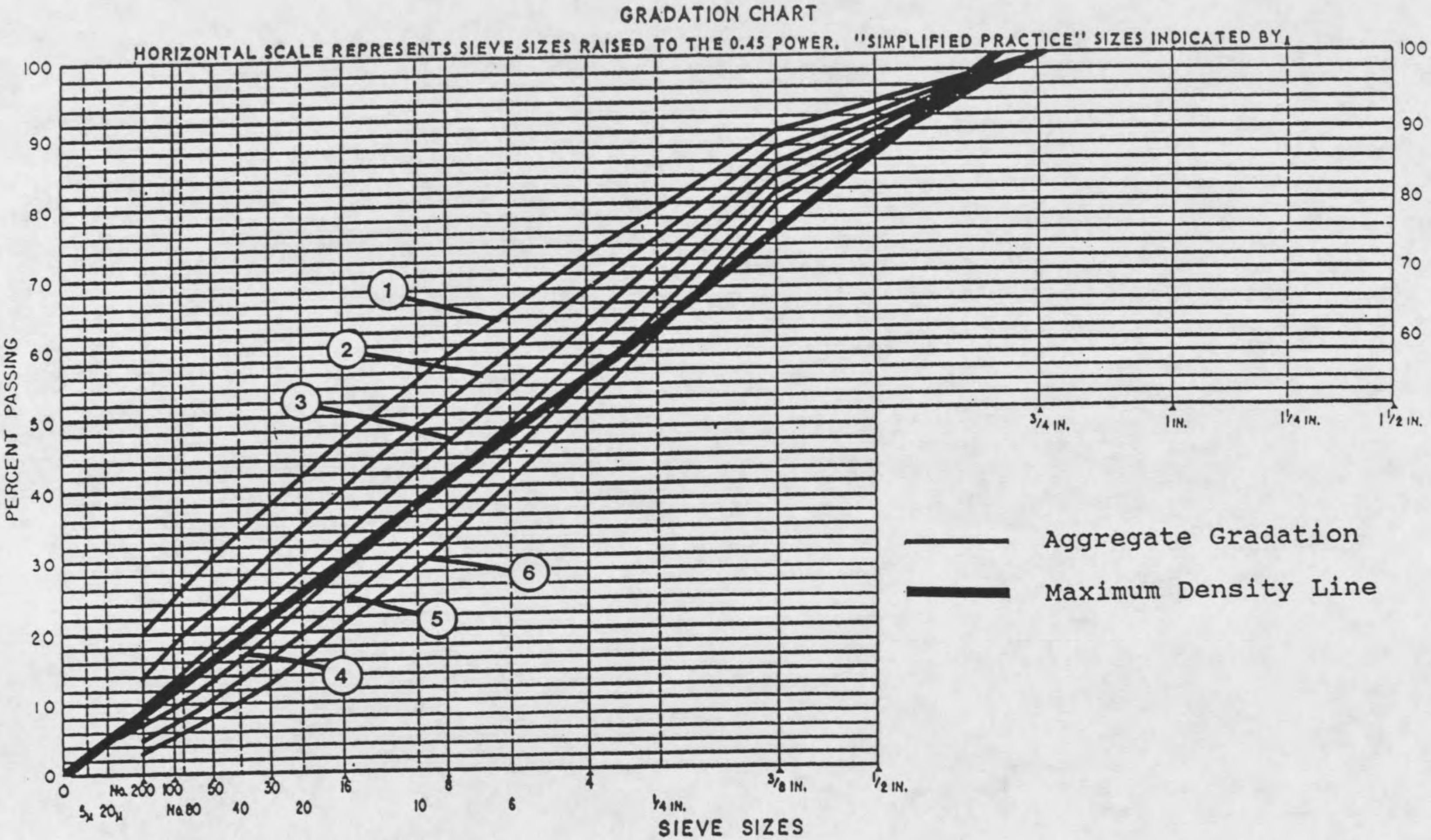

Figure 2. Well-Graded Aggregate Gradations as Listed in Table 6.

Table 7. Aggregate Gradations With Decreasing Top End Sizes.

#	1-1/2	3/4	3/8	#4	#8	#16	#30	#50	#100	#200
	Percent Passing Each Sieve Size									
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,

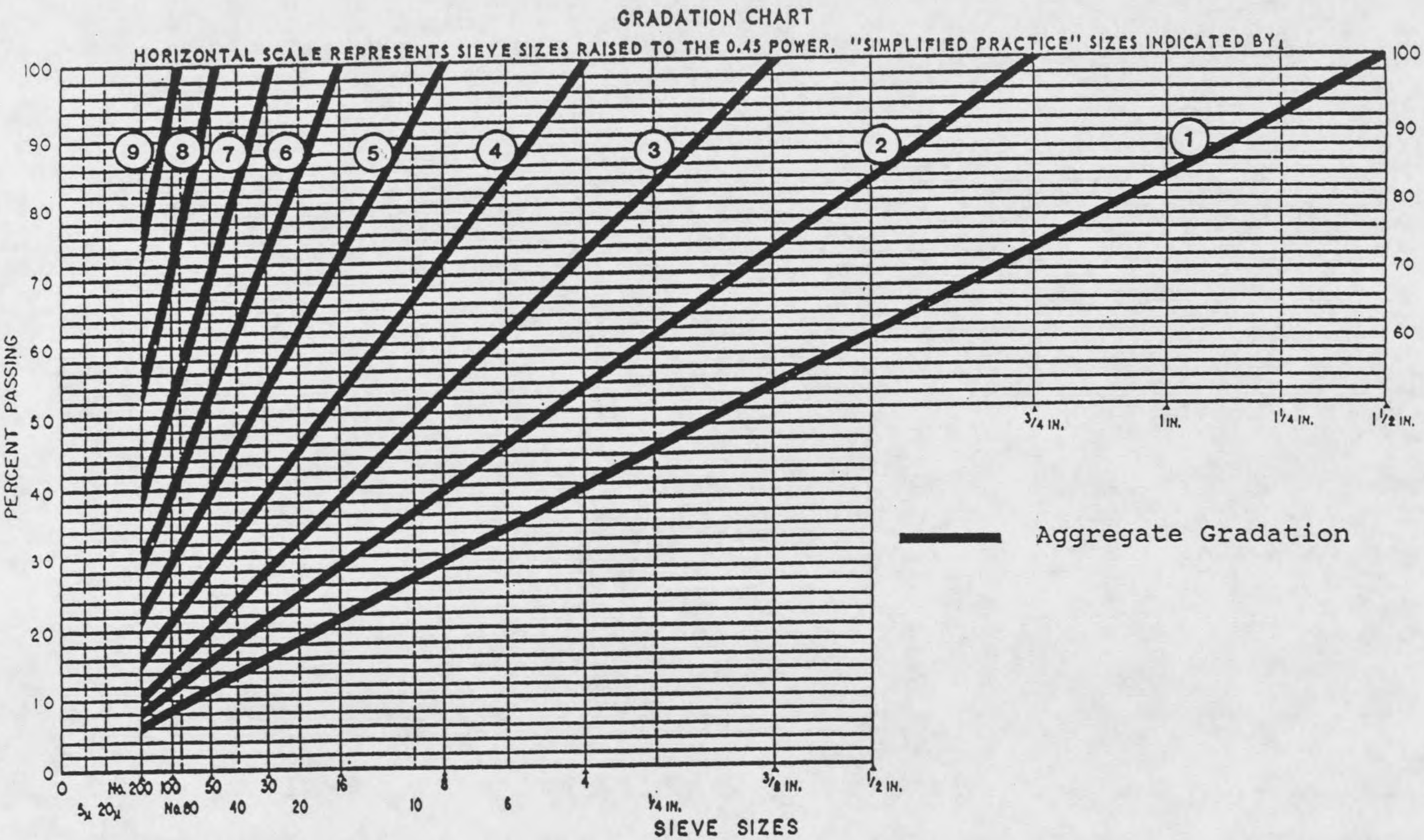

Figure 3. Aggregate Gradations of Decreasing Top End Sizes as Listed in Table 7.

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

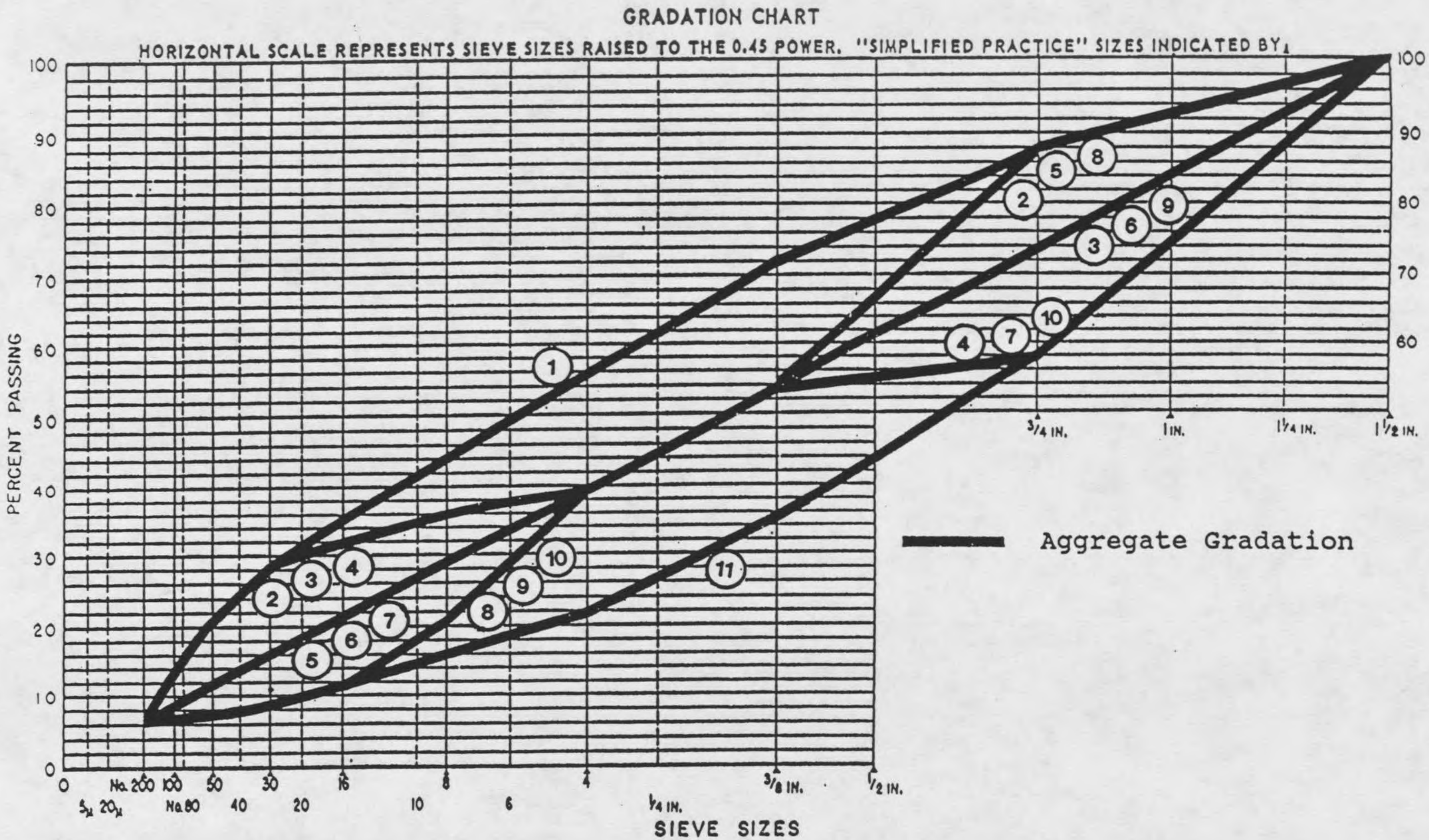

Figure 4. Aggregate Gradations of Various Shapes as Listed in Table 8.

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.

Gradation Analysis Using R-modulus

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

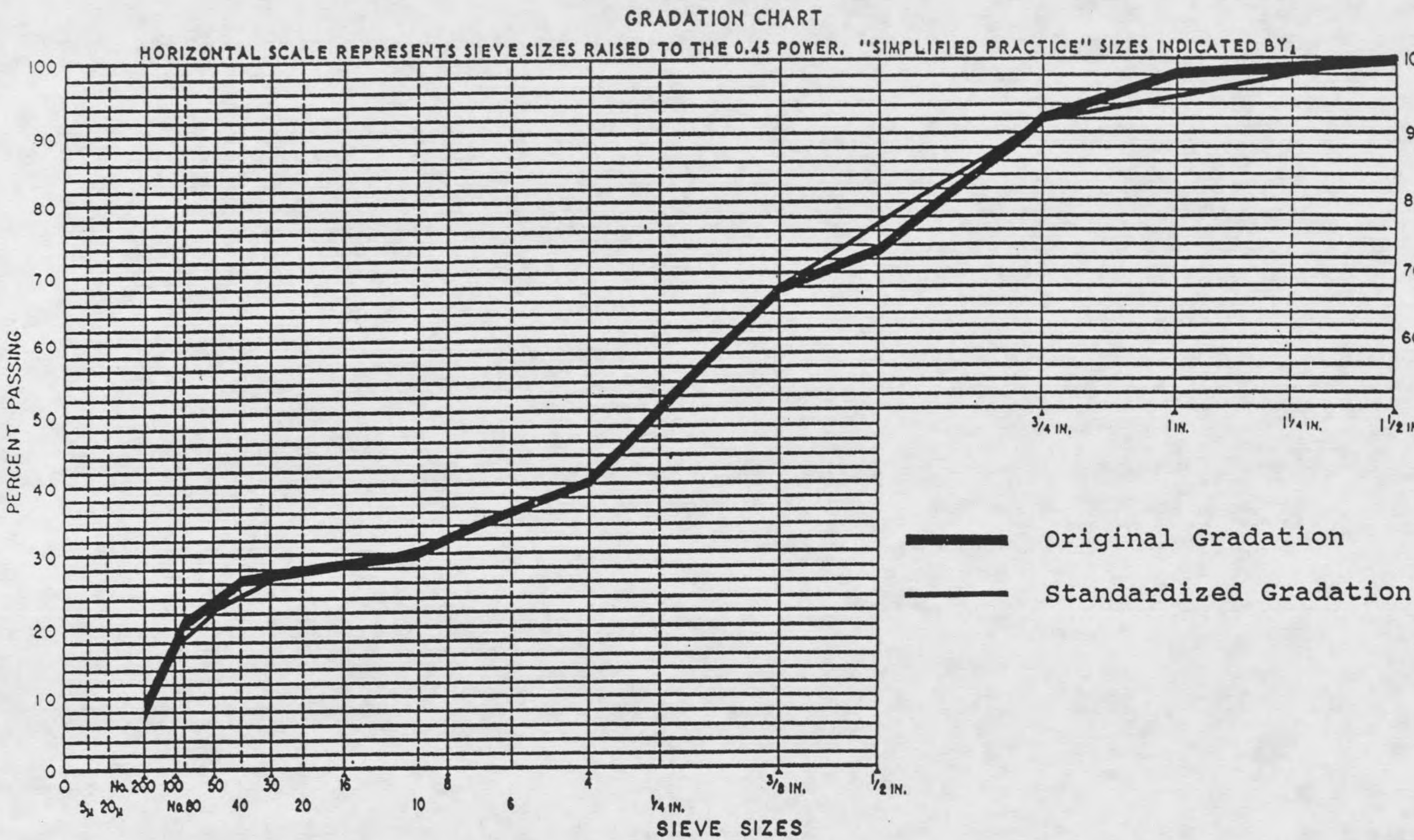

Figure 5. Original and Standardized Aggregate Gradations as Listed in Table 9.

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:

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

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

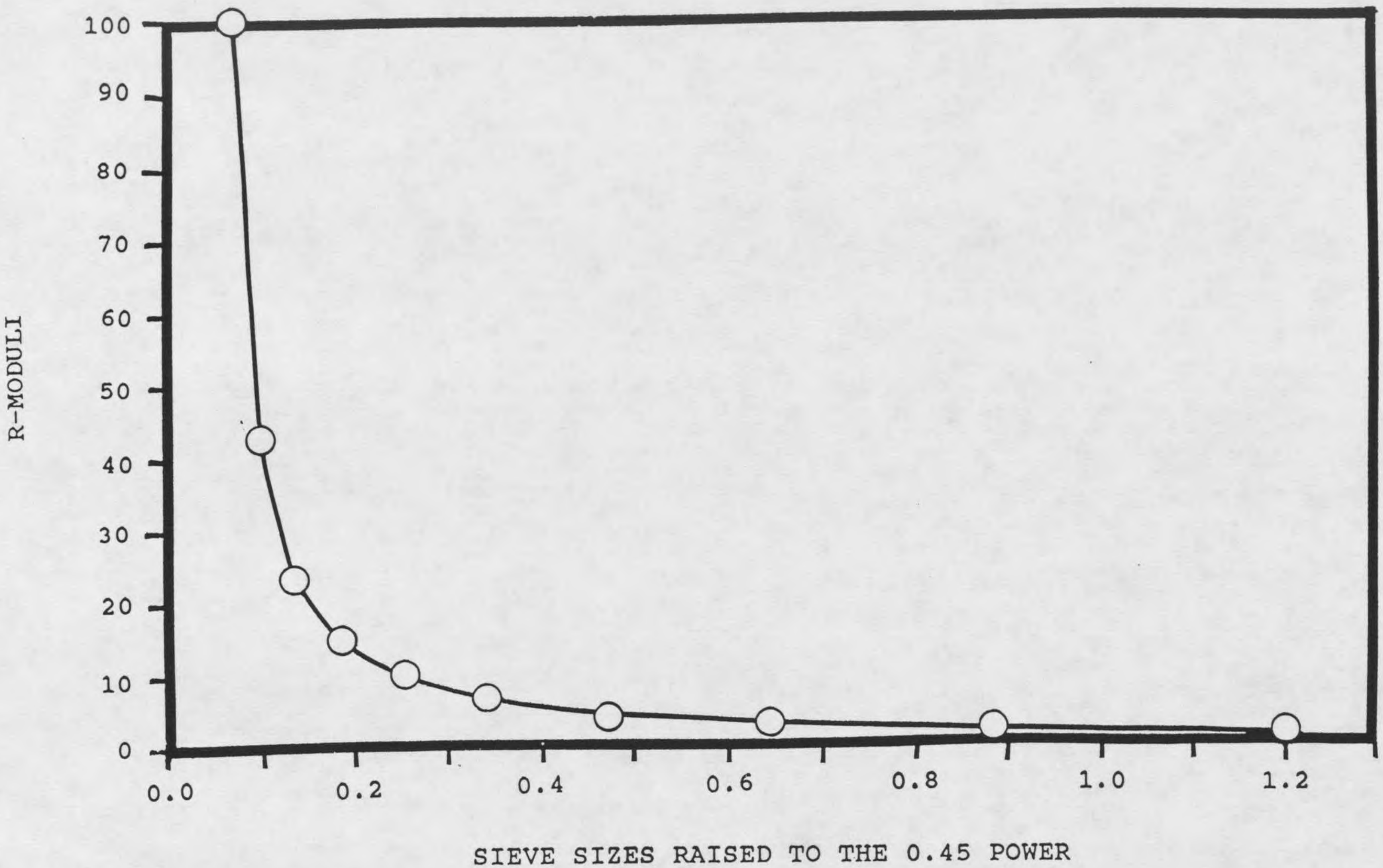

Figure 6. R-moduli Versus Sieve Sizes Raised to the 0.45 Power.

