Gradation Chart for Asphalt Mixes: Development

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Abstract: The gradation chart approach is based on the two parameters of Fuller's model (i.e., maximum size diameter and shape factor) which are obtained by fitting well-graded structures like those of Superpave or Covenin. ASTM mathematical definitions for gravel and sand, and Fuller's model are used to develop an analytical expression for a gravel-to-sand ratio used here to transform gradation into a numerical that may be correlated to HMA performance parameters. The gradation chart is a Cartesian plot conformed by shape factor and maximum size diameter and thus gradations, specification bands, gravel-to-sand ratios, and response parameters can be represented. Experimental results from recent research works performed by the National Center for Asphalt Technology on the mechanical and hydraulic performance of Superpave mixes are analyzed here. Based on these analyses, the writer resolved the controversy between below the restricted zone and above the restricted zone behavior, and found evidence that gradation specification bands (based on structure and maximum size diameter) would make no sense. Instead, the writer promotes "free design" in which a designer uses available aggregate, supported by a gradation-chart approach, to meet HMA performance parameters required by pavement design.

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Introduction

The gradation of a combination of aggregates is one of the key aspects when studying the mechanical and hydraulic behavior of asphalt mixes (for instance, Chowdhury et al. 2001; Anderson and Bahia 1997; El-Basyouny and Mamlouk 1999). Specifications on gradation are aimed to assure that the designer chooses the best possible combination of materials to obtain desirable responses (e.g., stability, flux, voids, Young modulus, rutting resistance, permeability).

Traditionally, gradation specifications are based on limits of maximum diameter and structures (e.g., fine-graded, coarse-graded). At present there is a controversy whether the structure produces better mixes (Kandhal and Cooley 2002). The maximum density line, a construction that divides fine structures from coarse structures, is said to produce mixes with unacceptable low voids (literature review from Kandhal and Cooley 2001), and is the director line of the Superpave's restricted zone. It is commonly accepted that aggregates with larger maximum diameter sizes will produce mixes with larger coefficients of permeability (Mallick et al. 2003; Cooley et al. 2002). Also, gradation specifications were originally proposed as a guide but today they represent a rigid control with considerable economical implications. In the opinion of the writer the study and understanding of the influence of gradation on HMA performance can be substantially enhanced by the use of quantitative classification, which in the present case means a transformation of gradation into a single number which would correlate with HMA response parameters.

RAMCODES, rational methodology for compacted geomaterials' densification and strength analysis (Sánchez-Leal 2004a), has a module for quantitative classification based on a characteristic factor. For soils, that is, geomaterials with fines (i.e., proportion through ASTM sieve No. 200) larger than 12%, the characteristic factor is a value obtained as a lineal product between finer-to-gravel ratio and liquid limit (the latter as an indirect measure of specific surface of fines), and has been successfully used to correlate properties of compacted soils such as Proctor's maximum dry density, optimum water content, and CBR (Sánchez-Leal 2002a,b, 2003). The objective of Part I of the present work is to develop a gradation-chart approach and the introduction of some basic applications to prove its utility on HMA research and design. Part II is devoted to analyzing data from the National Center for Asphalt Technology (NCAT) experimental track, years 2000–2002. Part III will present the application of this approach to HMA design.

Development

RAMCODES Postulates

This paper introduces the gradation-chart approach as a part of the development of the RAMCODES quantitative classification module applied to asphalt mixes. The following postulates of RAMCODES are applied in the development of the gradation-chart concept:

1. A compacted geomaterial can be soil, soil-cement, asphalt mix, or hydraulic cement mix (cemented soil). Thus concepts and criteria developed for each material could be applied to the rest.
2. Any classification system for geomaterials should consider at least gradation and the amount of specific surface of fines (indirectly accounted for by the plasticity concept) as the

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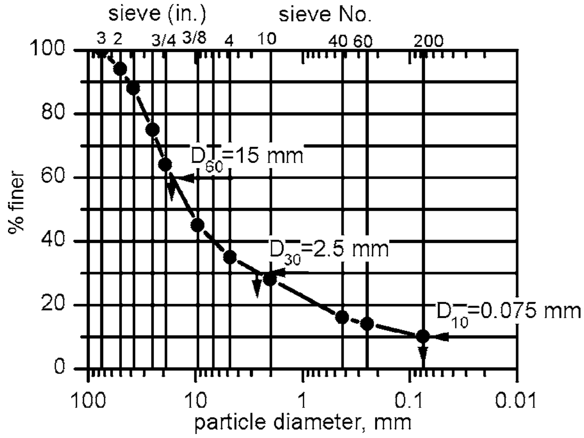

Fig. 1. Classical representation for a geomaterial's gradation

Table 1. Fuller's Model Fit for a Given Gradation

D_i (mm)	P_i	p_i	$(C2\text{-}C3)^2$	P_i^2
75	1	1.06044	0.003653	1
50	0.94	0.912709	0.000745	0.8836
37.5	0.88	0.82055	0.003534	0.7744
25	0.75	0.706238	0.001915	0.5625
19	0.64	0.638046	3.82E-06	0.4096
9.5	0.45	0.493709	0.00191	0.2025
4.75	0.35	0.382023	0.001026	0.1225
2	0.28	0.277392	6.8*E*-06	0.0784
0.425	0.16	0.156393	1.3*E*-05	0.0256
0.25	0.14	0.128514	0.000132	0.0196
0.075	0.1	0.082316	0.000313	0.01
Σ	5.69	5.658332	0.013251	4.0887

main inherent factors that influence their mechanical and hydraulic behavior.

