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.

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CHAPTER 1

INTRODUCTION

Background

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

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

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

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

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

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

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

Information from the core samples:

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

Information from the extracted aggregate:

5. Aggregate Gradation
6. Percent Fractured Faces

Information from the extracted asphalt:

7. Ductility at 77^0 F
8. Penetration at 40^0, 70^0, and 90^0 F
9. Viscosity at 140^0 and 275^0 F
10. High Pressure - Gel Permutation Chromatography (HP-GPC)

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

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

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

Description of Proposal

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

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

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

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

Scope of Proposal

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

Anticipated Results

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

CHAPTER 2

REVIEW OF LITERATURE

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

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

This thesis examines only the gradation in depth.

Methods of Representing an Aggregate Gradation

Abrams' Fineness Modulus

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

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

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

Table 1. Calculation of Abrams' Fineness Modulus

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

FM = 132.2 / 100 = 1.32

Turnbull's Soil Classification

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

Table 2. Calculation of Turnbull's Soil Classification.

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

Area = (13.634) X (log 2)* = 4.104

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

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

Surface Area

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

Table 3. Calculation of Equivalent Surface Area.

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

Surface Area = 48.7 sq. ft. / lb.

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

FHWA's 0.45 Power Gradation Chart

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

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