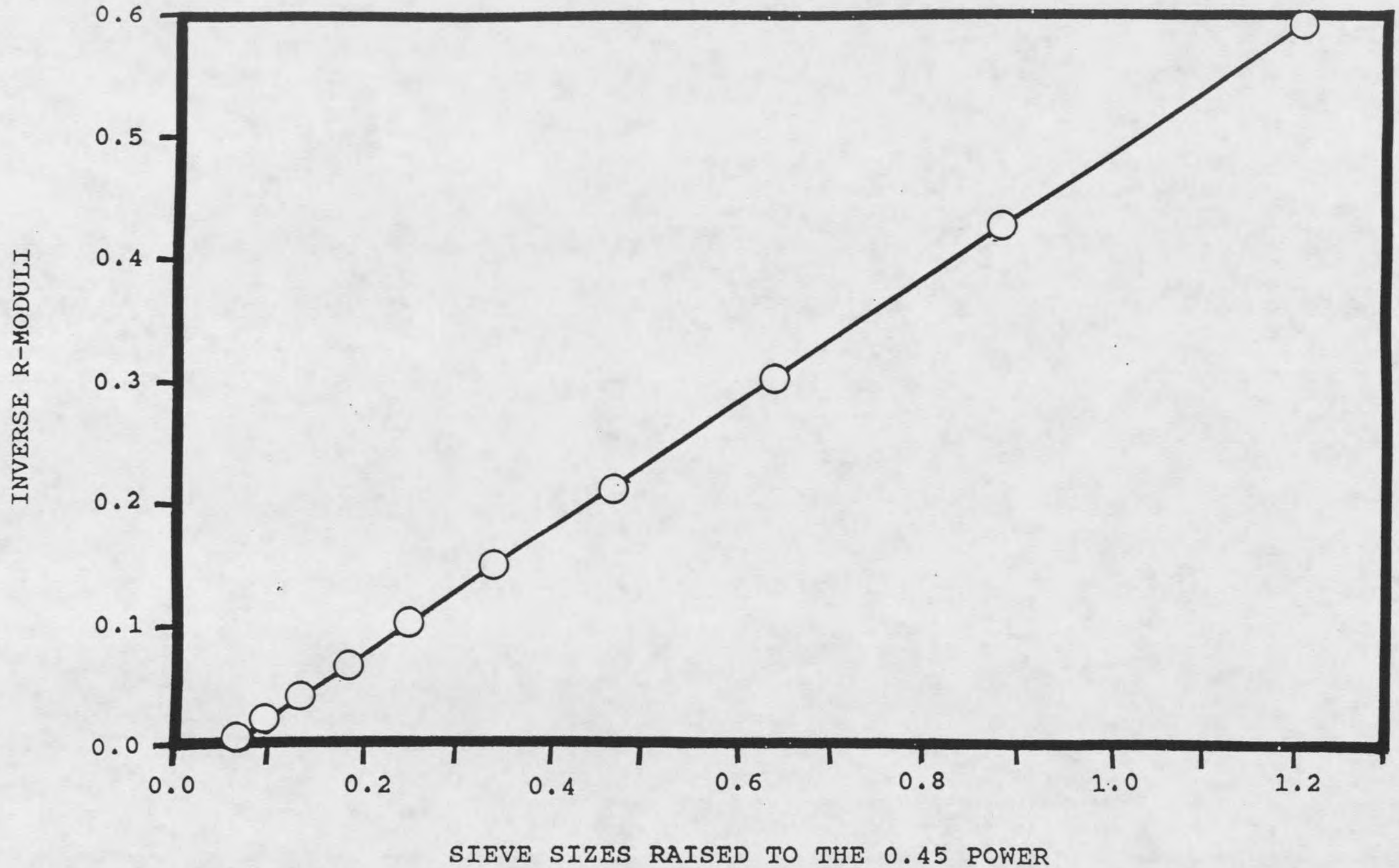

Figure 7. Inverse R-moduli Versus Sieve Sizes Raised to the 0.45 Power.

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 #	0.525	1/2	3/8	#4	#8	#16	#30	#50	#100	#200
	Percent Passing Each Sieve Size									
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.

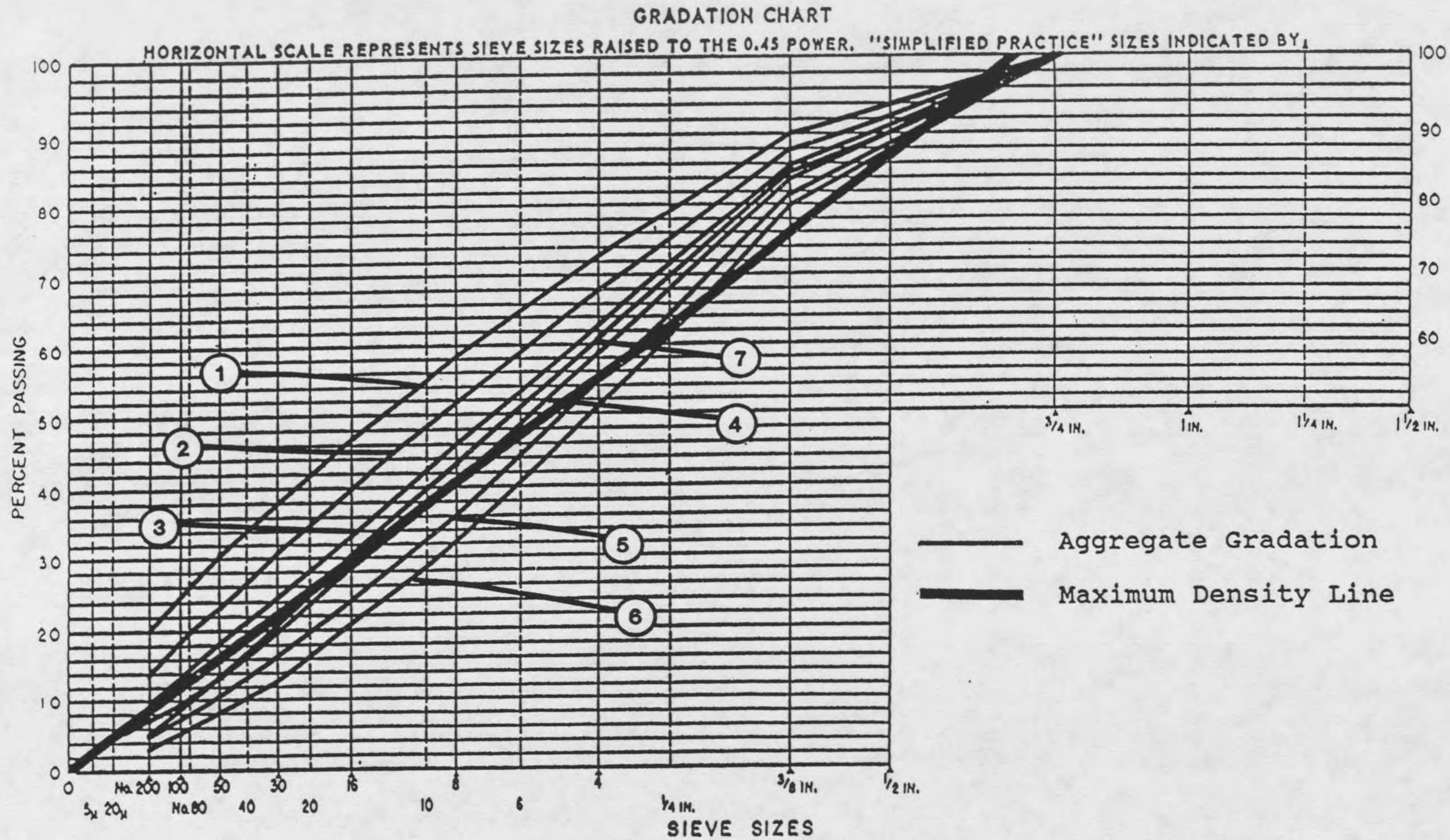

Figure 8. Well-Graded Aggregate Gradations as Listed in Table 15.

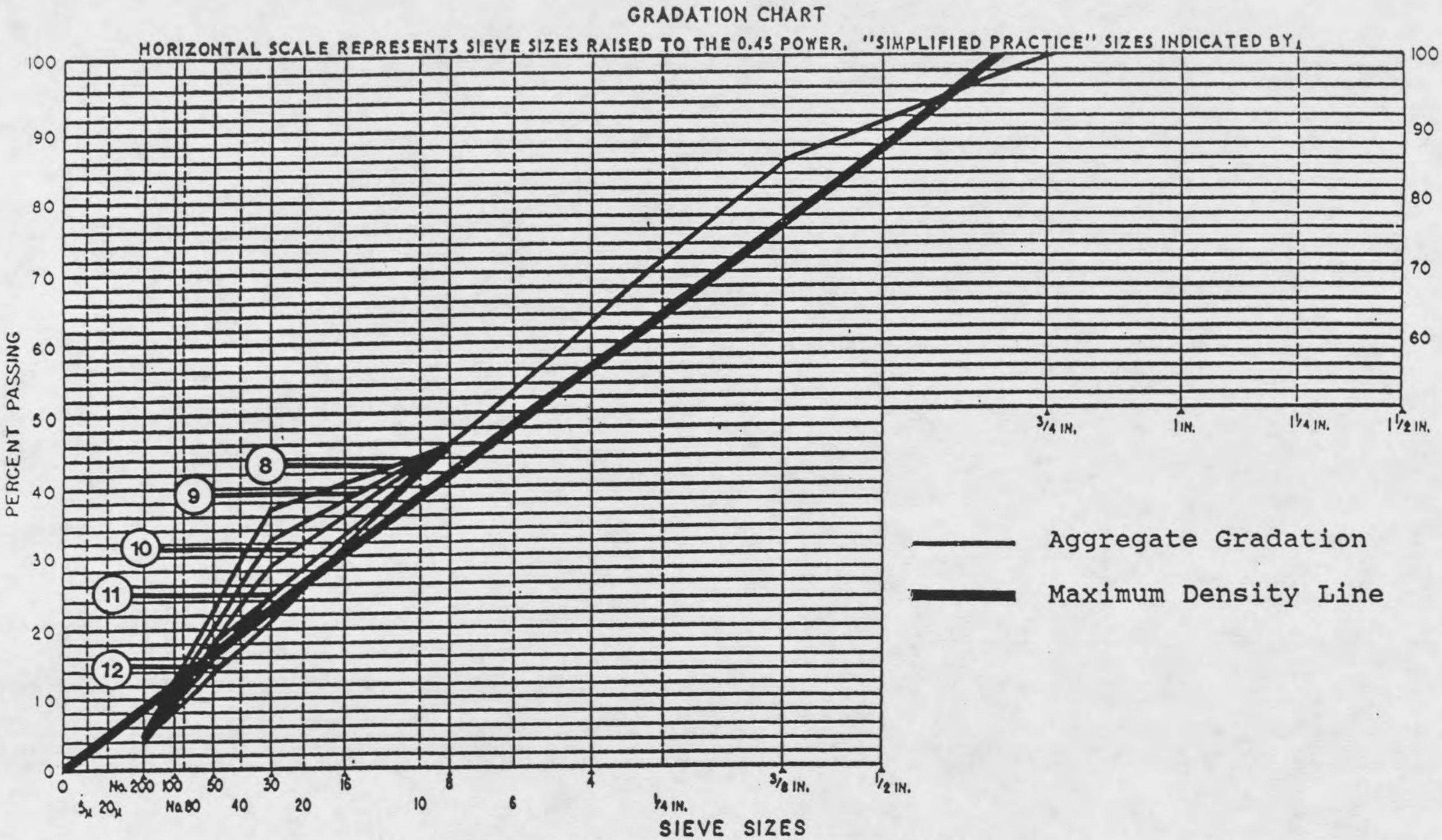

Figure 9. "Hump" Graded Aggregate Gradations, Medium Sand, as Listed in Table 15.

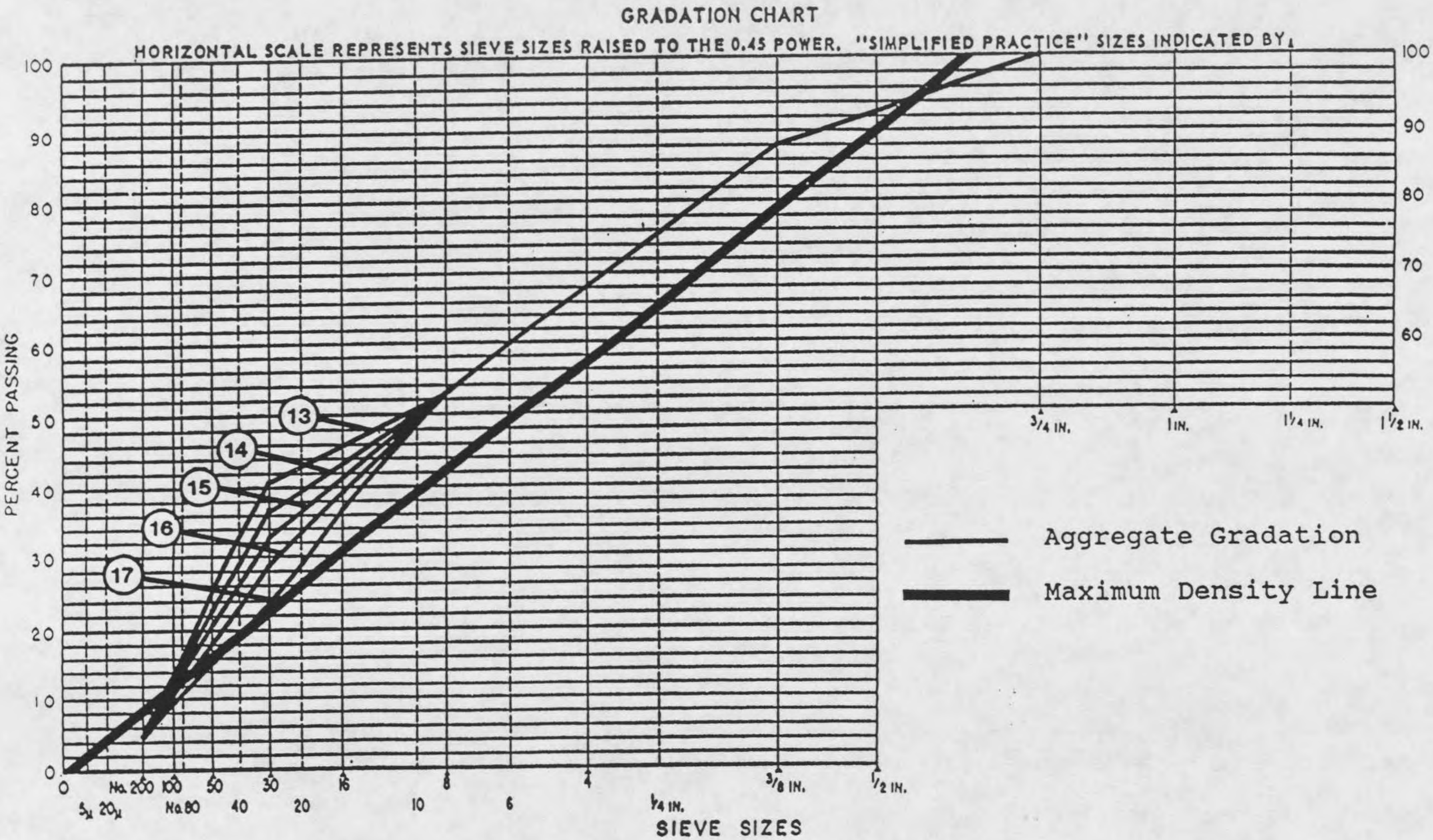

Figure 10. "Hump" Graded Aggregate Gradations, High Sand, as Listed Table 15.

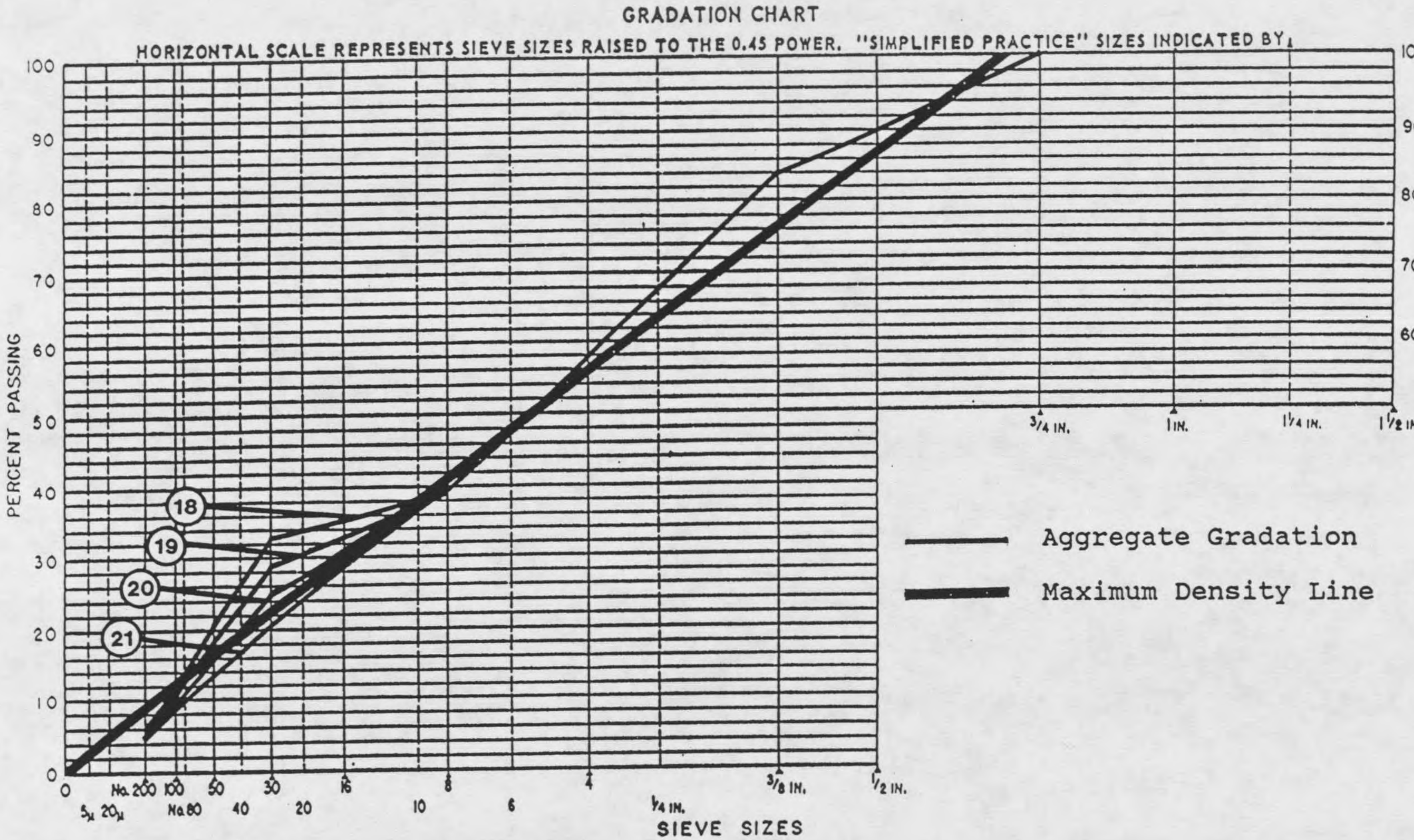

Figure 11. "Hump" Graded Aggregate Gradations, Low Sand, as Listed in Table 15.