3. To enhance behavior interpretation, data collection, and design, a classification system should not only be qualitative, but quantitative as well. That is, it should output a number related to a continuous scale in order to correlate response parameters to classification.

Fuller, Good Gradation, and Classification

The gradation, or sieve analysis, of a geomaterial is obtained by means of a graphic plot of a series of sieves that compound a set (see Fig. 1). In a well-graded material, proportions are distributed in similar quantities along the whole size range. On the other hand, the material on a uniform or poorly graded aggregate is concentrated within a single size or size range. Even though it is not the only factor, gradation has a notable influence on the densification potential and mechanical and hydraulic behavior of coarse-graded materials, so that its determination is therefore important (Juárez-Badillo and Rico-Rodríguez 1975). For instance, well-graded materials are prone to reach the largest density and strength, whereas the poorly graded are in turn the most permeable and weak.

The Unified Soil Classification System, as contained in ASTM D 2487-92 (2001), uses coefficient of uniformity, C_u, and coefficient of curvature, C_c, to quantify the gradation of a soil with less than 12% of fines, which is the range for most gradations for structural asphalt mixes. The coefficient of uniformity is defined as follows:

$$C_u = \frac{D_{60}}{D_{10}} \tag{1}$$

What this coefficient expresses is the nonuniformity of a material because its numerical value decreases as uniformity increases. Gravels and sands are considered well-graded when C_u is larger than 4 and 6, respectively. On the other hand, soils are considered very poorly graded when $C_u<3$.

Coefficient of curvature is defined by

$$C_c = \frac{(D_{30})^2}{D_{60} \times D_{10}} \tag{2}$$

This relationship has a value ranging between 1 and 3 on well-graded soils or aggregates.

It is very important to emphasize that well-gradation definition makes sense only on coarse-grained materials, that is, in which proportion finer than No. 200 sieve is equal to or less than 12%.

The gradation plot for a nonpoorly, coarse-grained material can be fit by an allometric (i.e., related to relative growth) model, known in HMA design jargon as "Fuller's model" (Asphalt Institute 1992), described as follows:

$$p_i = \left(\frac{D_i}{D_{\max}}\right)^n \tag{3a}$$

where, subindex "i" represents a particular sieve; D_i=any diameter sieve; p_i=percentage finer than diameter D_i; $D_{\max}$=the maximum size of aggregate; and n will be called the shape factor.

Eq. (3*a*) can also be written as

$$p_i = aD_i^n \tag{3b}$$

where

$$a = D_{\max}^{-n}$$

Hence

$$D_{\max} = \sqrt[n]{\frac{1}{a}} \tag{3c}$$

Applied to Fuller's model, the coefficient of determination [R^2, defined in Eq. (3*d*)] is the proportion of observed variation in sieves' passing percentage (P_i) that can be explained by the model. A value of $R^2=0$ means that the model cannot explain the data. On the other hand, a value of $R^2=1$ implies that data are fully explained by the model (Devore 1995)

$$R^2 = 1 - \frac{\sum\left(P_i - \left[\left(\frac{D_i}{D_{\max}}\right)^n\right]^2\right)}{\sum P_i^2 - \frac{(\sum P_i)^2}{N}} \tag{3d}$$

where N=number of sieves considered and P_i=observed passing percentage through D_i.

Let a particular gradation be given in Table 1 by a series of diameters (D_i) and respective sieves' passing percentages (P_i). A good coefficient of determination was reached (i.e., $R^2=0.9884$) at $n=0.37$ and $D_{\max}=64$ mm. These parameters were found using a commercial statistical software. Fig. 2 shows the plot for data and fit

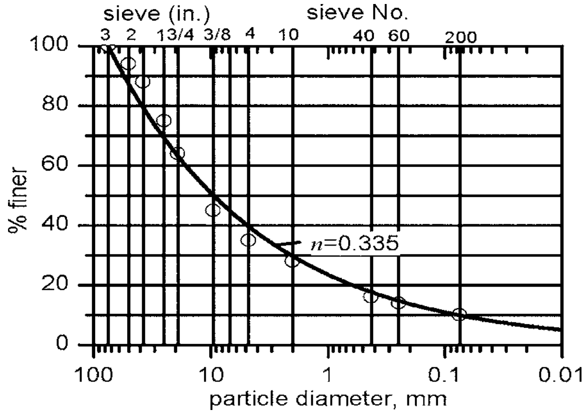

Fig. 2. Allometric of Fuller's model fit for data in Fig. 1

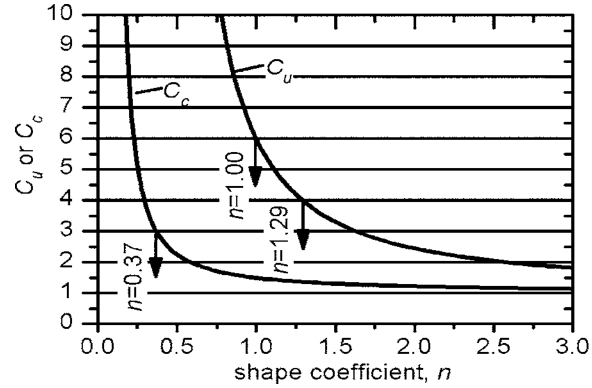

Fig. 3. Relation between ASTM's well-gradation coefficients and shape factor

$$R^2 = 1 - \frac{0.013251}{4.0887 - \dfrac{5.69}{11}} = 0.9884$$

Based on his experience, the writer considers that Fuller's model acceptably explains gradation data when R^2 is larger than 0.97. By using Fuller's model, a considerable quantity of asphalt mix gradations can be expressed by means of two numbers, namely, a coefficient of shape (i.e., n) and the aggregate's maximum size (i.e., D_{max}). As a matter of fact, Fuller's model has been successfully used by the writer in Covenin, Superpave, and some free-drain gradations. However, gradations for stone matrix asphalt (SMA) and open grade friction courses (OGFC), for instance, definitely do not fit the model (Sánchez-Leal 2004b).

The writer expressed C_u and C_c coefficients by means of Fuller's model that permitted one to transform ranges for good gradation into values of shape coefficient. In the following, new original expressions for C_u and C_c are developed.

From Eq. (3*a*)

$$0.60 = \left(\frac{D_{60}}{D_{max}}\right)^n \Rightarrow D_{60} = D_{max}(0.60)^{1/n} \qquad (4a)$$

$$0.30 = \left(\frac{D_{30}}{D_{max}}\right)^n \Rightarrow D_{30} = D_{max}(0.30)^{1/n} \qquad (4b)$$

$$0.10 = \left(\frac{D_{10}}{D_{max}}\right)^n \Rightarrow D_{10} = D_{max}(0.10)^{1/n} \qquad (4c)$$

Substituting Eqs. (4*a*) and (4*c*) into Eq. (1), yields

$$C_u = \frac{D_{60}}{D_{10}} = \frac{D_{max}(0.60)^{1/n}}{D_{max}(0.10)^{1/n}} = 6^{1/n}$$

Then, substituting Eqs. (4*a*)–(4*c*) into Eq. (2), yields

$$C_c = \frac{(D_{30})^2}{D_{60} \times D_{10}} = \frac{D_{max}^2(0.30)^{2/n}}{D_{max}(0.60)\dfrac{1}{n} \times D_{max}(0.10)^{1/n}} = \frac{(0.09)^{1/n}}{(0.06)^{1/n}} = 1\,.\,5^{1/n}$$

In consequence

$$C_u = 6^{1/n} \qquad (5a)$$

$$C_c = 1\,.\,5^{1/n} \qquad (5b)$$

From these equations it can be easily proved that at: C_u=4, n=1.29 (well-gradation condition for gravels); C_u=6, n=1.00 (well-gradation condition for sands); C_c=1, $n \to \infty$; and C_c=3, n=0.37.

These relations can be appreciated in Fig. 3. Observe that well-graded gravels have a shape coefficient of between 0.37 and 1.29, and for well-graded sands, n have a range of 0.37–1.00. Notice that Eqs. (5*a*) and (5*b*) are independent of aggregate maximum size (D_{max}); and these conclusions in consequence are applicable to all materials.

The Unified Soil Classification System (ASTM 2001) defines "gravel" as particles of rock that will pass a 3 in. (75 mm) sieve and be retained on a No. 4 (4.75 mm) U.S. standard sieve. Also, it defines "sand" as particles of rock that will pass a No. 4 (4.75 mm) sieve and be retained on a No. 200 (75 μm) U.S. standard sieve. These definitions are evidently applicable to aggregate, and if this aggregate would fit a Fuller's model, then a mathematical condition can be determined to decide whether the aggregate is gravel or sand from the model's parameters (n and D_{max}). Hence, by definition, the gravel content (G) can be expressed as

$$G = 1 - p_{4.75} \qquad (6)$$

The finer content (F) is simply

$$F = p_{0.075} \qquad (7)$$

Finally, sand content (S) is given by

$$S = 1 - (1 - p_{4.75}) - p_{0.075} = p_{4.75} - p_{0.075} \qquad (8)$$

An aggregate for asphalt mixes would be gravel or sand based upon which is the larger proportion present. Then, logically, an aggregate is gravel when G is larger than S, otherwise it is sand. The frontier between gravel and sand is, in consequence, given by G=S