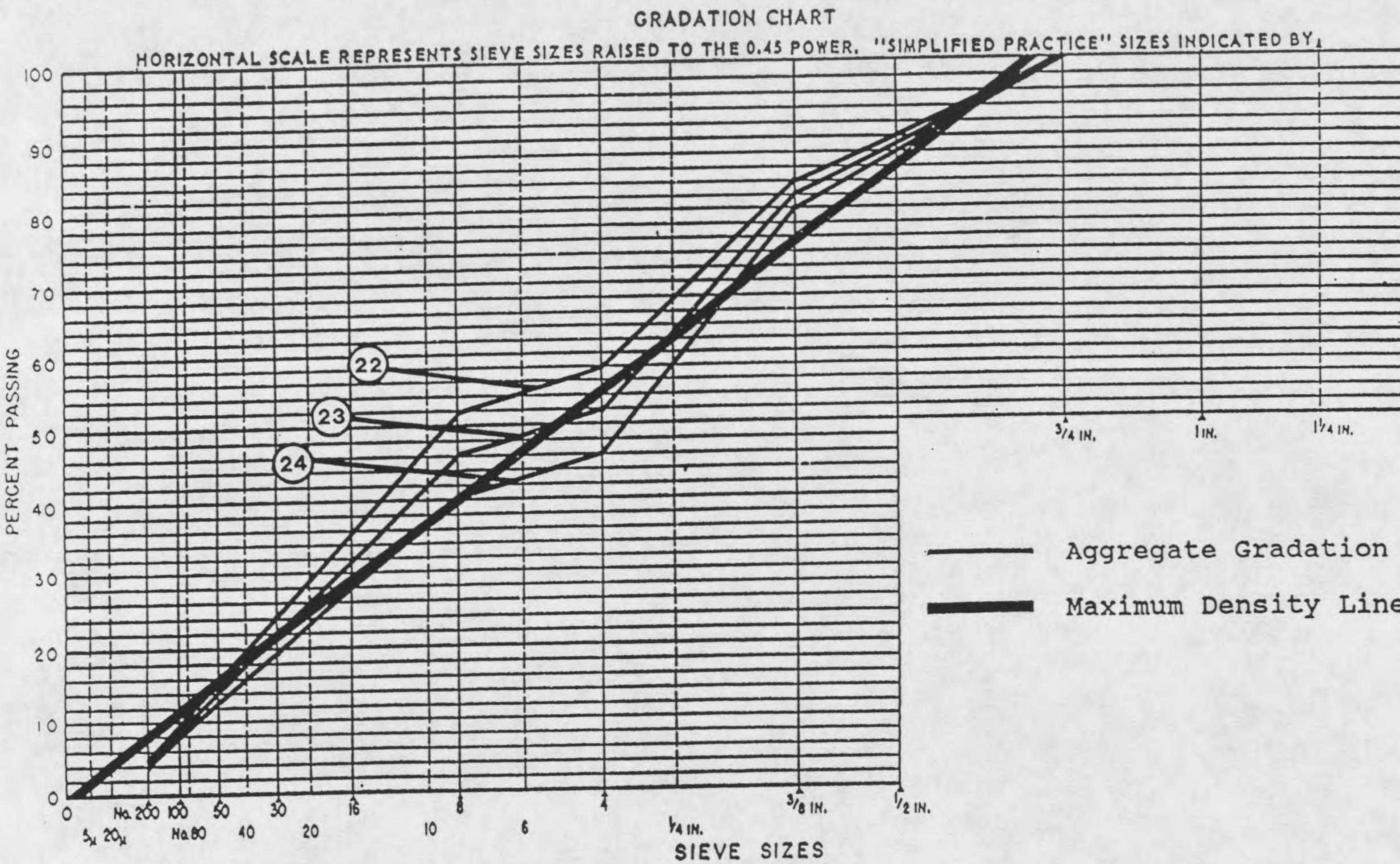

Figure 12. "Skip" Graded Aggregate Gradations as Listed in Table 15.

Figure 13 is a plot of these well-graded, hump, and skip gradation types which shows Marshall stability versus the actual R-modulus. It shows the effect of variation in a gradation's R-modulus on Marshall stability. The Gradations #1 to #7 are all well-graded samples which vary widely in Marshall stability. The R-modulus theory would predict that Gradation #7 should have the highest Marshall stability because it represents the smallest R-modulus value. This, however, does not occur. Instead, the plot for highest Marshall stability peaks at Gradation #2.

This may be due to Goode and Lufsey's use of constant asphalt content. Each aggregate gradation has an optimum asphalt content which may vary from 4 to 6 percent. Goode and Lufsey's constant asphalt content may not have represented the optimum asphalt content for many of the gradations. This would have affected the Marshall stability results. The fact that the plot of R-modulus versus Marshall stability peaks at Gradation #2 (rather than at Gradation #7 as anticipated) may indicate that the asphalt content was at its optimum level for this particular gradation. Of the seven gradations, Gradation #2 could have had the optimum aggregate gradation, for the constant asphalt content of 5.5 percent.

Table 16. Calculated and Measured Data of Goode and Lufsey.

Asphalt, 5.5 percent; air voids, variable

A	B	C	D	E	F	G	H	I
1	4.502	2.594	1.908	5.83	2.68	4.2	1620	9
2	3.538	2.524	1.014	5.34	2.96	2.5	1930	10
3	2.747	2.476	0.271	4.94	3.18	2.1	1650	10
4	2.111	2.442	-0.331	4.62	3.32	2.9	1280	9
5	1.612	2.416	-0.804	4.36	3.43	4.4	1000	9
6	1.206	2.395	-1.189	4.13	3.51	6.2	770	9
7	1.820	2.458	-0.638	4.66	3.34	4.7	1070	9
8	2.225	2.476	-0.252	5.12	2.95	7.0	810	7
9	2.148	2.476	-0.328	5.02	3.04	6.1	860	8
10	2.057	2.476	-0.419	4.93	3.14	5.4	990	8
11	1.955	2.476	-0.522	4.83	3.23	4.8	1100	9
12	1.869	2.476	-0.607	4.76	3.31	5.3	1030	8
13	2.329	2.524	-0.195	5.39	2.82	9.0	570	7
14	2.256	2.524	-0.268	5.29	2.92	7.9	710	7
15	2.178	2.524	-0.346	5.20	3.01	7.2	800	7
16	2.085	2.524	-0.439	5.10	3.11	7.3	780	8
17	1.981	2.524	-0.543	5.01	3.20	6.9	860	8
18	2.113	2.442	-0.329	4.85	3.07	5.2	980	7
19	2.061	2.442	-0.381	4.86	3.07	4.1	1220	8
20	1.927	2.442	-0.515	4.66	3.26	3.8	1230	9
21	1.810	2.442	-0.632	4.57	3.36	4.1	1080	8
22	1.953	2.442	-0.489	4.84	3.09	5.9	960	8
23	1.856	2.416	-0.560	4.61	3.18	4.3	1080	8
24	1.751	2.395	-0.645	4.39	3.26	2.9	1260	8

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 - Percent Air Voids
Column H - Marshall Stability
Column I - Marshall Flow

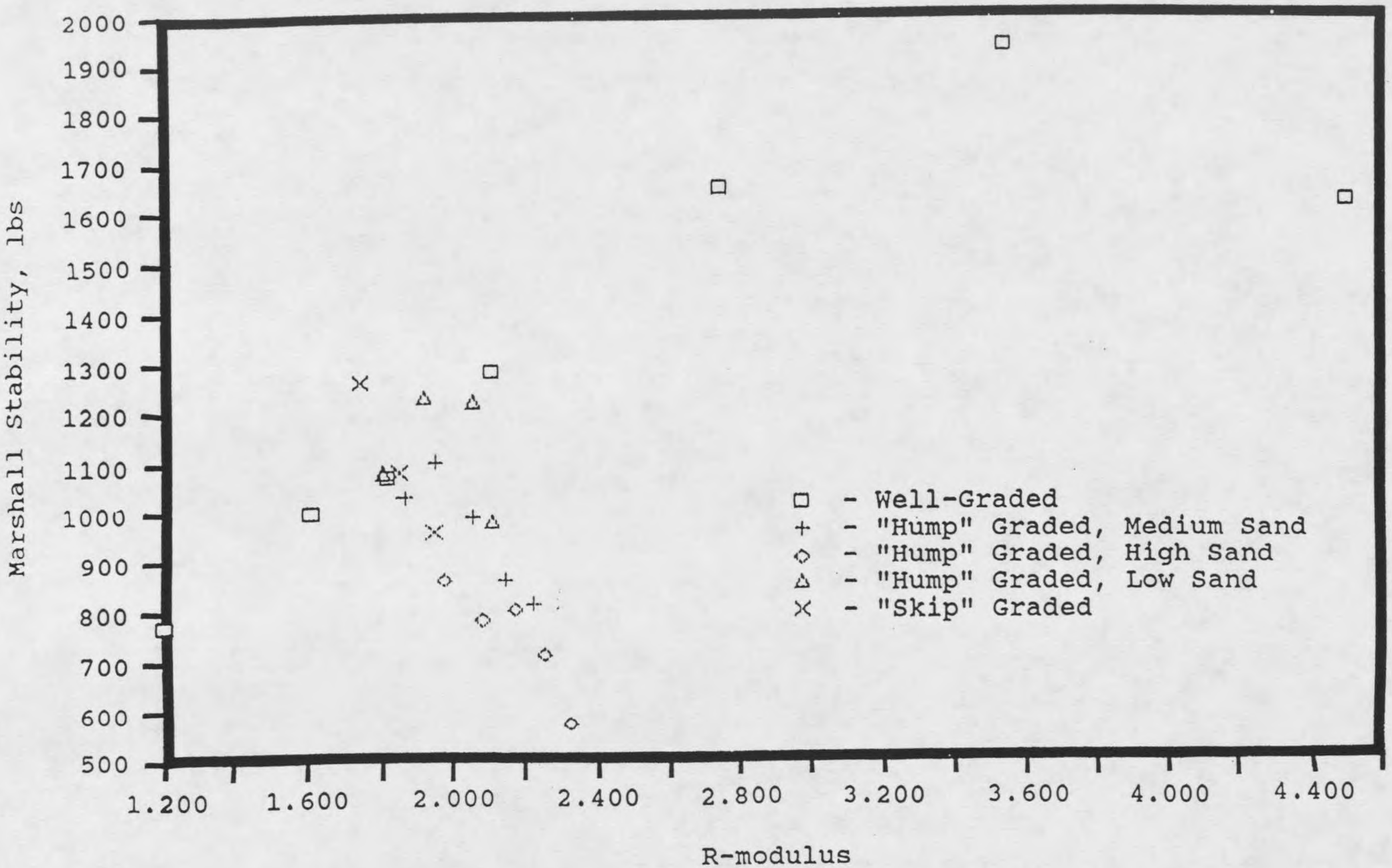

Figure 13. Marshall Stability Versus R-modulus.

It should be pointed out that it is possible to have different Marshall stabilities for different R-moduli. This can clearly be seen in Figure 13. Once again, the reason for this may be due to the possibility that the asphalt content was not optimum for all the asphalt gradations.

When designing an asphalt mixture, the gradation is usually kept constant, and the asphalt content varied, in order to find the optimum level of asphalt content which will result in the highest mix stability. The unexpected peak in Gradation #2, and the varying stabilities for gradations with similar R-moduli, may illustrate an example of what happens when the asphalt content is kept constant and the gradation varied.

Had the mixes been designed using the optimum asphalt content for each gradation, the Goode and Lufsey study could have been more useful in checking the validity of the R-modulus theory. At present however, it is possible only to observe what seem to be general trends.

Referring to Figure 13 again, the plots for R-modulus versus Marshall stability in Gradations #8 to #24, though tightly clustered, still exhibit the expected trends. Gradations #8 to #12 (hump-shaped plots with medium sand content) have mid-range R-moduli and stabilities. Gradations #13 to #17 (hump-shaped plots with high sand content) have higher R-moduli and lower stabilities. Gradations #18 to #21 (hump-shaped plots, with low sand content) show lower R-moduli and higher Marshall stabilities. As the magnitude of the differences between the actual R-modulus, and the maximum density R-modulus increase negatively, the Marshall stabilities increase.

Trends can also be seen in the skip-graded Gradations #22 to #24. As the R-moduli for the actual gradation decrease in these gradations, their relative coarseness increases, as shown by the difference in the R-moduli for the actual and maximum density gradations. It would be expected then that Gradation #24 would have the highest stability, while Gradation #22 would have the lowest. By inspection, this is indeed what has occurred.

These trends apply specifically to this data set and may not apply accurately to all data sets. These trends need a statistical verification which is not fully within the scope of this thesis.

Abrams' Data

The twenty-seven aggregate gradations listed in Table 17 are what Abrams reported in 1919. These are standardized in Table 18. Note that at that time the sieves were numbered slightly differently, using the Tyler sieves, and the percent coarser was used instead of percent passing.

Table 17. Abrams' Original Gradations.

Gradation #	Percent Retained on Each Sieve Size 1-1/4	3/4	3/8	#4	#8	#14	#28	#48	#100
1	0.0	24.0	49.0	68.0	81.0	90.0	95.0	98.0	99.0
2	0.0	22.0	46.0	67.0	84.0	92.0	96.0	98.0	99.0
3	0.0	29.0	52.0	67.0	80.0	88.0	93.0	97.0	98.0
4	0.0	35.0	58.0	67.0	77.0	85.0	91.0	94.0	97.0
5	0.0	39.0	67.0	67.0	75.0	82.0	87.0	92.0	95.0
6	0.0	55.0	62.0	67.0	73.0	78.0	84.0	90.0	95.0
7	0.0	62.0	67.0	67.0	67.0	75.0	82.0	89.0	95.0
8	0.0	40.0	58.0	67.0	72.0	79.0	91.0	97.0	100.0
9	7.0	27.0	50.0	67.0	83.0	88.0	93.0	97.0	100.0
10	16.0	27.0	47.0	67.0	77.0	86.0	94.0	97.0	99.0
11	0.0	22.0	50.0	83.0	83.0	83.0	90.0	95.0	98.0
12	0.0	18.0	55.0	80.0	83.0	86.0	90.0	94.0	98.0
13	0.0	39.0	60.0	80.0	80.0	80.0	80.0	90.0	96.0
14	0.0	23.0	50.0	75.0	81.0	87.0	92.0	96.0	100.0
15	0.0	40.0	59.0	73.0	77.0	82.0	87.0	91.0	95.0
16	0.0	32.0	61.0	73.0	76.0	80.0	88.0	95.0	95.0
17	0.0	56.0	66.0	73.0	75.0	78.0	81.0	85.0	90.0
18	0.0	47.0	63.0	73.0	73.0	73.0	82.0	93.0	100.0
19	0.0	26.0	45.0	60.0	81.0	92.0	100.0	100.0	100.0
20	0.0	31.0	50.0	60.0	80.0	90.0	95.0	98.0	100.0
21	0.0	28.0	50.0	55.0	84.0	92.0	96.0	99.0	100.0
22	0.0	38.0	50.0	50.0	80.0	91.0	96.0	99.0	100.0
23	0.0	57.0	57.0	57.0	84.0	84.0	84.0	84.0	98.0
24	0.0	38.0	38.0	76.0	80.0	86.0	91.0	98.0	99.0
25	0.0	30.0	46.0	76.0	80.0	86.0	91.0	98.0	99.0
26	0.0	15.0	61.0	76.0	80.0	86.0	91.0	98.0	99.0
27	0.0	8.0	67.0	76.0	80.0	86.0	91.0	98.0	99.0

Table 18. Standardized Gradations From Abrams'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	76.0	51.0	32.0	19.0	10.0	5.0	2.0	1.0	0.2
2	100.0	78.0	54.0	33.0	16.0	8.0	4.0	2.0	1.0	0.2
3	100.0	71.0	48.0	33.0	20.0	12.0	7.0	3.0	2.0	1.2
4	100.0	65.0	42.0	33.0	23.0	15.0	9.0	6.0	3.0	0.7
5	100.0	61.0	33.0	33.0	25.0	18.0	13.0	8.0	5.0	2.7
6	100.0	45.0	38.0	33.0	27.0	22.0	16.0	10.0	5.0	1.2
7	100.0	38.0	33.0	33.0	33.0	25.0	18.0	11.0	5.0	0.5
8	100.0	60.0	42.0	33.0	28.0	21.0	9.0	3.0	0.0	0.0
9	100.0	73.0	50.0	33.0	17.0	12.0	7.0	3.0	0.0	0.0
10	100.0	73.0	53.0	33.0	23.0	14.0	6.0	3.0	1.0	0.0
11	100.0	78.0	50.0	17.0	17.0	17.0	10.0	5.0	2.0	0.0
12	100.0	82.0	45.0	20.0	17.0	14.0	10.0	6.0	2.0	0.0
13	100.0	61.0	40.0	20.0	20.0	20.0	20.0	10.0	4.0	0.0
14	100.0	77.0	50.0	25.0	19.0	13.0	8.0	4.0	0.0	0.0
15	100.0	60.0	41.0	27.0	23.0	18.0	13.0	9.0	5.0	2.0
16	100.0	68.0	39.0	27.0	24.0	20.0	12.0	5.0	1.0	0.0
17	100.0	44.0	34.0	27.0	25.0	22.0	19.0	15.0	10.0	6.2
18	100.0	53.0	37.0	27.0	27.0	27.0	18.0	7.0	0.0	0.0
19	100.0	74.0	55.0	40.0	19.0	8.0	0.0	0.0	0.0	0.0
20	100.0	69.0	50.0	40.0	20.0	10.0	5.0	2.0	0.0	0.0
21	100.0	72.0	50.0	45.0	16.0	8.0	4.0	1.0	0.0	0.0
22	100.0	62.0	50.0	50.0	20.0	9.0	4.0	1.0	0.0	0.0
23	100.0	43.0	43.0	43.0	16.0	16.0	16.0	16.0	2.0	0.0
24	100.0	62.0	62.0	24.0	20.0	14.0	9.0	2.0	1.0	0.2
25	100.0	70.0	54.0	24.0	20.0	14.0	9.0	2.0	1.0	0.2
26	100.0	85.0	39.0	24.0	20.0	14.0	9.0	2.0	1.0	0.2
27	100.0	92.0	33.0	24.0	20.0	15.0	9.0	2.0	1.0	0.2

Note that the percent passing the #200 sieve was unobtainable from the original data. The values for the #200 sieve shown in Table 18 are extrapolated values based on the slope of the line from the #50 sieve to the #100 sieve, an assumption that is not necessarily accurate.