$$1 - p_{4.75} = p_{4.75} - p_{0.075}$$

$$1 = 2p_{4.75} - p_{0.075}$$

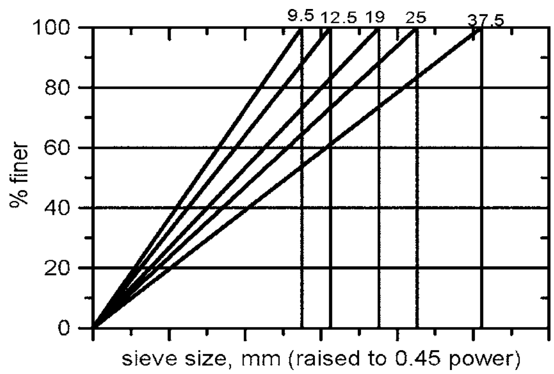

Fig. 4. FHwA representation for a gradation

$$1 = 2\left(\frac{4.75}{D_{\max}}\right)^n - \left(\frac{0.075}{D_{\max}}\right)^n$$

$$D_{\max} = (2 \times 4.75^n - 0.075^n)^{1/n} \tag{9}$$

This relation defines the gravel-sand frontier which will be used further in this paper.

Further, a general expression can be inferred for any combination of gravel (G) and sand (S) content by dividing Eq. (6) by Eq. (8) as follows:

$$\frac{G}{S} = \frac{D_{\max}^n - 4.75^n}{4.75^n - 0.075^n} \tag{10a}$$

Reordering this equation, the general expression yields

$$D_{\max} = \left[\left(1 + \frac{G}{S}\right) \times 4.75^n - \frac{G}{S} \times 0.075^n\right]^{1/n} \tag{10b}$$

G/S will be, as per RAMCODES, the characteristic factor for HMA.

Representations of Gradation

The classical representation of gradation looks like the Fig. 1 plot where the particle diameter (on x axis) is in logarithmic scale whereas percentage finer is in natural scale. Federal Highway Administration (FHwA) representation is shown in Fig. 4. Observe that particle diameter is raised to the 0.45 power. This representation was introduced in the 1960s to enhance the visualization of the line of maximum density (i.e., a gradation with allometric model parameter $n=0.45$), and has been adopted by Superpave technology (University of Texas at Austin 1996). It is well accepted that maximum density line should be avoided because gradations on this line would produce unacceptably low voids in mineral aggregate (Muench et al. 2003).

The point-ambit representation is introduced within the development of the quantitative classification module of RAMCODES. Point-ambit consists in the representation of Fuller's model parameters in the same Cartesian plane, that is, shape coefficient on x axis, and $D_{\max}$ on y axis. Therefore, a given gradation curve in point-ambit representation would be a "point" with coordinates (n, $D_{\max}$), which hereafter in this paper will be written as $n/D_{\max}$; thus, for instance, a gradation 0.40/22 means a gradation fit at $n=0.40$ and $D_{\max}=22$ mm, as can be seen in Fig. 5.

In traditional representation (e.g., diameter versus percent finer) any specification band is given by an upper and a lower limit (see Fig. 6). All gradation curves belonging to that specification band would lie between those limits. If possible, each limit

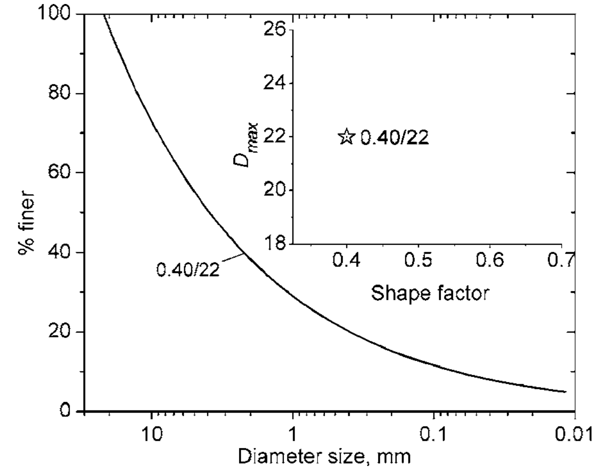

Fig. 5. Point-ambit representation for a gradation. A point is any curve.

could be fitted by Fuller's model. Let n_1/D_1 and n_2/D_2 be upper and lower limits, respectively. The other two limit combinations would be n_2/D_1 and n_1/D_2 as shown in Fig. 6. Hence, in a point-ambit representation, a specification band would be a rectangle or "ambit" as is also shown in Fig. 6, with vertices n_1/D_2, n_2/D_2, n_2/D_1, and n_1/D_1. In the point-ambit representation, in consequence, an ambit contains all gradation curves (or points) that would comply with the equivalent specification band.