These gradations were used in Portland Cement Concrete (PCC) design mixtures and 28-day compressive strengths were measured. The gradation moduli and the reported compressive strengths of the concrete are summarized in Table 19. In his report, Abrams was attempting to show the variation of PCC compressive strengths with aggregate gradations of the same overall fineness modulus. He maintained a constant water to cement ratio, the actual value of which was not reported, and then added 10% more water to his mix for a second set of cylinder compressive strengths. Even though Abrams' overall modulus is the same for all of these gradations, his fineness modulus which is now in use, Hudson's-A, and the R-modulus vary. It should be noted again that in 1919 Abrams used two fineness moduli. His overall modulus was the sum of the percent material retained on the sieves of 1-1/4, 3/4, 3/8, #4, #8, #14, #28, #48, and #100 divided by 100. Keep in mind that these Taylor sieve designations were later changed as

Table 19. Calculated and Measured Values of Abrams' Data.

A	B	C	D	E	F	G	H	I
1	0.144	1.702	-1.558	2.96	6.04	5.80	3300	2890
2	0.143	1.712	-1.569	2.96	6.04	5.82	2950	2650
3	0.496	1.684	-1.189	2.97	6.04	5.75	3120	2760
4	0.449	1.670	-1.221	2.97	6.04	5.69	3140	2790
5	1.047	1.663	-0.616	2.99	6.04	5.65	3100	2800
6	0.731	1.645	-0.913	2.97	6.04	5.49	2830	2740
7	0.398	1.640	-1.242	2.97	6.04	5.42	2680	2580
8	1.643	1.661	-0.018	2.96	6.04	5.64	3070	2690
9	1.444	1.691	-0.247	2.95	6.12	5.78	3080	2500
10	0.592	1.691	-1.099	3.06	6.10	5.67	3150	2710
11	0.981	1.712	-0.731	2.96	6.04	5.82	3080	2500
12	1.009	1.738	-0.729	2.96	6.04	5.86	3050	2550
13	1.663	1.663	0.000	2.95	6.05	5.66	2970	2550
14	1.702	1.707	-0.005	2.96	6.04	5.81	2930	2710
15	0.930	1.661	-0.731	2.98	6.04	5.64	3000	2580
16	0.684	1.676	-0.992	2.96	6.04	5.72	2950	2740
17	1.769	1.644	0.125	3.02	6.04	5.48	2680	2440
18	2.737	1.652	1.085	2.96	6.04	5.57	2820	2620
19	4.093	1.694	2.399	2.96	6.04	5.78	3040	2780
20	1.088	1.679	-0.591	2.96	6.04	5.73	2900	2770
21	0.665	1.687	-1.022	2.96	6.04	5.76	2940	2750
22	0.677	1.664	-0.987	2.96	6.04	5.66	3080	2750
23	1.205	1.643	-0.438	2.95	6.05	5.48	3000	2780
24	0.147	1.664	-1.517	2.94	6.06	5.68	2940	2700
25	0.147	1.681	-1.534	2.94	6.06	5.76	3020	2660
26	0.147	1.768	-1.621	2.94	6.06	5.91	2930	2670
27	0.147	1.943	-1.795	2.96	6.04	5.96	2970	2630

Column A - Aggregate Gradation Number
Column B - Actual Aggregate Gradation R-modulus
Column C - Maximum Density Line's R-modulus
Column D - Difference Between B and C
Column E - Hudson's-A
Column F - Abrams' Overall Fineness Modulus
Column G - Abrams' Fineness Modulus
Column H - Concrete Compressive Strength, psi
Column I - Concrete Compressive Strength (10% extra water)

discussed previously. Abrams' fineness modulus was the sum of the percent material retained on the sieves of #4, #8, #28, #48, and #100. His overall modulus is no longer in use.

Plotting the R-Modulus versus compressive strength in Figure 14 results in scatter. This may be due to various shaped gradations (smooth, hump, or skip) as illustrated previously with Goode and Lufsey's data. Mixes with smooth shaped gradations, hump shaped gradations, and skip graded gradations may all behave differently, although gradations are not the only factor which affects a test measurement. Abrams did vary his cement content and this may have contributed some to the variability.

There is no method at this time to determine the shape of an aggregate gradation from a gradation modulus. An inspection of the gradation itself, as plotted on a 0.45 power gradation chart needs to be done to see its shape. A comparison of R-moduli for Abrams' gradations of similar shape can be made with compressive strengths if Gradations #8 to #14, #16, and #18 to #23, are excluded. These gradations are excluded because they have no material that passes the #200 sieve. Less scatter is evident when the remaining R-moduli are plotted against compressive strengths of concrete with 10% more water, as shown in Figure 15.

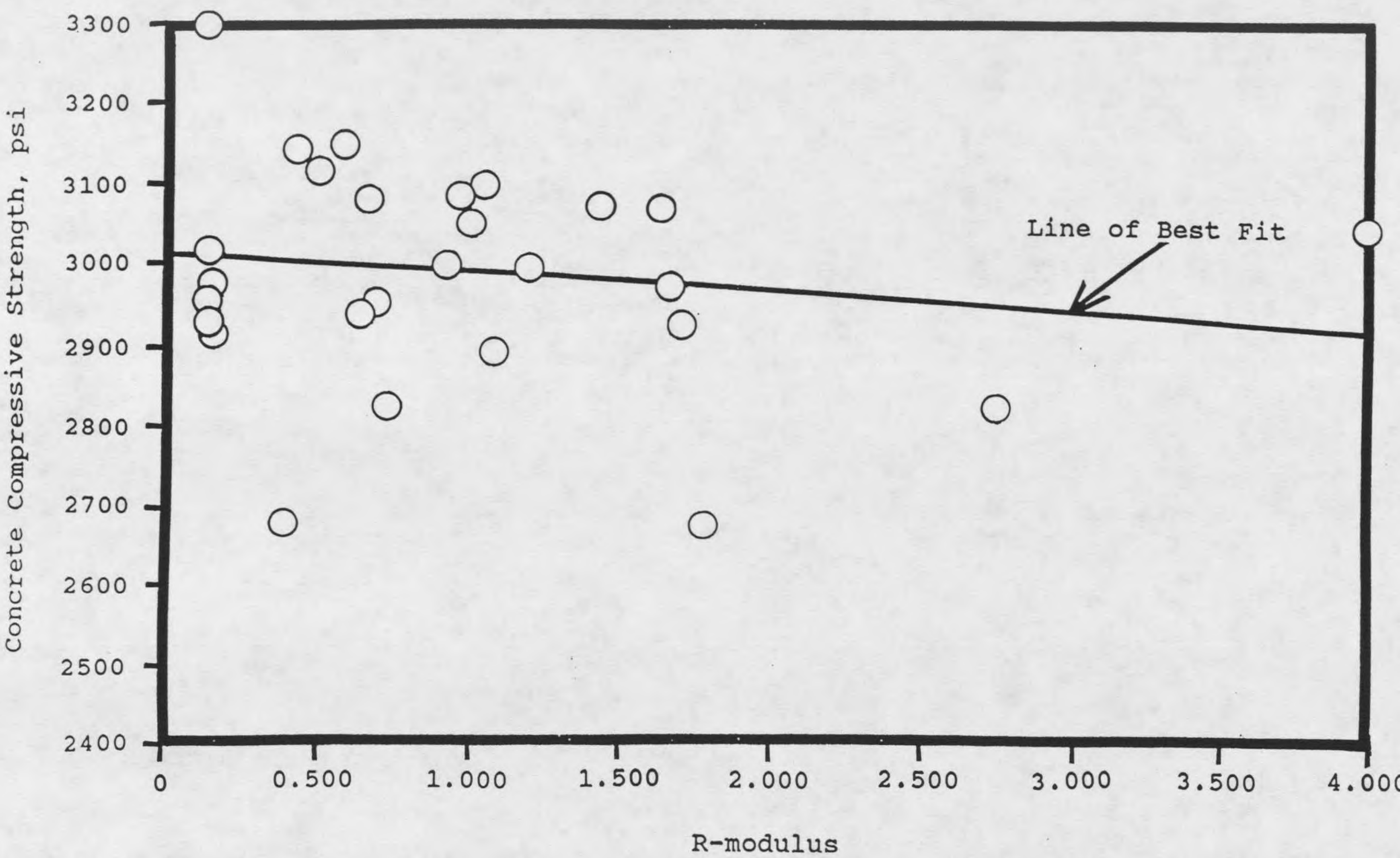

Figure 14. All Concrete Compressive Strengths Versus R-modulus.

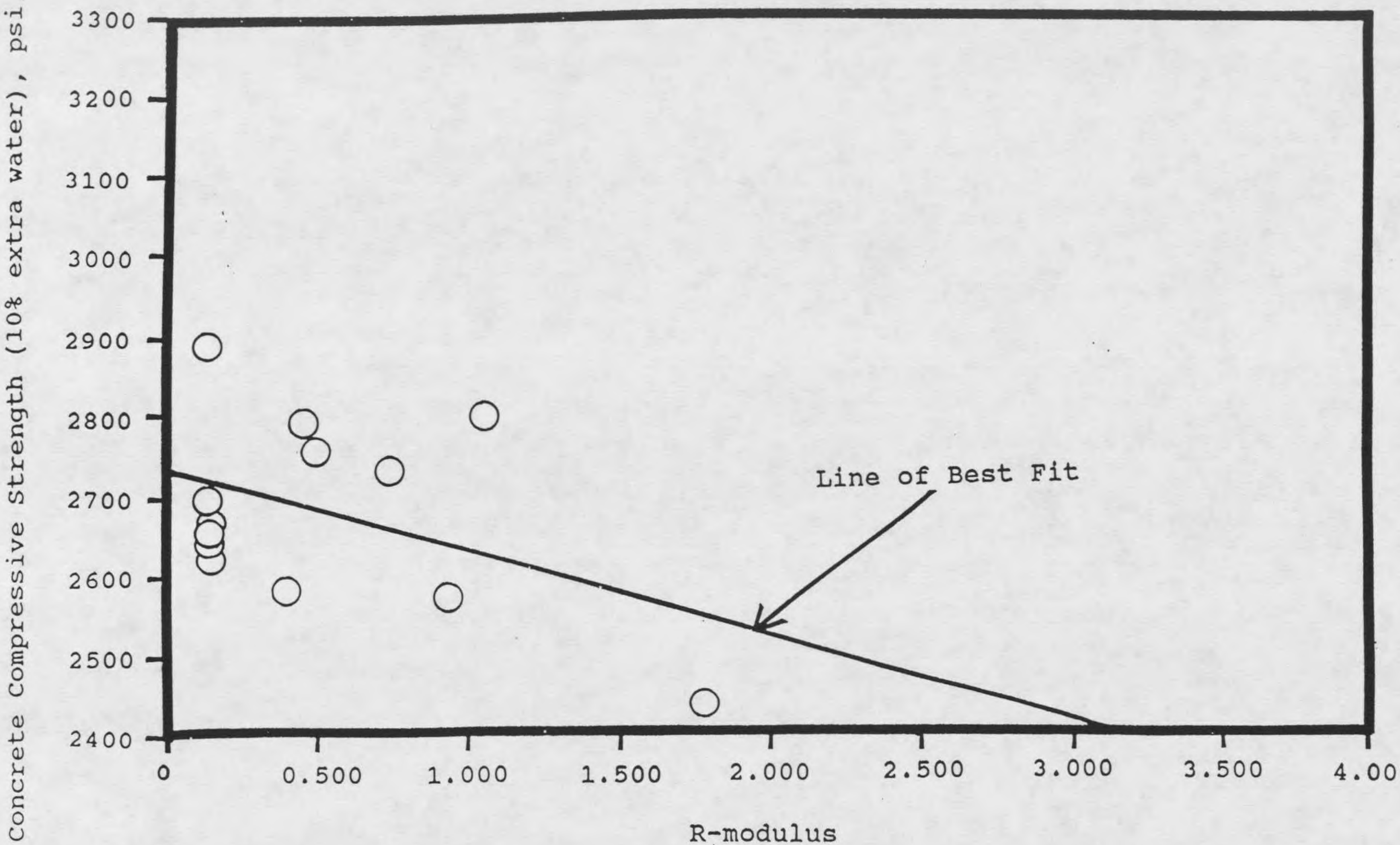

Figure 15. Selected Concrete Compressive Strengths (10% extra water) Versus R-modulus.

In an attempt to find some meaning to this data, a comparative measure of association called the coefficient of correlation[5], r, was used. This coefficient of correlation gives an indication of the scatter about the linear relationship of the two variables. A value of 1 indicates a perfect relationship between variables, while a value of 0 indicates no relationship. The equation for the coefficient of correlation is:

$$r = \frac{n * \Sigma(x*y) - (\Sigma x) * (\Sigma y)}{(n * \Sigma(x^2) - (\Sigma x)^2)^{1/2} * (n * \Sigma(y^2) - (\Sigma y)^2)^{1/2}} \qquad \text{Eq. 10}$$

where
- r = Coefficient of Correlation
- n = Number of Samples in the Data Set
- Σ = Summation of the Value
- x = First Variable
- y = Second Variable

A positive value of r means a direct correlation between variables in which an increase in one is accompanied by an increase in the other. A negative value of r means an inverse correlation in which an increase in one of the variables is accompanied by a decrease in the other.

A measure of the proportion of the variance (the square of the standard deviation) in one variable that is determined by another variable, is obtained by squaring the coefficient of correlation. This r^2 is called the coefficient of determination.

For example, r^2 can be used to explain the influence aggregate gradation, represented by the R-modulus, has on concrete compressive strengths. A high r^2, nearer to 1, indicates a high interrelation between the two. A low r^2, near to 0, indicates a low one.

If one studies a small number of samples, perhaps less than thirty, this r^2 should be adjusted for an exaggeration of its value. The correction is obtained as follows:

$$r_a^2 = 1 - (1 - r^2) * \frac{n - 1}{n - 2} \qquad \text{Eq. 11}$$

where
r^2 = Coefficient of Determination
r_a^2 = Adjusted r^2
n = Number of Samples in the Data Set

Table 20 shows the adjusted coefficients of determination of the different moduli with concrete compressive strength for those thirteen samples that were not excluded due to lack of material at the #200 sieve size.

As the R-modulus increases, the compressive strengths of the concrete decrease, as evident by the negative correlation. Comparing the correlation of the different moduli with compressive strength, the R-modulus has a higher corrected r^2 than Hudson's-A, but lower than the fineness modulus.

Relating the moduli to the compressive strengths for the mixes with 10 percent more water, the R-modulus has a higher r^2 than Hudsons-A or the fineness moduli.

Table 20. Coefficient of Determination (r^2) Matrix For Calculated and Measured Values From Abrams' Data.

	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
#1	1.00	-.19	.98	.87	-.18	-.40	-.15	-.20	-.25	-.31
#2		1.00	-.29	-.10	.00	.60	.02	.00	-.07	.00
#3			1.00	.83	-.16	-.49	-.14	-.17	-.24	-.28
#4				1.00	-.48	-.33	-.09	-.14	-.19	-.24
#5					1.00	.09	.00	.00	.00	.00
#6						1.00	.33	.10	.27	.02
#7							1.00	.68	1.00	.65
#8								1.00		1.00

#1 - Actual Aggregate Gradation R-modulus
#2 - Maximum Density Line's R-modulus
#3 - Difference of the Actual and Maximum Density R-moduli
#4 - Hudson's-A
#5 - Abrams' Overall Fineness Modulus
#6 - Abrams' Fineness Modulus
#7 - Concrete Compressive Strength, psi
#8 - Concrete Compressive Strength (10% extra water)
#9 - Adjusted r^2 for #7
#10 - Adjusted r^2 for #8

It can be argued the since the r^2 is so low, comparisons are meaningless. This may be so, but the aggregate gradations which these moduli represent are only one characteristic of the mix which contributes to the final compressive strengths. What could be done, but which is not attempted here, is to relate several of the mix variables with compressive strengths, looking for not only linear correspondence, but non-linear interrelationships. The sample size should also be increased to eliminate the need to adjust the r^2.

Jennings et al's Data

Aggregate gradations from the Jennings et al[33] research project, described in Chapter 1, were examined. This data set was large enough to be considered statistically significant. The Marshall stability and flow, percent fractured faces of the aggregate, and the aggregate gradations were made available to this author. The gradations were standardized using the method described in Chapter 4, Table 9. Other data was not obtainable at the writing of this thesis.

The calculated average values of the data set for the different moduli and, the Marshall stability and flow, are given in Table 21. The correlation of these variables is shown in Table 22. As in the previous data set, since r^2

Table 21. Basic Statistics of Jennings et al's Data.

#	Value	Mean	s	Max	Min
1.	Marshall Stability	1478	547	4530	150
2.	Marshall Flow	9.4	2.6	22.0	3.0
3.	Percent Fractured Faces	81.1	13.0	100	35
4.	Actual R-modulus	2.272	0.318	3.333	1.191
5.	Max. Density R-modulus	2.309	0.194	3.092	1.554
6.	Difference of R-moduli	-0.037	0.308	0.852	- 1.080
7.	Hudson's-A	4.70	0.26	5.50	3.56
8.	Abrams' Fineness Modulus	2.89	0.39	3.80	1.54

where
Mean - Average Value of All Samples
s - Standard Deviation of the Mean
Max - Maximum Value Encountered in All Samples
Min - Minimum Value Encountered in All Samples

Table 22. Coefficient of Determination (r^2) Matrix for Calculated and Measured Values of Jennings et al's Data.

	#1	#2	#3	#4	#5	#6	#7	#8
#1	1.00	.02	.04	.08	.08	.01	.02	.10
#2	. . .	1.00	.08	.03	.02	.01	.00	.03
#3	. . .	. . .	1.00	.06	.16	.00	.02	.19
#4	. . .	. . .	. . .	1.00	.12	.65	.40	.07
#5	. . .	. . .	. . .	. . .	1.00	-.07	.37	.72
#6	. . .	. . .	. . .	. . .	. . .	1.00	.07	-.07
#7	. . .	. . .	. . .	. . .	. . .	. . .	1.00	.21
#8	. . .	. . .	. . .	. . .	. . .	. . .	. . .	1.00

where
#1 - Marshall Stability
#2 - Marshall Flow
#3 - Percent Fractured Faces
#4 - Actual Aggregate Gradation R-modulus
#5 - Maximum Density Line's R-modulus
#6 - Difference of Actual and Maximum Density R-moduli
#7 - Hudson's-A
#8 - Abrams' Fineness Modulus

is closer to 0.0 than it is to 1.0 for most of the relationships, any conclusions would be meaningless.

What is needed here, as suggested above for Abrams' data, is a multivariable analysis which addresses not only aggregate gradation, but asphalt content and grade, and other variables. This could not be done with the available information when this thesis was being researched.

ALF Data

The Accelerated Loading Facility (ALF) was a device which caused the failure of asphalt pavements. The failure process induced by the ALF took a short time of several months, which under actual roadway conditions might take many years. Failure of the pavement was determined either by development of a rut depth that made the ALF wheel carriage drag on the pavement surface, or a pothole that caused the ALF to bounce.

The Pavement Testing Facility (PTF) where the ALF was located was composed of a pavement roadway of two different thicknesses. The construction of the roadway consisted of an asphalt concrete wearing course and an asphalt concrete binder course, an untreated crushed aggregate base, and a silt subgrade. Also located on the PTF was a mobile trailer which housed the computer equipment that ran and monitored the ALF, and recorded pavement loads and strains from sensors buried in the pavement.