Gradation Specifications

Gradation specifications are regulations aimed at assuring that the designer chooses a gradation that will produce a compacted mix that meets all desired performance responses related to the traffic to be served and the pavement structural function. There is a variety of aggregate specifications for asphalt mixes among which the writer cites Hveem specification (still used in some U.S. states), and FHwA 1996 specifications. In this work, the traditional AASHTO gradations, adopted by Venezuelan standards Covenin 2000-80 (Sanabria et al. 1980) will be used. Also, Su-

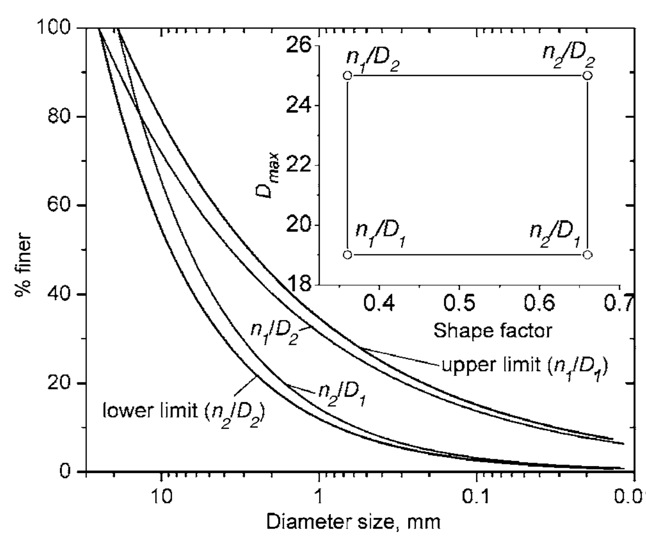

Fig. 6. Specification band on classical representation and point-ambit representation

Table 2. Traditional Dense Gradations (with Data from Covenin 2000-80)[a]

Sieve	Diameter (mm)	Type I surface	Type II surface	Type III surface	Type IV surface or interm.	Type V interm. or base
$1\frac{1}{2}$ in.	37.5					100
1 in.	25.0				100	80–100
$\frac{3}{4}$ in.	19.0	100		100	80–100	70–90
$\frac{1}{2}$ in.	12.5	85–100	100	80–100		
$\frac{3}{8}$ in.	9.5		80–100	70–90	60–80	55–75
No. 4	4.75	65–80	50–75	50–70	48–65	45–62
No. 8	2.36	50–65	35–50	35–50	35–50	35–50
No. 30	0.500	25–40	18–29	18–29	19–30	19–30
No. 50	0.300	18–30	13–23	13–23	13–23	13–23
No. 100	0.149	10–20	8–16	8–16	7–15	7–15
No. 200	0.075	3–10	4–10	4–10	2–8	2–8
Upper	n/D_{max}	0.33/9.5	0.44/9.5	0.40/12.5	0.34/19.0	0.32/25.0
	R^2	0.973	0.996	0.998	0.991	0.9889
Lower	n/D_{max}	0.40/12.5	0.60/12.5	0.49/19.5	0.46/25.0	0.42/37.5
	R^2	0.981	0.994	0.9989	0.990	0.990

[a]Values are percent finer. D_{max} values are in millimeter.

perpave gradation specifications will be used. For the sake of comparison, gradation specifications for two free-drain mixes will be shown. As expressed before, all specifications are regularly given with an upper and a lower limit gradation curve. Tables 2–5 show all gradation specifications used in this work given both in the common D_i-p_i way and in the point-ambit approach. Point-ambit parameters were obtained by Fuller-fitting correspondent D_i-p_i data; and R^2 values for each fit are also shown.

Specifications for traditional mixes are presented in Tables 2 (dense-structured) and 3 (open-structured). The terms “dense-structured” and “open-structured” are stated in the cited standard itself. From Tables 2 and 3 it can be seen that dense gradations have a shape coefficient lower than 0.45, and open gradations, in turn, exhibit shape coefficients larger that 0.45. Provided that $n=0.45$ is the maximum density line’s definition, these facts make the terms “dense” with “fine-graded,” and “open” with “coarse-graded” coincide. Also, in the upper row of each Tables 2 and 3, a recommendation for pavement structure function for each gradation is given. For instance, open gradations are mostly used for base or intermediate courses, and dense gradations are used for top or surface courses. Dense gradations have been commonly used in Venezuela for surface courses, especially Types III and IV, but open gradations have never been used practically. Base courses are built locally by means of compacted crushed gravel or natural gravelly soil.

Table 4 resumes specifications for Superpave gradations given by upper and lower limit control points. Superpave specifications are composed by five types, each differentiated by its nominal maximum aggregate size (NMAS). Point-ambit coordinates in the last rows of each table were obtained by Fuller-fitting diameter-passing data of each control point limit. Notice that the maximum diameter is correspondent to several traditional mixes in Tables 2

Table 3. Traditional Open Gradations (with Data from Covenin 2000-80)[a]