The pavement section was constructed in two lanes, each 12 feet wide and 200 feet long. While each lane was to have a uniform depth throughout its length, lane two had a thicker pavement depth than lane one. The lanes were each divided into four parts, for a total of eight test sections. The ALF was positioned over each section and run at given loads and tire pressures until the pavement failed. The ALF was deactivated during wet spells to minimize the effect of water intrusion into the base and subgrade, through surface cracks. This intrusion could have resulted in the saturated pavement pushing subgrade material out through the cracks.

Pavement ruts and cracks were measured periodically throughout the life of each pavement, and a complete excavation and evaluation was done at the end of each test to determine which layer of the pavement rutted. Table 23 is a summary of unpublished data collected as of July 1988. Two pavement sections were still being trafficked at that time.

The objective of the study was to determine what caused the most pavement damage; tire pressure, tire load, or tire type. Bonaquist, Surdahl, and Mogawer[11] found that pavement failure by rutting, cracking, or a

Table 23. Accelerated Loading Facility Performance Data.

Value	L1S1	L1S2	L1S3	L1S4	L2S1	L2S2	L2S3	L2S4
Rutting (inches)	1.08	0.2	1.08	2.31	**	1.43	0.5	**
Cracking (inches)	1097	372	899	1318	**	1061	121	**
Cracking (sq.in.)	2208	520	1678	2463	**	1861	3	**
# Passes	37033	147696	66523	14240	**	578142	502662	**
EAL's (1000's)	203.3	385.7	174.3	149.5	**	6498.2	5511.8	**
Load(lb)	14100	11600	11600	16400	16400	19000	19000	**
Tire(psi)	100	100	100	100	100	140	100	**
Start Date	03/24/88	12/14/87	09/04/86	03/01/88	**	06/18/87	01/08/87	**
End Date	04/04/88	02/18/88	12/23/86	03/08/88	**	11/24/87	06/04/87	**
Failure Mode*	1	2	**	1	**	2	2	**
Pavement Thickness (inches)	4.2	4.9	4.8	4.8	**	6.7	6.9	**
A.C.% (Wearing)	5.7	5.7	5.6	5.4	5.2	5.1	5.2	5.6
A.C.% (Binder-Top)	3.9	4.4	5.2	3.5	4.3	4.4	4.3	4.5
A.C.% (Binder-Bottom)	----	----	----	----	5.1	4.2	4.9	4.4
CAB Thickness	5.3	4.8	5.2	5.4	**	10.7	11.8	**

* Failure Modes are: 1 = Subgrade rutting, 2 = Asphalt fatigue. L = Lane, S = Section, EAL = Equivalent Axle Load, A.C. = Asphalt Cement, CAB = Crushed Aggregate Base, ---- not applicable, ** data unavailable

combination of these, was primarily caused by wheel load, in combination with higher air ambient temperatures. No tire type could be said to cause the greater damage. The increase in tire pressure provided a very slight increase in pavement damage.

It is difficult to see any obvious trends in the data for the wearing course, binder course, crushed aggregate base (CAB), and subgrade listed in Tables 24 to 28, which would cause rutting and cracking. this is due to the fact that the sections were tested under different conditions. The condition that varied the most, and probably had the largest effect, was the environment. The asphalt's visco-elastic properties were different for each test since the temperature varied with the season in the unprotected environment of the PTF.

The magnitude of the axle load affected the type of pavement failure. A lower load induced repeated small flexures in the asphalt layers to the point where a fatigue failure occurred. Initial shallow ruts of about one-third of an inch remained stable until cracking occurred. An increase in the rutting followed. A higher axle load had the effect of overstressing the crushed aggregate base and subgrade before the asphalt layers failed by flexure. A classic soil mechanics shear failure

Table 24. Aggregate Gradations (construction loose mix samples) and Calculated Values for the Wearing Course of Each Lane and Section.

Sieve Number	L1S1	L1S2	L1S3	L1S4	L2S1	L2S2	L2S3	L2S4
1-1/2	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3/4	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3/8	96.0	95.1	94.6	94.4	94.2	91.8	94.7	94.0
#4	64.0	64.1	62.2	60.4	58.4	58.1	60.6	61.6
#8	45.6	45.9	44.3	43.0	42.5	41.3	42.9	43.7
#16	34.0	34.3	33.5	32.9	33.1	31.8	32.9	33.3
#30	24.7	24.9	24.5	24.6	24.2	23.8	24.5	24.6
#50	16.0	16.1	16.0	16.4	14.5	15.8	16.1	16.0
#100	10.9	11.0	11.0	11.5	9.4	10.9	11.3	11.2
#200	8.9	9.1	8.3	9.5	7.8	8.3	8.2	8.1
Actual R-modulus	2.535	2.563	2.477	2.600	2.292	2.431	2.474	2.465
Max-Dens R-modulus	3.137	3.118	3.020	2.982	2.947	2.692	3.040	2.916
R-modul Difference	-0.602	-0.555	-0.543	-0.382	-0.656	-0.260	-0.566	-0.451
Hudson's A	5.00	5.01	4.94	4.93	4.84	4.82	4.91	4.93
Fineness Modulus	3.81	3.74	3.76	3.78	3.83	3.69	3.80	3.74

Table 25. Aggregate Gradations (construction loose mix samples) and Calculated Values for the Upper Layer Binder Course of Each Lane and Section.

Sieve Number	L1S1	L1S2	L1S3	L1S4	L2S1	L2S2	L2S3	L2S4
1-1/2	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3/4	77.8	76.9	84.7	71.7	82.0	76.4	83.0	77.4
3/8	48.1	46.5	58.8	39.9	53.2	42.3	52.7	44.3
#4	40.4	38.5	51.7	34.9	46.2	36.8	46.5	39.0
#8	34.4	32.6	42.4	29.6	38.8	31.3	39.1	33.1
#16	27.9	26.5	32.9	23.7	30.4	24.9	30.5	26.1
#30	21.2	20.0	24.0	17.7	21.9	18.2	22.0	19.1
#50	13.7	12.6	14.6	10.9	13.4	11.2	13.5	11.9
#100	9.6	8.6	9.7	7.3	9.0	7.5	9.2	8.0
#200	7.6	6.2	7.1	5.1	6.8	5.5	6.6	6.1
Actual R-modulus	1.930	1.738	2.032	1.499	1.898	1.571	1.895	1.680
Max-Dens R-modulus	1.710	1.706	1.764	1.686	1.738	1.704	1.746	1.708
R-modul Difference	0.220	0.032	0.268	-0.187	0.161	-0.133	0.149	-0.029
Hudson's A	3.81	3.68	4.26	3.41	4.02	3.54	4.03	3.65
Fineness Modulus	1.41	1.40	1.78	1.15	1.60	1.24	1.55	1.29

Table 26. Aggregate Gradations (construction loose mix samples) and Calculated Values for the Lower Layer Binder Course of Each Lane and Section.

Sieve Number	L1S1	L1S2	L1S3	L1S4	L2S1	L2S2	L2S3	L2S4
1 1/2	----	----	----	----	100.0	100.0	100.0	100.0
3/4	----	----	----	----	81.3	80.7	81.7	73.8
3/8	----	----	----	----	43.4	42.8	42.7	45.8
#4	----	----	----	----	37.8	37.4	37.3	40.3
#8	----	----	----	----	32.0	31.4	31.5	34.3
#16	----	----	----	----	25.4	24.9	24.8	27.2
#30	----	----	----	----	18.8	18.2	18.1	20.2
#50	----	----	----	----	11.7	11.2	11.2	12.3
#100	----	----	----	----	8.0	7.4	7.1	8.3
#200	----	----	----	----	5.7	5.3	5.4	6.5
Actual R-modulus	----	----	----	----	1.636	1.557	1.549	1.751
MaxDens R-modulus	----	----	----	----	1.732	1.728	1.735	1.693
R-modul Difference	----	----	----	----	-0.096	-0.170	-0.187	0.058
Hudson's A	----	----	----	----	3.64	3.59	3.60	3.69
Fineness Modulus	----	----	----	----	1.27	1.26	1.26	1.32
Effective Maximum Size (in)	----	----	----	----	1.43	1.43	1.42	1.50

---- not applicable

Table 27. Aggregate Gradations and Calculated Values for the Crushed Aggregate Base Course of Each Lane and Section. (sampled from rut location)

Sieve Number	L1S1	L1S2	L1S3	L1S4	L2S1	L2S2	L2S3	L2S4
1 1/2	100.0	100.0	100.0	100.0	**	100.0	100.0	**
3/4	90.8	88.1	88.4	92.8	**	86.1	83.9	**
3/8	73.1	71.3	72.8	79.6	**	69.4	66.4	**
#4	62.7	60.4	62.6	49.9	**	58.9	56.3	**
#8	49.7	47.9	49.9	56.6	**	46.7	44.3	**
#16	38.2	37.0	38.5	44.0	**	36.1	34.0	**
#30	29.6	28.9	29.6	34.4	**	28.1	26.3	**
#50	22.1	21.8	21.9	26.2	**	21.4	19.6	**
#100	16.0	16.1	15.7	19.9	**	11.9	10.1	**
#200	11.6	12.0	10.9	15.2	**	11.9	10.1	**
Actual R-modulus	3.080	3.070	3.013	3.685	**	3.018	2.742	**
Max-Dens R-modulus	2.012	2.000	2.002	2.100	**	1.970	1.969	**
R-moduli Difference	1.068	1.070	1.010	1.585	**	1.047	0.773	**
Hudson's A	4.94	4.84	4.90	5.38	**	4.75	4.55	**
Fineness Modulus	2.20	2.16	2.19	2.27	**	2.09	2.04	**

** data not available

Table 28. Aggregate Gradations and Calculated Values for the Subgrade of Each Lane and Section. (sampled from rut location)

Sieve Number	L1S1	L1S2	L1S3	L1S4	L2S1	L2S2	L2S3	L2S4
1-1/2	100.0	100.0	100.0	100.0	**	100.0	100.0	**
3/4	96.2	99.9	100.0	99.4	**	100.0	100.0	**
3/8	94.4	99.6	98.0	98.2	**	97.9	100.0	**
#4	92.9	99.2	96.6	97.2	**	97.0	99.3	**
#8	92.2	99.0	95.6	96.6	**	96.4	98.8	**
#16	88.8	95.2	93.2	92.8	**	91.7	96.7	**
#30	85.4	91.5	90.9	89.1	**	87.1	94.6	**
#50	73.8	79.0	79.9	77.1	**	74.9	82.7	**
#100	57.4	61.5	63.9	60.6	**	58.6	65.1	**
#200	45.0	48.2	51.7	48.0	**	46.2	51.7	**
Actual R-modulus	7.766	8.240	9.069	8.118	**	8.669	10.213	**
Max-Dens R-modulus	2.746	9.321	6.797	7.235	**	6.920	12.556	**
R-moduli Difference	5.020	-1.081	2.272	0.883	**	1.749	-2.343	**
Hudson's A	8.26	8.73	8.70	8.59	**	8.50	8.89	**
Fineness Modulus	0.76	0.72	0.68	0.76	**	0.82	0.63	**

** data not available

occurred in the crushed aggregate base (CAB) and subgrade. Rutting and cracking then occurred simultaneously.

The key to the secondary causes of pavement failure may be found in part by an analysis of the pavement characteristics. The summary in Table 23 of the values of the pavement design and measured distress for the sections, shows that although the PTF was to have been constructed uniformly, there were minor variations in asphalt content, pavement thickness and gradations.

Assuming validity of the R-modulus as an indicator of the role aggregate gradation plays in pavement performance, some determination may be made to explain the different results of the several sections' pavement failures.

Table 29 lists the R-moduli, and the moduli difference between the actual gradations and the maximum density gradations, for the various layers in the pavement sections. These moduli are also rated numerically from 1 to 4, where 1 is the most desirable condition and 4, the least.

A load on a pavement causes horizontal compressive forces in the upper portion, and horizontal tensile forces in the lower. Compressive forces cause consolidation and displacement, or a pushing aside, by material flow.

Table 29. Summary of R-moduli for all Pavement Layers for Each Lane and Section, Rated by Desirability.

	Actual R-modulus							
Layer	L1S1	L1S2	L1S3	L1S4	L2S1	L2S2	L2S3	L2S4
Wearing	2.535^{2}	2.563^{3}	2.477^{1}	2.600^{4}	2.292^{1}	2.431^{2}	2.474^{4}	2.465^{3}
Binder Top	1.930^{2}	1.738^{3}	2.032^{1}	1.499^{4}	1.898^{1}	1.571^{4}	1.895^{2}	1.680^{3}
Binder Bottom	----	----	----	----	1.636^{2}	1.557^{3}	1.549^{4}	1.751^{1}
CAB	3.080^{3}	3.070^{2}	3.013^{1}	3.685^{4}	**	3.018^{2}	2.742^{1}	**
Sub Grade	7.766^{1}	8.240^{3}	9.069^{4}	8.118^{2}	**	8.669^{1}	10.213^{2}	**

	R-moduli Difference							
Layer	L1S1	L1S2	L1S3	L1S4	L2S1	L2S2	L2S3	L2S4
Wearing	$-.602^{1}$	$-.555^{2}$	$-.543^{3}$	$-.382^{4}$	$-.656^{1}$	$-.260^{4}$	$-.566^{2}$	$-.451^{3}$
Binder Top	$.220^{2}$	$.032^{3}$	$.268^{1}$	$-.187^{4}$	$.161^{1}$	$-.133^{4}$	$.149^{2}$	$-.029^{3}$
Binder Bottom	----	----	----	----	$-.096^{2}$	$-.170^{3}$	$-.187^{4}$	$.058^{1}$
CAB	1.068^{2}	1.070^{3}	1.010^{1}	1.585^{4}	**	1.047^{2}	$.733^{1}$	**
Sub Grade	5.020^{4}	-1.081^{1}	2.272^{3}	$.883^{2}$	**	1.749^{2}	-2.343^{1}	**

---- not applicable
** data not available

Tensile forces cause displacement, or a tearing apart, by material separation. An asphalt mix with larger aggregate material should withstand compressive forces better than a mix with smaller aggregate material. Conversely, a mix with a higher percentage of smaller material should withstand tensile forces better than a mix with a higher percentage of larger material.

The top wearing course layer was subjected to the highest concentration of loads from the wheels. A good asphalt mixture, designed to withstand these loads without rutting, should conceivably have been coarser than the lower layers. The lowest R-modulus therefore was assigned the value of 1, while the largest R-modulus was assigned a value of 4.

The binder course layers were subjected to lower maximum pressures but had higher tensile stress induced by flexure as the wheel passed. Generally, a finer mix withstands this type of distress better than a coarser one, so this time the highest R-moduli were assigned a value of 1, and the lowest, a value of 4.

The CAB and the subgrade both should have had the capability of high stability. The values were assigned as they were in the wearing course; the lowest R-modulus received a 1, and the highest a 4.

The rating numbers for both the actual gradation, and the difference between the actual and maximum density gradations are shown in Table 29. The rating numbers were averaged and are summarized in Table 30.

Table 30. Averages of the Desirability Ratings for Actual and Maximum Density Line R-moduli.

A	B	C	D	E	F	G	H	I
L1S1	1.50	2.00	----	2.50	2.50	2.13	1.08	1097
L1S2	2.50	3.00	----	2.50	2.00	2.50	0.20	372
L1S3	2.00	1.00	----	1.00	3.50	1.88	1.08	899
L1S4	4.00	4.00	----	4.00	2.00	3.50	2.31	1318
L2S1	1.00	1.00	2.00	**	**	**	**	**
L2S2	3.00	4.00	3.00	2.00	1.50	2.70	1.43	1061
L2S3	3.00	2.00	4.00	1.00	1.50	2.30	0.50	121
L2S4	3.00	3.00	1.00	**	**	**	**	**

Column A - Lane and Section Number
Column B - Wearing Course
Column C - Upper Binder Course
Column D - Lower Binder Course
Column E - Crushed Aggregate Base
Column F - Subgrade
Column G - Overall Average Rating for Each Section
Column H - Rut Depth in Inches
Column I - Total Crack Lengths in Inches
** data not available

For example, in Table 29 for Lane 1, Section 3, the R-modulus of 9.069 is rated fourth of the four sections. For the same lane and section, the R-modulus of 2.272 for the difference of the R-moduli is rated third. Averaging four and three, since they are both charateristics of the aggregate gradation, gives 3.5 as shown in Table 30.

A direct comparison between Lanes 1 and 2 cannot be done since Lane 2 had an extra binder layer, which would change the stresses in the CAB and subgrade. However, comparisons between the four sections in each lane are valid.

Comparing the average of the ratings of the pavement layers, Lane 1, Section 3 had the better average rating of the four with a 1.88; Section 4 had the worst average rating of 2.30. Lane 2, Section 3 had a better average rating of 2.30 than Section 2's average rating of 2.70.

Theoretically, the pavement section with the lowest average rutting should have had the least ruts and cracks. Lane 1, Section 3 therefore, should have been the most durable pavement section in terms of rutting and cracking; in fact it was not. Section 2, which was rated third, had the least pavement distress. Section 4, which was rated last, did have the most rutting and cracking. Lane 2, Section 3, which was better rated than Section 2, had the least rutting and cracking.

It could be argued that these comparisons demonstrate that the validity of the R-modulus theory is inconclusive. However, by relating each section's rutting and cracking to a combination of asphalt content other trends may be identified.

A larger R-modulus, as discussed above, would require more asphalt for a uniform coating of the particles than a smaller R-modulus. Even though the pavement sections were of one mix design, minor plant variability could be expected, as well as small amounts of segregation. The aggregate for the wearing course in Lane 1, Section 4 had the highest R-modulus and so it should have had the highest asphalt content, but instead, it had the lowest asphalt content. This may explain why it had the highest amount of pavement distress. Section 3, which had the lowest R-modulus, had a lower asphalt content than the remaining Sections 1 and 2, therefore it should have had the least pavement distress, when in fact it was Section 2. Factors other than aggregate gradation probably contributed to this.

The differences of asphalt contents and R-moduli for the wearing course in Lane 2 were small, so this is not the apparent reason for Section 2 to rut and crack any more than Section 3.

In comparing the R-moduli to the asphalt content in the binder courses for both Lanes 1 and 2, some variation is evident. The R-moduli for the aggregate gradations vary from 1.499 to 2.032, while the percent asphalt contents vary from 3.5% to 5.2%. Since the increasing R-moduli do not always correspond to an increasing asphalt content, as is predicted by the R-modulus theory, this would indicate that some of the mixtures did not have optimum asphalt content. There is no way of determining this without examining the original mix designs first. This mix design was not obtained for this thesis.

The trends above really are inconclusive. There may be some relationship between the R-modulus and pavement rutting and cracking. Research in which all variables are tightly controlled and documented will be necessary to validate, or invalidate, the R-modulus theory.

CHAPTER 6

SUMMARY AND CONCLUSIONS

In summary, the reasons why an asphalt pavement behaves as it does are still not clearly understood. Many researchers have made great advances toward explaining a pavement's behavior but much is still unknown. What is known is that the interactions between the components of an asphalt pavement are complex and all relationships are difficult to define. Aggregate composes approximately 95 percent of the volume of a mix, but its role in performance may be given little attention. To relate material relationships to pavement performance, a gradation modulus was developed to try to represent the working properties of an aggregate gradation in a mixture subjected to loads.

The conclusions which can be drawn about this are:

1. A new aggregate gradation modulus called the R-modulus was developed for use in statistical analysis. This R-modulus indicates an aggregate's gradation relative size distribution,

and also its relative fineness or coarseness as compared to its maximum density line.

2. Based on the limited data examined, the use of the R-modulus as a tool in indicating an aggregate's contribution to a pavement's performance is inconclusive. Neither can conclusions be drawn that it is better or worse than the fineness modulus or Hudson's-A as an indicator of the effect an aggregate gradation has on pavement performance.
3. No one value of pavement characteristic can be used to predict pavement behavior. The materials all interact together.

Recommendations For Further Research

Bridge Scour Problems

Numerous cases of stream bed scour around bridge abutments and piers have been examined by various researchers[13,17,65] in both the laboratory and in the field. It has been found that the standard deviation of stream bed particles can be used as a predictor for scour around these bridge supports.

This standard deviation is defined as:

$$STD = d_{84} / d_{16} \qquad \text{Eq. 12}$$

where

STD	=	geometric standard deviation of grain size distribution
d_{84}	=	size of river bed material grain size diameter corresponding to 84 percent passing on a gradation
d_{16}	=	size of river bed material grain size diameter corresponding to 16 percent passing

A well-graded material, that is, one that has a good representation of all particles, produces a larger standard deviation than a uniformly graded material, that is, one that has a majority of only one size. Researchers have found that if the standard deviation is increased, the bridge scour will decrease.

It could be shown here that a high R-Modulus would indicate a high amount of scour. As the R-Modulus decreased, the scour would also decrease.

The current problem of beach erosion may be investigated using the R-modulus as an indicator of the material on the beach. Due to the predominantly smaller sized particles on most beaches or stream beds, a modification of the method of calculating the modulus could be developed to encompass this.

Performance Versus Gradation Variations

Since the results of this study were inconclusive, a project could be undertaken to determine the extent to which each of the moduli indicates a pavement's performance. The limited work Goode and Lufsey[24] did was valuable, but more tests should be done. There are a multitude of ways to vary aggregate gradations and keep the asphalt content constant. The behavior of each mix should also be evaluated at a constant temperature. The gradation modulus of the aggregate could then be used to predict pavement behavior for that particular asphalt content.

Abrams'[1] attempts to relate his modulus with concrete compressive strengths could be done for asphalt pavement. For different aggregate gradations with the same modulus and constant asphalt content, the performance could be evaluated. What one should look for is a modulus that predicts the pavement's behavior independent of aggregate gradation shape as plotted on the 0.45 power gradation chart.

It has been suggested by Acott[2] that asphalt pavement mixes should use larger size aggregates to reduce the rutting caused by heavier traffic loads. This could be tested, and aggregate gradation moduli could be specified for the desired conditions.

Using Moduli for Asphalt Pavement Design

After the behavior of an asphalt pavement is established for certain parameters, design charts or nomographs could be developed which may eliminate the trial and error method of mix design in the laboratory. The design parameters could be an asphalt content, an asphalt temperature susceptibility, and an aggregate coefficient based on a combination gradation modulus, aggregate shape, percent fractured, aggregate type, in conjunction with traffic loads and environmental conditions.

One representation not examined in this thesis was a ratio of the actual aggregate gradation R-modulus to the maximum density line's R-modulus. In this case, a relatively finer aggregate gradation would have a ratio greater than 1.0. A relatively coarser aggregate gradation would have a ratio less than 1.0.

No matter how one views materials and their behavior, one may always conclude that more investigation is needed. Although there were no conclusive conclusions, this thesis provides a compilation of some work which previous researchers have conducted, and is a base for future researcher's work.

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APPENDIX

DESCRIPTION OF JENNINGS ET AL'S DATA

COLUMN 1.	Site location number. The 185 sites resulted in 659 samples.
COLUMN 2.	Location in the pavement of the sample in terms of vertical placement. A "1" indicates the most recent asphalt pavement overlay.
COLUMN 3.	Location in the roadway of the sample in terms of horizontal placement. "1" and "2" indicate the samples were taken from the wheel path and shoulder, respectively.
COLUMN 4.	Marshall Stability in pounds, of the core sample as measured in the laboratory.
COLUMN 5.	Marshall Flow in 1/100 inches, of the core sample as measured in the laboratory.
COLUMN 6.	Percent passing the 1-1/2 inch sieve.
COLUMN 7.	Percent passing the 1 inch sieve.
COLUMN 8.	Percent passing the 3/4 inch sieve.
COLUMN 9.	Percent passing the 1/2 inch sieve.
COLUMN 10.	Percent passing the 3/8 inch sieve.
COLUMN 11.	Percent passing the #4 sieve.
COLUMN 12.	Percent passing the #10 sieve.
COLUMN 13.	Percent passing the #40 sieve.
COLUMN 14.	Percent passing the #80 sieve.
COLUMN 15.	Percent passing the #200 sieve.
COLUMN 16.	Percent fractured faces of the material retained above the 3/8 inch sieve.

NOTE: * denotes information not available.

Table 31. Original Jennings Et Al's Data.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	1	1	1790	10	100	100	100	90	78	58	40	23	13	9	83
1	1	2	950	8	100	100	100	95	85	61	42	22	13	9	79
1	2	1	1090	6	100	100	99	84	75	60	44	23	11	6	68
1	2	2	700	6	100	100	98	81	75	59	44	23	10	6	69
2	1	1	850	8	100	100	97	87	79	58	41	25	14	10	71
2	1	2	1110	13	100	100	96	87	78	58	40	25	13	10	93
2	2	2	920	11	100	100	99	92	84	62	44	29	12	9	75
3	1	1	1800	7	100	100	98	89	75	53	38	27	11	8	71
3	1	2	1160	7	100	100	99	91	83	61	44	30	12	9	67
3	2	1	1580	8	100	100	100	88	77	57	42	31	12	8	99
3	2	2	940	9	100	100	100	89	75	54	40	30	11	8	61
4	1	2	610	9	100	100	100	96	80	48	33	24	11	8	78
5	1	1	2210	8	100	100	100	95	88	67	43	24	15	8	78
5	1	2	2250	12	100	100	100	95	85	63	40	22	13	8	85
5	2	1	3880	15	100	100	100	94	85	60	36	19	13	8	69
5	2	2	1320	10	100	100	100	96	85	61	37	21	12	8	66
6	1	1	2040	12	100	100	100	94	85	62	39	22	14	8	100
6	1	2	1570	10	100	100	100	90	74	49	31	19	12	7	86
6	2	1	1900	8	100	100	100	92	80	58	37	20	12	8	84
6	2	2	2960	8	100	100	100	91	78	56	36	20	12	8	75
7	1	2	2020	16	100	100	100	93	85	60	39	23	14	8	100
7	2	1	1650	10	100	100	100	98	89	62	40	24	14	10	88
7	2	2	2320	12	100	100	100	99	89	58	37	24	17	12	100
8	2	1	2050	13	100	100	100	97	90	60	39	25	16	10	78
8	2	2	1570	10	100	100	100	99	89	60	40	26	16	10	99
9	1	1	1990	8	100	100	100	97	88	61	40	23	14	8	89
9	1	2	1400	9	100	100	100	94	84	57	36	21	13	7	100
9	2	1	2230	8	100	100	100	90	80	55	40	31	17	7	87
9	2	2	*	*	100	100	100	92	82	56	40	31	17	8	77
10	1	1	1560	8	100	100	100	95	86	60	42	25	13	7	59
10	1	2	720	7	100	100	100	96	87	62	44	25	12	7	51
11	1	1	1290	8	100	100	100	92	81	55	39	27	13	7	67
11	1	2	1730	6	100	100	100	93	82	55	39	25	12	6	93
11	2	1	2770	8	100	100	100	92	82	57	38	21	12	7	79
11	2	2	2080	7	100	100	100	93	84	55	38	21	12	7	88
11	3	1	2080	10	100	100	100	89	79	51	34	18	11	6	81
11	3	2	1740	8	100	100	100	94	86	58	39	20	12	7	85
12	1	1	1300	6	100	100	100	92	80	56	40	27	12	6	69
12	1	2	1210	7	100	100	100	90	77	51	37	25	11	5	74

Table 31 - Continued

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
12	2	1	2650	8	100	100	100	92	85	58	39	22	11	6	79
12	2	2	1580	7	100	100	100	94	83	55	37	22	11	6	78
12	3	1	2660	10	100	100	100	91	83	56	37	21	11	6	78
12	3	2	1490	9	100	100	100	93	82	56	37	21	10	5	82
13	1	1	1460	11	100	100	100	92	84	59	39	22	15	9	98
13	1	2	1400	9	100	100	100	96	84	59	40	22	13	9	70
14	1	1	1880	9	100	100	100	88	80	54	35	21	14	8	97
14	1	2	1160	9	100	100	100	92	80	53	36	18	13	8	63
14	2	1	1770	7	100	100	100	90	75	54	39	22	12	8	59
14	2	2	1890	10	100	100	100	90	77	54	40	22	11	7	61
15	1	1	1740	3	100	100	100	94	89	63	42	21	14	8	78
15	1	2	1890	8	100	100	100	94	86	62	43	20	13	8	66
15	2	1	3300	7	100	100	100	96	88	64	46	18	11	6	45
15	2	2	1590	6	100	100	100	95	87	64	46	18	12	7	44
16	1	1	1330	9	100	100	100	92	81	59	41	26	12	7	75
16	1	2	1480	14	100	100	100	92	77	54	39	25	11	6	81
16	2	1	*	*	100	100	100	99	90	62	41	23	13	8	64
16	2	2	*	*	100	100	100	91	81	58	42	25	13	7	68
16	3	1	2040	8	100	100	100	98	91	61	41	25	12	7	84
16	3	2	1730	9	100	100	100	99	87	59	41	25	12	7	83
17	1	1	1550	10	100	100	100	94	82	55	39	24	12	7	76
17	1	2	1270	11	100	100	100	91	77	53	37	23	11	6	83
17	2	1	2040	6	100	100	100	94	82	60	44	24	14	6	90
17	2	2	1660	10	100	100	100	91	81	60	44	24	13	6	81
18	1	1	1070	11	100	100	100	94	80	57	42	23	12	7	88
18	1	2	1490	12	100	100	100	90	76	51	38	21	10	6	77
18	2	1	940	8	100	100	100	88	76	59	48	26	15	7	79
18	2	2	1160	7	100	100	100	85	72	56	45	25	14	6	82
18	3	1	1360	18	100	100	93	67	58	43	33	20	11	6	64
18	3	2	1460	9	100	100	80	56	47	35	27	17	10	5	60
19	1	1	1500	6	100	100	100	92	75	55	37	19	10	5	85
19	1	2	1530	11	100	100	100	90	77	54	37	19	10	5	88
19	2	1	990	11	100	100	100	94	85	64	48	27	16	9	87
19	2	2	1160	11	100	100	100	94	84	64	48	26	15	8	69
19	3	1	760	7	100	100	92	73	64	47	37	24	14	7	63
19	3	2	950	9	100	100	86	65	57	43	34	22	13	7	65
20	1	1	1430	10	100	100	100	92	74	54	39	21	10	6	82
20	1	2	1560	11	100	100	100	93	75	53	39	20	10	6	78
20	2	1	1210	9	100	100	100	93	80	56	43	24	11	6	71
20	2	2	1210	10	100	100	100	90	78	55	42	24	11	6	77
20	3	1	1780	8	100	100	83	68	61	45	34	21	9	5	58
20	3	2	1350	8	100	100	83	63	57	41	32	20	9	5	58
21	1	1	1460	8	100	100	100	88	75	54	40	21	11	6	85
21	1	2	1790	7	100	100	100	89	70	48	35	19	10	6	84
21	2	1	1150	7	100	100	100	94	84	63	48	26	13	7	71
21	2	2	980	9	100	100	98	92	80	55	41	23	11	6	67

Table 31 - Continued

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
21	3	1	1440	7	100	100	84	61	52	38	31	20	9	5	53
21	3	2	1210	7	100	100	93	85	76	58	46	30	13	7	58
22	1	1	1800	7	100	100	100	89	73	53	38	19	10	6	82
22	1	2	1580	9	100	100	100	93	81	57	41	21	10	6	92
22	2	1	1220	7	100	100	100	95	87	59	41	21	13	8	73
22	2	2	1100	9	100	100	100	93	82	55	39	21	12	7	83
23	1	1	1800	6	100	100	100	100	87	59	39	22	14	10	100
23	1	2	1370	15	100	100	100	99	91	59	38	21	14	10	100
23	2	1	1450	11	100	100	100	90	75	51	36	20	13	9	63
23	2	2	2190	10	100	100	100	91	77	53	36	18	12	7	100
24	1	1	2930	7	100	100	100	97	82	52	33	17	13	9	100
24	1	2	1140	12	100	100	100	97	81	49	31	17	13	9	100
24	2	1	1500	13	100	100	100	94	85	57	36	21	15	11	100
24	2	2	1550	13	100	100	100	92	82	53	35	20	14	10	100
25	1	1	1060	8	100	100	100	95	78	55	39	20	13	8	93
25	1	2	1550	15	100	100	100	94	78	55	39	20	13	8	84
25	2	1	1990	9	100	100	100	88	75	53	38	19	11	6	85
25	2	2	1300	10	100	100	100	90	76	53	38	19	11	5	96
26	1	1	1530	10	100	100	100	93	78	56	38	20	13	8	90
26	1	2	1700	9	100	100	100	91	76	53	38	21	14	9	91
26	2	1	2340	8	100	100	100	87	78	55	41	17	9	4	72
26	2	2	970	8	100	100	100	88	78	57	43	18	9	4	75
27	1	1	1540	10	100	100	100	93	76	50	35	17	11	7	85
27	1	2	1230	11	100	100	100	92	79	54	38	19	12	7	81
27	2	1	1960	7	100	100	100	92	77	53	39	19	11	6	66
27	2	2	1140	10	100	100	100	93	81	59	43	21	13	7	84
28	1	1	1770	13	100	100	100	91	76	53	38	20	13	8	95
28	1	2	1620	12	100	100	100	93	81	56	41	21	14	9	91
28	2	1	1430	9	100	100	100	96	80	51	35	16	10	6	86
28	2	2	1350	10	100	100	100	95	86	61	45	23	14	8	81
29	1	1	3330	6	100	100	100	90	76	54	41	23	12	6	88
29	1	2	640	6	100	100	100	92	77	55	41	24	13	6	85
29	2	1	2420	5	100	100	100	94	77	52	37	20	14	9	86
29	2	2	1120	10	100	100	100	94	80	53	38	21	14	9	90
30	1	1	1440	11	100	100	100	96	83	53	38	20	14	9	88
30	1	2	1760	9	100	100	100	98	84	57	40	21	13	8	88
30	2	1	1180	8	100	100	100	93	84	64	48	25	15	8	92
30	2	2	1560	8	100	100	100	91	82	59	43	24	15	8	93
31	1	1	1710	7	100	100	100	96	81	53	38	21	14	9	90
31	1	2	1920	4	100	100	100	95	78	50	36	20	14	9	93
31	2	1	1740	7	100	100	100	91	82	61	46	22	13	6	68
31	2	2	930	7	100	100	100	92	83	60	43	24	15	8	90
32	1	1	1030	10	100	100	100	93	83	62	41	16	9	5	94
32	1	2	690	10	100	100	100	94	87	68	45	16	9	5	90
32	2	1	1540	10	100	100	100	86	71	47	32	11	6	3	71
32	2	2	1500	10	100	100	100	88	71	48	33	11	6	3	74

Table 31 - Continued

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
33	1	1	2090	12	100	100	100	93	84	60	40	17	10	6	80
33	1	2	1060	11	100	100	100	97	87	63	41	16	9	5	81
33	2	1	2280	12	100	100	100	91	80	54	36	17	9	5	78
33	2	2	1510	10	100	100	100	86	70	49	35	12	5	3	78
34	1	1	1590	8	100	100	100	90	80	62	47	21	11	5	79
34	1	2	1290	8	100	100	100	90	77	59	46	20	9	4	78
35	1	1	1780	10	100	100	100	96	86	62	42	23	16	10	89
35	1	2	1950	12	100	100	100	96	88	64	43	23	16	10	91
35	2	1	1420	11	100	100	100	90	82	62	46	20	11	5	93
35	2	2	940	11	100	100	100	92	80	58	43	19	11	6	87
36	1	1	1550	10	100	100	100	94	82	57	39	21	15	9	93
36	1	2	1970	10	100	100	100	89	78	56	38	21	14	8	85
36	2	1	1120	9	100	100	100	84	73	55	42	21	12	7	89
36	2	2	1100	11	100	100	100	87	74	60	45	21	13	8	86
37	1	1	1470	5	100	100	100	89	75	54	39	18	10	5	95
37	1	2	710	9	100	100	100	91	81	60	43	20	12	5	97
37	2	1	1480	13	100	100	100	96	86	65	48	20	11	6	90
37	2	2	1420	11	*	*	*	*	*	*	*	*	*	*	*
38	1	1	1330	6	100	100	100	95	84	63	45	19	10	5	91
38	1	2	920	8	100	100	100	95	84	64	45	19	10	5	85
38	2	1	2220	8	100	100	100	93	81	59	43	19	10	5	89
38	2	2	1670	10	100	100	100	93	84	63	46	21	12	6	84
39	1	1	1150	7	100	100	100	82	66	43	31	19	9	4	70
39	1	2	1360	6	100	100	100	90	78	53	37	22	11	5	75
39	2	1	1710	8	100	100	100	88	78	59	45	26	15	8	89
39	2	2	1810	8	100	100	100	88	76	56	40	23	14	6	100
40	1	1	420	5	100	100	100	80	69	46	33	20	9	4	80
40	1	2	1160	7	100	100	100	91	82	57	40	23	11	5	74
40	2	1	1850	10	100	100	100	93	84	59	41	24	11	5	73
40	2	2	1250	11	100	100	100	93	86	69	51	28	16	7	100
41	1	1	940	7	100	100	100	83	69	48	34	20	10	5	93
41	1	2	670	6	100	100	100	87	72	47	34	20	9	4	77
41	2	1	1640	6	100	100	100	90	80	60	45	20	11	6	100
41	2	2	1190	7	100	100	100	92	83	64	49	21	12	6	100
42	1	1	1210	10	100	100	100	93	84	67	51	23	13	6	97
42	1	2	1120	9	100	100	100	90	80	61	46	22	13	6	94
43	1	1	1660	8	100	100	100	95	83	60	44	20	11	6	94
43	1	2	1570	10	*	*	*	*	*	*	*	*	*	*	*
44	1	1	1280	9	100	100	100	98	89	58	41	23	12	7	74
44	1	2	1200	9	100	100	100	98	86	56	39	22	12	7	78
44	2	1	1450	8	100	100	100	94	79	56	40	26	14	7	71
44	2	2	1160	10	100	100	100	90	77	54	39	24	12	6	71
45	1	1	1770	7	100	100	100	96	80	48	34	20	11	6	73
45	1	2	1410	7	100	100	100	97	85	57	40	22	12	7	74
45	2	1	2270	6	100	100	100	96	91	69	46	24	18	13	100
45	2	2	1660	11	100	100	100	98	94	71	47	24	18	13	100