Sieve	Diameter (mm)	Type VI surface	Type VII surface or interm.	Type VIII base course	Type IX base course	Type X base course
$1\frac{1}{2}$ in.	37.5					100
1 in.	25.0				100	75–100
$\frac{3}{4}$ in.	19.0		100	100	75–100	60–85
$\frac{1}{2}$ in.	12.5	100	75–100	75–100		
$\frac{3}{8}$ in.	9.5	75–100	60–85	60–85	45–70	40–65
No. 4	4.75	35–55	35–55	30–50	30–50	20–50
No. 8	2.36	20–35	20–35	20–35	20–35	10–35
No. 30	0.500	10–22	10–22	5–20	5–20	5–20
No. 50	0.300	6–16	6–16	3–12	3–12	3–12
No. 100	0.149	4–12	4–12	2–8	2–8	2–8
No. 200	0.075	2–8	2–8	0–6	0–6	0–6
Upper	n/D_{max}	0.58/9.5	0.52/12.5	0.58/12.5	0.50/19.0	0.46/25.0
	R^2	0.969	0.9906	0.9923	0.9981	0.9967
Lower	n/D_{max}	0.90/12.5	0.70/19.0	0.78/19.0	0.74/25.0	0.70/37.5
	R^2	0.9929	0.9982	0.9976	0.995	0.9975

[a]Values are percent finer. D_{max} values are in millimeter.

Table 4. Superpave Gradations (Control Points)[a] (with Data from The University of Texas at Austin 1996)

Sieve	Diameter (mm)	37.5 mm	25 mm	19 mm	12.5 mm	9.5 mm
2 in.	50.0	100				
$\frac{1}{2}$ in.	37.5	90–100	100			
1 in.	25.0		90–100	100		
$\frac{3}{4}$ in.	19.0			90–100	100	
$\frac{1}{2}$ in.	12.5				90–100	100
$\frac{3}{8}$ in.	9.5					90–100
No. 4	4.75					
No. 30	2.36	15–41	19–45	23–49	28–58	32–67
No. 50	0.500					
No. 50	0.30					
No. 100	0.149					
No. 200	0.075	0–6	1–7	2–8	2–10	2–10
Upper	n/D_{max}	0.36/37.5	0.38/25.0	0.36/19.0	0.36/12.5	0.36/9.5
	R^2	0.992	0.9928	0.9928	0.9902	0.978
Lower	n/D_{max}	0.60/50.0	0.60/37.5	0.61/25.0	0.58/19.0	0.68/12.5
	R^2	0.9966	0.989	0.9972	0.985	0.995

[a]Values are percent finer. D_{max} values are in millimeter.

and 3, but shape coefficient range is so wide, approximately 0.36–0.74, that it may contain both dense and open gradations for the same NMAS. In other words, each Superpave gradation specification contains both dense and open structures. In current literature, gradation curves that pass above the restricted zone (ARZ) are considered fine graded, and curves that pass below the restricted zone (BRZ) are considered coarse graded (Kandhal and Cooley 2002). The definition of the restricted zone does not appear in Table 5 because this requirement has been deleted from Superpave (Kandhal and Cooley 2001).

Finally, Table 5 resumes gradation data for a couple of free-drain mixes (Muñoz Rojas and Ruiz Rodrigo 1999). Note that these mixes have a large value for shape coefficient. Free-drain mixes are used to fight hydroplaning and splash and spray problems sustained by highway under rainy conditions. Free-drain mixes usually reach field arrangements with an effective porosity (i.e., related to interconnected pores) ranging between 18 and 25%, which produces a considerable permeability. For instance, Reyes (personal communication, 2004) reported permeability values between 280 and 720×10^{-5} cm/s on free-drain mixes prepared with polymer-modified binder.

Table 5. Free-drain Gradations[a] (with data from Muñoz and Ruiz 1999)

Sieve	Diameter (mm)	PA-10	PA-12
$\frac{3}{4}$ in.	19.0	—	100
$\frac{1}{2}$ in.	12.5	100	70–80
$\frac{3}{8}$ in.	9.5	70–90	50–60
No. 4	4.75	15–30	15–30
No. 8	2.36	10–22	10–22
No. 30	0.600	6–13	6–13
No. 200	0.075	3–6	3–6
Upper	n/D_{max}	0.98/12.5	0.74/19.0
	R^2	0.9613	0.9847
Lower	n/D_{max}	1.62/12.5	1.10/19.0
	R^2	0.9867	0.9866

[a]Values are percent finer. D_{max} values are in mm.

Gradation Chart

The gradation chart is based on the point-ambit representation where specifications for several gradations can be depicted as well as contours for gravel-to-sand ratios, mechanical, or hydraulic properties. The gradation chart has the same intention of association and prediction as the plasticity chart for soils. Pure-cohesion soils' properties are organized in the plasticity chart related to the liquid limit and the plasticity index because plasticity (a measure of mineral specific surface) is the main inherent factor affecting behavior of this type of soil. Correspondingly properties of pure-friction soils, that is, aggregate, can then be organized in a gradation chart in relation to the maximum diameter and structure (by means of shape coefficient) because gradation is the main inherent factor influencing the behavior of these materials (RAMCODES postulate 2).