Table 31 - Continued

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
46	1	1	1830	9	100	100	100	91	85	65	42	19	14	9	100
46	1	2	1770	10	100	100	99	91	84	62	42	20	17	12	100
46	2	1	1400	10	100	100	91	75	67	49	31	15	11	8	100
46	2	2	1430	10	100	100	90	75	67	48	30	15	11	8	100
46	3	1	1740	13	100	100	100	91	82	66	52	24	12	6	85
46	3	2	1510	12	100	100	100	91	83	66	53	24	12	6	83
47	1	1	3020	6	100	100	100	95	87	59	35	17	13	9	100
47	1	2	1170	10	100	100	100	96	88	59	35	17	13	9	100
47	2	1	920	8	100	97	95	78	71	52	37	15	10	7	99
47	2	2	930	9	100	94	93	79	71	55	39	15	10	7	100
47	3	1	1610	13	100	100	89	76	70	53	35	17	12	9	100
47	3	2	1730	16	100	100	95	81	73	53	34	17	12	9	100
47	4	1	1490	11	100	100	100	92	82	64	50	24	14	8	85
47	4	2	1610	11	100	100	100	90	82	66	52	24	13	7	83
48	1	1	1670	10	100	100	100	90	71	45	32	19	11	5	81
48	1	2	1850	12	100	100	100	95	81	53	38	22	11	6	89
48	2	1	2370	7	100	100	100	95	86	61	43	22	12	7	84
48	2	2	2220	7	100	100	100	95	88	63	45	23	15	10	84
48	3	1	1690	7	100	100	99	83	70	53	38	16	9	5	75
48	3	2	800	7	100	100	99	80	69	51	37	16	10	6	68
48	4	1	1630	8	100	100	97	90	82	65	46	19	11	7	72
48	4	2	1040	11	100	100	100	92	85	65	46	20	12	7	70
49	1	1	1450	10	100	100	100	96	85	57	41	21	11	5	85
49	1	2	1560	11	100	100	100	95	81	55	38	20	11	5	79
49	2	1	1410	8	100	100	100	95	80	55	39	21	10	5	82
49	2	2	1920	10	100	100	100	95	86	61	42	21	14	9	81
49	3	1	1840	14	100	100	97	78	68	49	35	17	10	6	78
49	3	2	1200	8	100	100	98	75	65	48	35	17	10	6	81
49	4	1	1920	8	100	100	99	90	82	64	47	18	10	6	61
49	4	2	1330	12	100	100	100	89	81	65	47	19	11	6	75
50	1	1	1230	12	100	100	100	93	81	52	36	25	18	8	99
50	1	2	950	12	100	100	100	91	78	51	36	26	19	8	85
50	2	1	2810	11	100	100	100	97	88	60	38	23	18	10	100
50	2	2	4530	10	100	100	100	98	89	60	38	23	18	10	100
51	1	1	2110	8	100	100	100	94	83	58	40	27	20	9	100
51	1	2	1830	10	100	100	100	90	78	49	34	24	18	8	100
51	2	1	2150	10	100	95	82	57	50	38	28	15	9	6	70
51	2	2	*	*	100	94	74	57	51	37	28	14	9	6	59
51	3	1	1100	10	100	100	88	68	60	47	35	17	10	6	61
51	3	2	1430	12	100	100	95	71	61	46	34	16	10	6	78
53	1	1	870	7	100	100	100	94	82	61	44	27	14	7	86
53	1	2	1180	8	100	100	100	87	75	51	37	23	12	6	87
53	2	1	990	7	100	100	84	69	61	49	40	23	13	7	65
53	2	2	610	12	100	100	87	69	61	49	40	23	13	7	55
54	1	1	1340	13	100	100	100	94	79	55	40	23	11	6	88
54	1	2	1590	9	100	100	100	91	74	50	36	21	10	5	87

Table 31 - Continued

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
54	2	1	560	6	100	100	82	60	49	37	29	17	9	5	67
54	2	2	420	21	100	100	86	71	63	49	40	23	14	7	65
55	1	1	1520	7	100	100	99	90	81	57	41	25	13	7	81
55	1	2	1050	7	100	100	100	91	80	56	40	24	13	7	83
55	2	1	1970	9	100	100	89	68	59	45	36	21	11	7	56
55	2	2	1000	9	100	100	94	75	67	52	41	23	12	7	69
56	1	1	1900	9	100	100	100	93	80	58	43	22	12	6	80
56	1	2	1260	7	100	100	100	89	79	60	46	21	11	6	92
57	1	1	1230	10	100	100	99	84	73	50	36	22	11	6	66
57	1	2	990	11	100	100	100	90	77	56	41	24	12	6	79
58	1	1	1170	10	100	100	100	91	80	59	44	23	13	7	89
58	1	2	1100	12	100	100	100	94	85	66	48	23	13	7	82
59	1	1	2090	7	100	100	100	93	78	55	41	23	11	6	95
59	1	2	1150	10	100	100	100	94	82	61	46	25	12	6	86
59	2	1	1360	7	100	100	100	98	88	56	36	18	10	6	83
59	2	2	920	8	100	100	100	94	84	52	34	18	10	5	85
60	1	1	1730	12	100	100	100	94	80	61	46	24	14	8	86
60	1	2	2410	13	100	100	100	96	81	60	45	24	14	8	87
60	2	1	1770	11	100	100	100	92	78	53	37	20	13	7	91
60	2	2	1500	13	100	100	100	93	83	58	41	22	14	7	75
61	1	1	1430	10	100	100	100	94	82	56	38	20	12	6	96
61	1	2	1680	9	100	100	100	95	86	60	42	22	14	8	97
61	2	1	1810	10	100	100	100	91	83	61	42	22	12	7	96
61	2	2	1230	9	100	100	100	94	85	62	42	21	12	6	97
61	3	1	1640	12	100	100	100	97	85	59	41	21	12	7	80
61	3	2	3050	15	100	100	100	96	84	59	42	23	14	9	83
62	1	1	1930	10	100	100	100	91	79	57	39	19	11	6	96
62	1	2	2070	12	100	100	100	92	83	62	41	21	12	6	98
62	2	1	1460	12	100	100	100	97	89	65	42	21	12	7	91
62	2	2	2370	9	100	100	100	99	90	61	43	26	14	7	80
63	1	1	1380	12	100	100	100	92	81	55	37	19	11	6	95
63	1	2	1620	13	100	100	100	89	78	54	36	19	11	6	99
63	2	1	2530	13	100	100	100	97	89	61	42	23	13	7	84
63	2	2	2040	10	100	100	100	96	87	56	40	24	12	6	69
64	1	1	1810	9	100	100	100	93	79	54	42	22	13	7	84
64	1	2	1560	10	100	100	100	92	78	57	44	23	14	7	84
64	2	1	1970	8	100	100	100	96	86	56	40	23	12	6	86
64	2	2	1830	8	100	100	100	95	84	59	42	25	14	8	81
64	3	1	2230	6	100	100	100	94	84	58	42	26	15	8	85
64	3	2	1340	9	100	100	100	90	80	56	40	24	13	7	73
65	1	1	2070	12	100	100	100	91	74	54	42	22	13	7	85
65	1	2	2310	9	100	100	100	92	79	60	46	24	14	7	85
65	2	1	1980	8	100	100	100	93	84	63	47	28	15	7	82
65	2	2	2470	12	100	100	100	91	80	55	39	24	13	6	82
66	1	1	2040	8	100	100	100	100	88	59	41	24	11	5	84
66	1	2	1920	9	100	100	100	99	92	63	42	26	12	5	84

Table 31 - Continued

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
67	1	1	2240	8	100	100	100	93	79	54	39	24	11	6	75
67	1	2	1610	12	100	100	100	93	82	57	41	25	14	7	72
68	1	1	1900	7	100	100	100	96	82	59	46	26	12	6	85
68	1	2	1050	9	100	100	100	93	81	57	44	25	12	5	81
68	2	1	1980	9	100	100	100	92	78	49	37	23	11	5	89
68	2	2	2340	8	100	100	100	93	80	54	39	23	11	5	85
69	1	1	1680	7	100	100	100	93	81	56	43	25	12	6	84
69	1	2	1000	11	100	100	100	94	78	55	43	25	12	6	87
69	2	1	1450	8	100	100	100	93	81	59	46	27	9	3	67
69	2	2	1410	11	100	100	100	88	73	52	42	26	9	3	81
70	1	1	700	13	100	100	100	91	72	45	36	21	10	5	85
70	1	2	980	10	100	100	100	93	78	54	41	24	11	5	81
70	2	1	1620	9	100	100	100	94	85	61	43	25	13	7	88
70	2	2	1970	11	100	100	100	96	88	62	44	25	13	7	78
71	1	1	1310	10	100	100	100	92	78	58	39	24	12	6	89
71	1	2	1570	9	100	100	100	90	77	57	38	24	12	6	91
71	2	1	3210	13	100	100	100	92	78	55	41	25	11	5	77
71	2	2	2010	11	100	100	100	95	80	57	42	25	11	5	79
72	1	1	3110	6	100	100	100	97	85	59	42	25	13	6	80
72	1	2	1780	14	100	100	100	96	85	61	43	26	14	7	74
73	1	1	1640	8	100	100	100	95	80	54	40	23	13	7	88
73	1	2	2010	10	100	100	100	92	79	53	39	23	13	7	83
73	2	1	1880	9	100	100	100	91	78	55	41	22	13	7	87
73	2	2	3180	9	100	100	100	95	84	61	45	24	14	7	87
73	3	1	1670	7	100	100	100	95	83	61	44	24	14	8	89
73	3	2	2200	8	100	100	100	92	79	55	41	22	13	7	88
74	1	1	1330	8	100	100	100	95	79	57	41	22	13	7	99
74	1	2	1790	9	100	100	100	95	81	55	40	22	13	7	94
74	2	1	1410	10	100	100	100	99	93	60	40	23	13	7	97
74	2	2	1270	10	100	100	100	100	93	61	40	23	12	6	82
75	1	1	1370	6	100	100	100	97	88	56	36	22	13	7	72
75	1	2	1170	9	100	100	100	98	87	56	37	23	14	8	61
76	1	1	1610	11	100	100	100	100	90	58	40	27	16	8	82
76	1	2	2170	12	100	100	100	99	89	60	41	28	16	8	79
77	1	1	1610	7	100	100	100	98	90	66	44	26	12	6	63
77	1	2	1330	9	100	100	100	98	87	58	36	19	10	5	67
78	1	1	1570	8	100	100	100	96	89	63	42	26	12	5	61
78	1	2	1090	10	100	100	100	100	90	61	39	22	11	5	68
79	1	1	2420	11	100	100	100	98	89	63	43	26	14	7	78
79	1	2	1400	13	100	100	100	98	90	61	42	26	15	8	75
79	2	1	1420	8	100	100	100	89	73	50	34	19	10	4	69
79	2	2	640	9	100	100	100	81	68	51	39	29	19	10	76
80	1	1	1700	9	100	100	100	91	74	47	35	22	14	8	88
80	1	2	1370	11	100	100	100	91	74	46	34	22	13	7	83
80	2	1	1010	10	100	100	100	94	78	48	33	19	12	7	89
80	2	2	2140	8	100	100	100	98	91	62	43	27	15	8	74

Table 31 - Continued

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
81	1	1	1680	8	*	*	*	*	*	*	*	*	*	*	*
81	1	2	1430	14	100	100	100	98	84	59	39	23	16	10	86
81	2	1	1300	6	100	100	100	86	73	51	38	28	18	8	72
81	2	2	2660	12	100	100	100	88	73	56	44	32	19	8	71
82	1	1	3630	9	100	100	100	98	89	56	36	18	12	7	78
82	1	2	*	*	100	100	100	97	83	52	32	17	13	8	90
82	2	1	1940	6	100	100	100	88	76	54	38	21	12	4	68
82	2	2	1890	8	100	100	100	88	77	53	38	26	17	7	69
83	1	1	1310	7	100	100	100	99	87	56	36	20	14	9	88
83	1	2	900	7	100	100	100	98	88	57	37	21	13	7	78
83	2	1	1460	8	100	100	100	90	77	53	38	26	16	8	68
83	2	2	1560	8	100	100	100	87	75	53	39	28	16	8	74
84	1	1	2200	8	100	100	100	95	85	54	38	26	16	8	78
84	1	2	1280	8	100	100	100	97	90	57	39	27	16	8	79
84	2	1	920	8	100	100	98	79	64	43	33	25	14	7	74
84	2	2	1350	7	100	100	100	89	75	46	33	22	15	8	67
85	1	1	2340	7	100	100	100	87	75	49	34	23	11	5	68
85	1	2	1050	8	100	100	98	92	81	54	38	26	12	5	72
85	2	1	1020	5	100	100	84	69	60	46	40	33	12	5	35
85	2	2	880	5	100	100	91	72	64	49	43	35	13	5	47
86	1	1	1240	7	100	100	100	86	69	42	29	18	10	6	89
86	1	2	1310	11	100	100	100	91	75	49	33	20	12	7	91
87	1	1	1590	13	100	100	100	95	89	61	36	18	14	10	98
87	1	2	1190	13	100	100	100	95	88	60	36	19	15	11	99
88	1	1	2040	10	100	100	100	90	77	50	36	23	10	5	71
88	1	2	3220	9	100	100	100	95	84	59	42	28	13	7	74
89	1	1	1720	7	100	100	100	97	85	59	40	23	14	7	80
89	1	2	1800	12	100	100	100	98	84	54	36	22	14	6	86
90	1	1	1680	8	100	100	99	81	68	43	32	24	13	5	65
90	1	2	1100	7	100	100	99	79	68	43	31	23	12	5	57
91	1	1	1160	9	100	100	98	86	72	50	38	29	15	6	57
91	1	2	1720	9	100	100	97	86	72	48	37	28	14	5	51
92	1	1	1990	5	*	*	*	*	*	*	*	*	*	*	*
92	1	2	1730	10	100	100	100	86	73	50	37	26	11	5	72
93	1	1	940	7	100	100	96	76	70	54	46	37	13	5	60
93	1	2	710	7	100	100	92	77	67	52	45	36	12	5	59
93	2	1	530	6	100	100	92	74	67	52	43	34	12	5	65
93	2	2	590	9	100	100	96	74	64	49	42	33	12	5	61
94	1	1	1600	7	100	100	99	85	76	56	46	37	17	8	62
94	1	2	1390	10	100	100	100	95	84	62	48	36	18	8	77
94	2	1	1090	9	100	100	85	67	59	44	36	30	14	6	64
94	2	2	1250	8	100	100	86	71	61	45	37	30	14	6	62
95	1	1	1970	9	100	100	100	92	82	59	40	24	11	5	82
95	1	2	1440	11	100	100	100	91	80	54	36	22	11	5	86
95	2	1	1730	8	100	100	100	100	95	65	46	34	13	4	74
95	2	2	1240	7	100	100	100	100	92	58	41	30	11	3	81

Table 31 - Continued

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
96	1	1	760	11	100	100	100	94	81	55	37	22	12	5	81
96	1	2	570	13	100	100	99	93	81	55	37	22	12	5	82
96	2	1	1120	14	100	100	100	100	95	68	50	39	16	5	80
96	2	2	1260	9	100	100	100	99	94	63	44	34	14	4	74
97	1	2	1280	12	100	100	100	87	72	51	37	22	12	6	77
97	2	2	2230	12	100	100	100	87	78	62	52	32	18	6	81
98	1	1	1840	8	100	100	100	96	85	60	45	32	12	5	60
98	1	2	1490	8	100	100	100	95	86	59	45	33	12	5	75
99	1	1	1630	8	100	100	100	95	79	50	38	29	11	5	63
99	1	2	810	8	100	100	100	91	76	50	39	30	11	4	69
99	2	1	2200	5	100	100	100	93	78	48	34	25	10	4	83
99	2	2	770	5	100	100	99	88	77	48	41	26	10	4	73
100	1	1	2260	5	100	100	100	98	88	52	35	24	12	5	88
100	1	2	1500	8	100	100	100	97	85	54	40	28	14	6	75
101	1	1	1350	8	100	100	100	91	76	47	30	17	9	4	84
101	1	2	990	10	100	100	100	96	80	53	34	19	10	5	75
101	2	1	1670	9	100	100	100	92	73	51	34	21	11	6	83
101	2	2	1420	10	100	100	100	90	78	57	44	34	13	5	60
102	1	1	1710	7	100	100	100	96	82	53	35	21	11	5	76
102	1	2	1180	10	100	100	100	97	84	58	38	22	12	6	76
102	2	1	1200	6	100	100	100	90	73	50	37	27	12	5	68
102	2	2	770	8	100	100	100	88	75	53	41	31	12	4	73
103	1	1	1340	8	100	100	100	96	80	51	34	22	11	6	85
103	1	2	920	7	100	100	100	90	74	50	33	21	11	6	79
103	2	1	1450	10	*	*	*	*	*	*	*	*	*	*	*
103	2	2	1460	10	100	100	100	91	76	56	44	35	13	4	62
104	1	1	1540	8	100	100	100	97	87	57	40	29	16	6	72
104	1	2	1350	6	100	100	100	96	86	57	40	29	16	6	72
104	2	1	920	8	100	100	90	72	63	46	39	35	18	6	54
105	1	1	2410	6	100	100	100	98	88	61	46	34	18	6	72
105	1	2	1900	6	100	100	100	96	80	53	40	29	16	6	77
105	2	1	770	5	100	100	86	68	57	42	35	31	16	5	43
105	2	2	450	6	100	100	96	74	65	47	39	35	18	6	42
106	1	1	1340	8	100	100	100	86	74	54	45	32	12	6	63
106	1	2	760	8	100	100	100	86	75	54	44	30	11	5	62
106	2	1	540	6	100	100	92	78	73	61	52	37	12	5	64
106	2	2	750	6	*	*	*	*	*	*	*	*	*	*	*
107	1	1	1300	10	100	100	100	89	77	54	41	22	12	6	93
107	1	2	1050	10	100	100	100	91	75	53	41	22	13	7	94
107	2	1	1480	9	100	100	100	87	74	49	34	22	12	6	86
107	2	2	1850	10	100	100	100	93	82	55	38	23	13	6	88
108	1	1	810	7	100	100	100	83	67	44	33	22	10	4	76
108	1	2	410	7	100	100	100	84	66	40	30	20	8	3	78
108	2	1	1060	7	100	100	100	96	87	56	40	25	14	7	64
108	2	2	1670	6	100	100	100	98	91	63	46	29	14	7	70
109	1	1	770	8	100	100	100	89	78	58	46	28	14	6	60

Table 31 - Continued

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
109	1	2	660	9	100	100	100	87	75	57	45	28	14	5	68
110	1	1	1930	5	100	100	100	86	73	48	35	18	10	6	65
110	1	2	830	8	100	100	100	90	80	58	43	22	13	7	71
111	1	1	*	9	100	100	100	95	82	50	35	21	12	5	77
111	1	2	1100	9	100	100	100	95	84	53	37	22	12	5	81
111	2	1	1460	5	100	100	100	93	80	51	36	21	12	5	80
111	2	2	610	8	100	100	100	94	80	50	34	20	11	4	87
111	3	1	930	5	100	100	93	79	71	55	46	31	17	6	36
111	3	2	600	6	100	100	84	73	64	51	42	29	15	5	60
112	1	1	1440	9	100	100	100	85	73	54	38	18	11	5	80
112	1	2	830	6	100	100	100	84	77	58	42	19	11	6	78
112	2	1	1450	8	100	100	100	90	80	55	36	18	11	6	75
112	2	2	1160	9	100	100	100	89	78	55	37	19	11	6	83
112	3	1	490	6	100	100	83	66	58	44	38	25	12	4	58
112	3	2	430	5	100	97	89	70	60	47	39	26	12	4	50
113	1	1	1500	10	*	*	*	*	*	*	*	*	*	*	*
113	1	2	1680	13	100	100	100	89	81	61	44	20	11	6	70
113	2	1	670	6	100	100	100	83	70	52	35	17	10	6	91
113	2	2	1090	6	100	100	100	86	77	58	43	22	12	6	71
113	3	1	700	6	100	98	87	75	70	61	54	27	9	4	84
113	3	2	280	4	100	100	92	83	77	66	59	29	10	4	52
114	1	1	1480	7	100	100	100	87	78	58	42	20	12	7	90
114	1	2	1260	9	100	100	100	85	76	57	41	20	12	6	95
114	2	1	1560	8	100	100	100	90	82	61	41	20	12	7	93
114	2	2	1530	9	100	100	100	90	82	60	41	20	13	6	92
114	3	1	880	6	96	86	80	71	66	56	50	30	12	4	51
114	3	2	580	8	100	90	82	73	66	56	50	29	11	4	56
116	1	1	1100	6	100	100	100	89	73	50	37	18	8	4	66
116	1	2	1060	9	*	*	*	*	*	*	*	*	*	*	*
116	2	1	490	6	100	100	90	69	62	48	40	24	10	3	56
117	1	1	760	10	100	100	100	92	80	59	45	23	10	4	73
117	1	2	590	6	100	100	100	88	76	55	42	21	10	5	64
117	2	1	500	6	100	100	88	71	64	51	41	23	9	3	60
117	2	2	290	6	100	100	93	73	67	53	43	24	9	3	43
118	1	1	1410	10	100	100	100	92	79	55	44	23	13	7	78
118	1	2	1560	8	100	100	100	88	75	52	42	22	12	6	73
118	2	1	340	5	100	100	100	91	78	58	45	25	12	6	82
118	2	2	770	7	100	100	100	90	78	56	43	24	12	6	72
122	1	1	1370	9	100	100	100	87	76	57	43	24	14	7	72
122	1	2	1270	8	100	100	100	89	78	59	44	25	14	7	74
122	2	1	1970	10	100	100	100	86	76	58	42	24	13	6	80
122	2	2	1670	10	100	100	100	87	76	55	38	22	13	6	81
122	3	1	1050	6	100	100	100	85	72	47	31	18	10	5	86
122	3	2	1340	9	100	100	100	91	80	55	37	20	11	5	89
123	1	1	1100	9	100	100	100	87	77	54	37	20	11	5	94
123	1	2	520	8	100	100	100	89	79	54	36	19	10	4	93

Table 31 - Continued

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
124	1	1	790	8	100	100	100	93	83	59	39	20	9	4	91
124	1	2	690	12	100	100	100	92	82	59	39	20	9	4	81
125	1	1	1120	10	100	100	100	90	78	56	39	21	12	7	85
125	1	2	1260	9	100	100	100	95	84	61	44	24	14	7	90
125	2	1	1510	10	100	100	100	88	77	57	41	23	12	6	85
125	2	2	2310	8	100	100	100	88	75	52	37	21	11	5	88
125	3	1	1350	6	100	100	100	80	67	44	31	18	10	5	89
125	3	2	1000	9	100	100	100	87	75	51	35	19	10	5	96
126	1	1	1820	5	100	100	100	97	89	58	38	20	14	9	92
126	1	2	850	14	100	100	100	98	90	59	38	19	13	8	87
127	1	1	2760	11	100	100	100	88	77	55	41	25	13	6	87
127	1	2	2250	11	100	100	100	86	76	55	40	24	12	5	94
128	1	1	1710	7	100	100	100	91	78	55	40	24	13	6	89
128	1	2	2000	11	100	100	100	86	75	51	37	23	12	6	88
129	1	1	2200	11	100	100	100	89	76	53	38	21	12	6	91
129	1	2	2600	12	100	100	100	89	75	53	37	22	13	7	89
130	1	1	1950	12	100	100	100	93	83	59	42	24	14	7	88
130	1	2	1630	11	100	100	100	90	82	60	43	25	14	8	99
131	1	1	1600	12	100	100	100	92	83	61	45	25	14	7	100
131	1	2	1670	16	100	100	100	94	83	60	44	25	14	7	100
133	1	1	1740	11	100	100	100	97	89	65	48	27	15	8	85
133	1	2	1250	13	100	100	100	95	84	61	47	26	14	7	89
133	2	1	1340	8	100	100	86	76	68	51	38	20	11	6	91
133	2	2	1400	8	100	97	90	74	68	51	38	20	12	6	79
134	1	1	1640	11	100	100	100	95	86	64	48	27	15	8	92
134	1	2	1230	11	100	100	100	96	85	66	49	27	15	8	88
134	2	1	2280	8	100	94	86	74	69	55	43	24	15	8	83
134	2	2	770	11	100	100	89	74	69	55	42	24	15	8	89
135	1	1	1300	12	100	100	100	92	83	62	47	26	15	8	81
135	1	2	1370	12	100	100	100	95	83	59	44	25	15	8	88
135	2	1	1440	11	100	100	83	63	54	39	30	17	10	5	82
135	2	2	830	14	100	90	80	64	56	43	33	19	11	6	84
136	1	1	880	5	100	100	100	90	75	52	39	19	9	4	84
136	1	2	940	7	100	100	100	89	75	53	41	19	9	4	82
137	1	1	930	7	100	100	100	90	77	56	44	21	11	6	73
137	1	2	1190	6	100	100	100	89	74	57	44	22	11	6	81
138	1	1	930	12	100	100	99	90	78	56	41	22	14	8	100
138	1	2	920	10	100	100	100	90	78	58	43	23	15	8	100
139	1	1	1160	10	100	100	100	93	81	59	44	24	16	9	98
139	1	2	910	7	100	100	100	91	81	59	43	22	14	8	100
140	1	1	1690	6	100	100	100	96	89	63	41	19	12	6	100
140	1	2	1130	12	100	100	100	95	82	55	36	17	11	6	100
140	2	1	1690	4	100	100	100	97	90	64	43	19	11	6	98
140	2	2	1070	6	100	100	100	93	83	59	39	18	12	7	100
141	1	1	1450	9	*	*	*	*	*	*	*	*	*	*	*
141	1	2	1670	9	100	100	100	95	79	58	41	18	11	6	95

Table 31 - Continued

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
141	2	1	1280	9	100	100	100	95	86	64	45	22	13	6	100
141	2	2	970	11	100	100	100	96	87	68	48	22	12	6	100
142	1	1	1730	9	100	100	100	88	80	60	42	17	12	7	90
142	1	2	1730	11	100	100	100	91	80	59	41	17	12	7	84
142	2	1	1450	10	100	100	99	87	79	63	48	23	14	7	100
142	2	2	1090	8	100	100	100	90	79	60	45	22	13	7	93
142	3	1	880	8	100	100	100	86	77	62	46	19	11	6	100
142	3	2	150	10	100	100	100	85	77	59	44	19	10	5	100
143	1	1	1480	8	100	100	100	90	81	60	43	20	13	6	98
143	1	2	1370	8	100	100	100	87	74	55	39	19	13	6	100
143	2	1	1050	8	100	100	100	94	83	63	46	24	15	8	99
143	3	1	620	9	100	100	100	81	74	59	44	14	7	4	84
143	3	2	830	10	100	100	99	81	69	48	34	12	7	4	92
144	1	1	890	6	100	100	100	94	83	62	44	20	11	6	75
144	1	2	860	8	100	100	100	95	82	60	42	19	11	6	84
145	1	1	1300	8	100	100	100	92	76	49	33	15	9	5	86
145	1	2	820	9	100	100	100	95	81	55	38	17	10	5	89
146	1	1	730	8	100	100	100	94	82	64	49	19	9	4	88
146	1	2	1180	12	100	100	100	90	77	56	42	18	10	6	69
147	1	1	1380	8	100	100	100	91	77	56	41	17	10	6	87
147	1	2	1270	11	100	100	100	91	80	60	44	18	11	7	97
148	1	1	1220	14	100	100	100	86	73	58	40	16	11	7	94
148	1	2	1090	13	100	100	100	88	76	62	43	17	11	7	94
148	2	1	1760	12	100	100	100	92	81	63	46	18	11	6	96
148	2	2	2080	12	100	100	100	93	83	62	47	20	13	6	89
149	1	1	1360	11	100	100	100	89	76	58	44	20	13	8	95
149	1	2	1350	18	100	100	100	87	71	51	38	17	11	7	94
149	2	1	1640	13	100	100	100	94	83	65	46	19	13	9	94
149	2	2	*	*	100	100	100	93	80	66	46	19	12	8	97
149	3	1	1940	9	100	100	100	98	89	64	46	21	13	8	93
149	3	2	2150	12	100	100	100	96	86	65	44	19	12	7	92
150	1	1	950	11	100	100	100	92	75	59	42	18	11	7	93
150	1	2	1050	13	100	100	100	88	73	56	39	16	11	7	99
150	2	1	1350	8	100	100	100	95	88	68	49	20	11	7	93
150	2	2	1860	11	100	100	100	96	89	64	44	19	11	7	93
151	1	1	1740	10	100	100	100	96	84	57	39	21	15	10	95
151	1	2	2070	16	100	100	100	93	82	56	39	21	16	11	94
151	2	1	1540	11	100	100	100	86	69	46	35	24	16	9	86
151	2	2	1610	14	100	100	100	85	70	48	36	23	15	8	100
152	1	1	2200	9	100	100	100	92	77	48	35	20	15	10	99
152	1	2	1730	14	100	100	100	91	75	49	36	20	15	10	96
152	2	1	1530	9	100	100	100	94	83	57	42	25	16	8	*
152	2	2	2570	12	100	100	100	90	75	52	40	24	15	8	84
153	1	1	1490	16	100	100	100	95	84	60	39	18	11	8	90
153	1	2	1690	18	100	100	100	94	83	58	38	17	11	7	92
153	2	1	1240	12	100	100	100	94	87	62	41	18	11	7	74

Table 31 - Continued

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
153	2	2	1350	16	100	100	100	92	84	60	40	18	11	7	76
154	1	1	1530	10	100	100	100	96	86	60	37	17	11	8	87
154	1	2	1310	12	100	100	100	97	90	64	40	17	11	8	86
154	2	1	2600	22	100	100	100	98	90	60	34	15	10	7	100
154	2	2	2100	13	100	100	100	93	80	52	31	14	10	7	100
155	1	1	1080	9	100	100	100	98	93	69	36	15	10	6	100
155	1	2	1090	13	100	100	100	95	90	64	38	16	11	8	100
156	1	1	1179	13	100	100	100	92	78	54	42	18	13	9	100
156	1	2	1557	14	100	100	100	94	82	62	46	19	13	9	100
156	2	1	2454	12	100	100	100	96	89	69	42	20	14	7	100
156	2	2	2705	11	100	100	100	96	91	69	43	21	15	7	99
157	1	1	1820	12	100	100	100	96	85	55	34	16	11	7	100
157	1	2	1580	14	100	100	100	94	83	57	35	17	11	7	100
157	2	1	1370	8	100	100	100	98	91	65	38	17	11	7	99
157	2	2	1660	11	100	100	100	99	91	64	39	17	12	5	99
158	1	1	1830	14	100	100	100	95	85	57	38	19	13	9	100
158	1	2	1910	14	100	100	100	96	82	56	37	19	13	8	100
158	2	1	1760	5	100	100	100	98	90	66	42	21	15	8	99
158	2	2	1310	11	100	100	100	98	91	66	42	21	16	8	98
159	1	1	1800	14	100	100	100	95	84	56	37	19	13	8	100
159	1	2	2180	12	100	100	100	94	83	56	37	20	14	8	100
159	2	1	1310	7	100	100	100	96	83	56	38	25	17	8	88
159	2	2	1370	10	100	100	100	95	83	56	38	24	17	7	80
160	1	1	1360	11	100	100	100	94	83	54	37	21	12	6	80
160	1	2	980	14	100	100	100	92	80	50	35	20	11	6	76
160	2	1	1120	8	100	100	100	96	87	57	39	24	14	7	88
160	2	2	1310	13	100	100	100	96	86	61	43	25	14	8	85
161	1	1	1130	13	100	100	100	94	85	56	39	22	12	7	81
161	1	2	1260	12	100	100	100	93	83	54	38	22	13	7	75
161	2	1	1430	8	100	100	100	98	88	63	43	21	13	7	84
161	2	2	1800	15	100	100	100	99	89	65	44	22	13	7	87
162	1	1	890	10	100	100	100	93	81	50	35	20	12	6	80
162	1	2	1490	12	100	100	100	90	80	51	36	21	12	7	65
162	2	1	1710	7	100	100	100	91	79	55	39	24	13	7	64
162	2	2	1390	9	100	100	100	91	79	51	36	21	11	5	72
163	1	1	640	10	100	100	100	91	77	48	34	21	11	6	84
163	1	2	690	13	100	100	100	93	80	52	38	23	13	6	85
163	2	1	1180	8	100	100	100	93	80	55	39	24	12	6	67
163	2	2	1790	10	100	100	100	94	84	60	43	26	13	7	61
164	1	1	1140	11	100	100	99	90	74	46	29	17	10	5	91
164	1	2	790	10	100	100	100	91	78	48	32	18	10	5	85
164	2	1	1790	6	100	100	100	89	76	56	43	25	13	6	82
164	2	2	1460	10	100	100	100	80	69	49	38	23	13	6	82
165	1	1	1280	10	100	100	100	89	76	51	33	19	11	6	91
165	1	2	1400	19	100	100	100	91	79	51	33	20	12	7	85
165	2	1	2220	5	100	100	100	90	77	57	43	25	13	6	78

Table 31 - Continued

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
165	2	2	1660	9	100	100	100	81	72	54	41	24	13	7	81
166	1	1	1650	13	100	100	100	96	85	59	39	22	13	8	78
166	1	2	1360	14	100	100	100	93	81	52	36	20	11	6	80
166	2	1	2110	9	100	100	100	83	75	53	39	23	12	5	75
166	2	2	1530	11	100	100	100	88	77	55	40	24	13	7	82
167	1	1	1720	10	100	100	100	91	77	51	36	22	12	6	93
167	1	2	1140	12	100	100	100	92	77	51	36	22	12	6	85
167	2	1	1030	6	100	100	100	92	82	58	41	25	13	7	97
167	2	2	1010	9	100	100	100	94	77	51	36	22	12	6	87
168	1	1	1130	6	100	100	100	90	78	52	36	22	12	7	82
168	1	2	1590	10	100	100	100	89	77	54	38	22	12	6	59
169	1	1	1530	4	100	100	100	90	79	57	42	24	12	6	86
169	1	2	850	8	100	100	100	91	80	56	41	24	13	7	78
170	1	1	2630	10	100	100	100	91	75	44	30	21	13	7	69
170	1	2	1360	14	100	100	100	94	82	51	34	22	14	7	69
171	1	1	1330	8	100	100	100	95	84	54	35	21	12	7	85
171	1	2	1800	11	100	100	100	94	82	51	33	21	12	7	88
171	2	1	1290	10	100	100	100	99	93	62	41	27	16	8	76
171	2	2	1420	6	100	100	100	98	89	58	39	26	16	8	83
172	1	1	2650	15	100	100	100	96	85	51	34	23	12	6	74
172	1	2	1720	10	100	100	100	97	86	58	39	25	13	6	66
172	2	1	1890	8	100	97	83	66	54	37	28	20	11	5	66
172	2	2	1440	8	100	100	92	69	57	36	27	20	10	4	59
173	1	1	2140	13	100	100	99	93	84	58	41	23	14	8	81
173	1	2	2120	12	100	100	96	90	79	54	38	25	13	7	70
173	2	1	1330	8	100	100	97	75	63	41	30	20	12	6	65
173	2	2	1720	11	100	100	100	82	67	45	32	21	12	6	70
174	1	1	1650	10	100	100	100	88	73	57	45	19	8	5	65
174	1	2	1540	14	100	100	100	91	80	63	49	21	9	5	78
174	2	1	1200	9	100	100	97	86	80	65	52	18	7	5	72
174	2	2	870	15	100	100	95	83	78	63	51	21	9	6	51
175	1	1	1320	8	100	100	100	92	78	61	49	24	11	7	72
175	1	2	1220	9	100	100	100	91	80	62	51	24	11	7	88
175	2	1	630	8	100	100	88	84	80	71	61	25	7	4	59
175	2	2	470	11	100	98	95	88	83	74	63	26	8	4	60
176	1	1	1450	12	100	100	100	93	84	58	38	21	12	8	87
176	1	2	1320	12	100	100	100	95	86	61	40	21	13	9	89
176	2	1	*	*	100	100	100	94	79	53	40	20	11	7	75
176	3	1	790	8	100	97	90	84	79	70	60	24	7	4	52
176	3	2	280	8	100	100	93	84	78	70	60	23	6	3	41
177	1	1	1550	15	100	100	100	88	78	55	37	17	11	7	97
177	1	2	1920	15	100	100	100	94	85	60	42	22	15	10	91
177	2	1	1130	6	100	100	100	97	88	58	43	23	15	8	81
177	2	2	720	9	100	100	100	98	90	64	47	26	18	9	77
178	1	1	2380	10	100	100	100	95	88	66	46	22	14	9	69
178	1	2	1390	12	100	100	100	99	91	64	45	22	14	9	71

Table 31 - Continued

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
179	1	1	860	8	100	100	100	91	82	59	42	18	10	6	60
179	1	2	1140	10	100	100	100	93	86	63	46	18	10	6	42
179	2	1	990	10	100	100	100	91	80	56	39	17	9	6	67
179	2	2	860	10	100	100	100	88	77	57	40	15	8	4	71
180	1	1	1260	11	100	100	100	93	84	61	45	19	11	6	51
180	1	2	1560	12	100	100	100	91	81	58	43	18	10	6	70
180	2	1	1890	9	100	100	100	92	81	58	41	20	10	5	88
180	2	2	1450	8	100	100	100	89	77	55	39	19	10	5	90
183	1	1	1410	9	100	100	100	88	75	56	46	22	11	7	73
183	1	2	1290	10	100	100	100	85	74	54	44	23	12	7	82
183	2	1	1210	8	100	100	96	84	77	62	52	22	10	6	57
183	2	2	600	16	100	100	96	81	75	61	51	23	11	6	90
184	1	1	1470	11	100	100	100	98	85	60	37	19	13	7	92
184	1	2	1620	14	100	100	100	95	84	61	37	19	12	7	77
184	2	1	2370	11	100	100	100	87	73	50	35	17	9	7	81
184	2	2	1780	10	100	100	100	88	70	46	35	18	10	6	72
184	3	1	1550	12	100	100	87	75	69	60	50	23	12	8	56
184	3	2	1390	9	100	93	82	72	68	57	48	22	12	7	74
185	1	1	1440	13	100	100	100	94	80	52	35	20	13	8	80
185	1	2	1590	10	100	100	100	96	82	55	35	19	13	7	84
185	2	1	1360	9	100	100	100	85	78	57	44	19	11	6	59
185	2	2	1660	10	100	100	100	90	79	59	44	19	11	6	70