Fig. 7 shows the general form of a gradation chart. Shape factor and maximum size diameter conform x and y axes, respectively. Eq. (9) curve divides sands from gravels. ASTM conditions for good gradation for sands and gravels obtained by means of Eqs. (5a) and (5b), as well as maximum density line ($n=0.45$) are also represented. Utilizing Eq. (10b), contours for

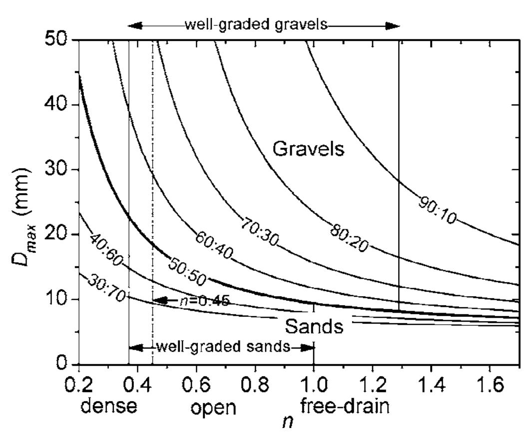

Fig. 7. General form of a gradation chart

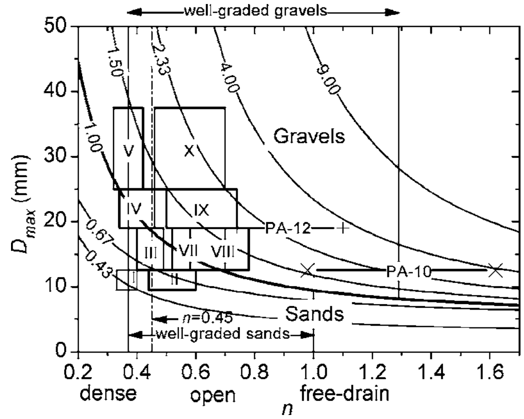

Fig. 8. Gradation chart for traditional (i.e., Covenin 2000-80) specifications. A couple of free-drain gradations are also depicted.

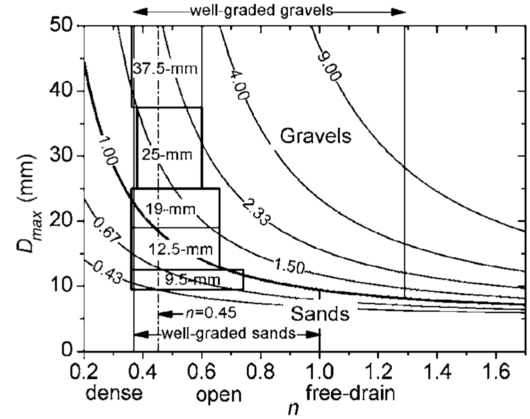

Fig. 9. Gradation chart for Superpave specifications

several gravel-sand proportions were represented in the chart. Each contour would imply that there are infinite combinations of shape factor and maximum size diameter that produce the same G/S ratio. On one hand, it seems logical to presume that, if other factors such as geological origin, particle shape, binder nature, temperature, among others, remain constant, HMA with similar G/S should have similar mechanical and hydraulic performance. On the other hand, it is commonly accepted that mixes with well-graded aggregate combinations would exhibit greater strengths and lower values of permeability compared to mixes with poorly graded aggregate (Juárez-Badillo and Rico-Rodriguez 1975); Eqs. (5*a*) and (5*b*) prove that shape factor, n, is a measure of good gradation. Also, gradations with larger maximum diameter size are expected to perform with larger values of permeability and greater strengths. These three assumptions seem to contradict each other because as can be seen in Fig. 7, or as anticipated in Eq. (10), there are infinite values of shape factor and maximum diameter size for the same G/S ratio, and also, there are infinite values of G/S for the same shape factor or maximum diameter size. The following paragraphs will be devoted to determining whether n, D_{max}, or G/S controls HMA performance.

In Fig. 8, ambits for dense and open Covenin gradations as well as the two free-drain mixes in Table 5 are represented. Specification ambits, summarized in Tables 2 and 3, are shown as rectangles labeled in the center. Observe that almost all traditional gradations are within well-gradation bounds. Also, contours for G/S factor are shown. Notice that several gradation ambits share the same G/S factor, and in consequence, two or more ambits should produce the same material. If the assumption that G/S controls gradation influence on HMA behavior is true, for instance, Gradations IX and X should be as permeable as free-drain mixes, or, for example, Gradations IV, III, VII, and VIII should present the same resistance to rutting.

Superpave ambits from NMAS 9.5 to 37.5 mm are portrayed in Fig. 9. Notice that these ambits cover a wide range of shape coefficients within well-gradation bounds, that is, Superpave gradations vary from dense to open structures, or fine to coarse-graded structures, following the line for $n=0.45$ as the division between both kinds of structures. Currently, there is a controversy over the differences in mechanical and hydraulic behavior between fine and coarse structures at the same NMAS (Kandhal and Cooley 2002). As in Covenin gradations, there are various Superpave ambits for the same G/S ratio. For instance, note that in Fig. 9 that there are NMAS 9.5, 12.5, and 19.0 mm gradations at $G/S=1$ or, there are NMAS 37.5, 25, 19, and 12.5 mm gradations at $G/S=1.50$.

Applications to Real Projects

Gradation Chart Approach on Workability

Workability is a term referred to the property describing the ease with which a HMA can be placed, worked by hand, and compacted (Gudimettla et al. 2003). This property is of interest when evaluating work yield on placing a HMA and the effect of polymer-modified binders. Workability is notably influenced by HMA temperature, the nature of the binder, and the particle shape, but also by gradation (Marvillet and Bougalt 1979). A gradation-chart approach may be used to perform factorial experiments conceived to evaluate the influence of gradation in HMA workability. For the purpose of this, experimental results were used for workability determination on NMAS 12.5 and 19 mm Superpave mixes published by NCAT (Gudimettla et al. 2003). As related by the cited research, a prototype device was developed, inspired in devices to measure workability on Portland concrete mixes, and successfully used to measure workability and evaluate the influence of several factors such as temperature, binder nature, particle shape, and gradation. The device immerses a paddle into a sample of HMA; the paddle is then rotated by an electric motor. The torque required to keep the paddle rotating at a constant speed within the sample is then measured. Workability was defined as the inverse of that torque. Although this device does not compose or belong to any standard, experimental results were used here to explore gradation chart approach. Gradations in the Gudimettla et al. (2003) study were all fitted by Fuller's model and n, D_{max}, and R^2 parameters were obtained. Observe that values for coefficient of determination are all larger than 0.97. G/S factor was computed according to Eq. (10*a*). Table 6 summarizes data. Fig. 10 shows the representation of gradation data on gradation chart. The study considered aggregates such as granite, limestone and crushed gravel; binders 64-22, 70-22, and 76-22; and HMA temperatures ranging from 120 to 170°C. However, due to limitations of space, only the torque results for crushed gravel, binder 70-22, and mix temperature of 120°C were considered for gradation chart approach, which are presented in Table 6. Figs. 11(a–c) present an interpretation of torque by G/S factor, D_{max}, and the shape factor, respectively.

Table 6. Gradation Data and Torque Values (with Data from Gudimettla et al. 2003)

HMA sieve (mm)	% passing			
	19-ARZ	19-BRZ	12.5-ARZ	12.5-BRZ
25.0	100	100		
19.0	95	95	100	100
12.5	80	80	95	95
9.5	68	68	86	86
4.75	45	45	61	61
2.36	41	29	45	33
1.18	31	19	35	23
0.60	24	14	26	16
0.30	19	11	19	13
0.15	11	9	11	9
0.075	4	4	4	4
n	0.41	0.51	0.42	0.50
D_{max}	24.2	22.6	15.5	16.0
R^2	0.9894	0.9916	0.9853	0.9759
G/S	1.16	1.38	0.78	0.96
Torque (m N)	29.3	32.2	27.0	29.2

Gradation Chart Approach on Rutting Resistance

Rutting resistance is one of the most important mechanical responses of a compacted HMA as it is the result of plastic deformation upon repeated loading (El-Basyouny and Mamlouk 1999; Chowdhury et al. 2001). A recent study (Kandhal and Cooley 2002) performed at the NCAT on rutting resistance of Superpave ARZ and BRZ mixes, measured by means of asphalt pavement analyzer (APA) and two other devices for performance evaluation, concluded that there is no significant difference for rutting resistance between fine and coarse structures at the same NMAS. APA device, which is considered an empirical test (Kandhal and Mallick 1999), was selected in the present work for the sake of the application of gradation chart approach on rutting resistance. Before the above-cited work there were some DOTs preferring ARZ over BRZ, or vice versa because it was supposed that different structures meant different behaviors, especially on rutting resistance.

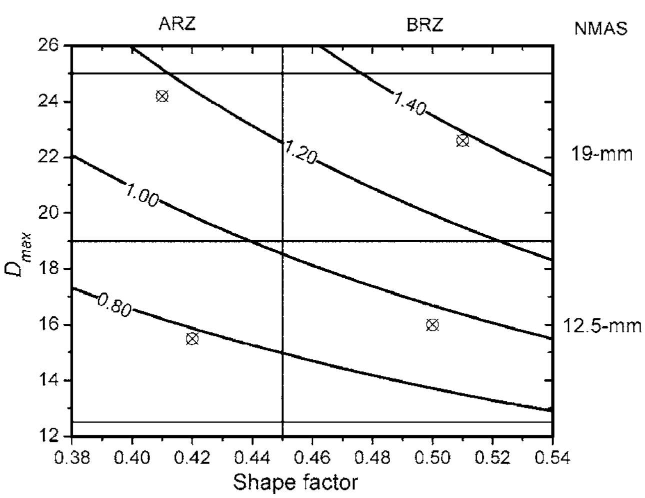

Fig. 10. Representation in gradation chart of gradations considered in workability study (with data from Gudimettla et al. 2003)

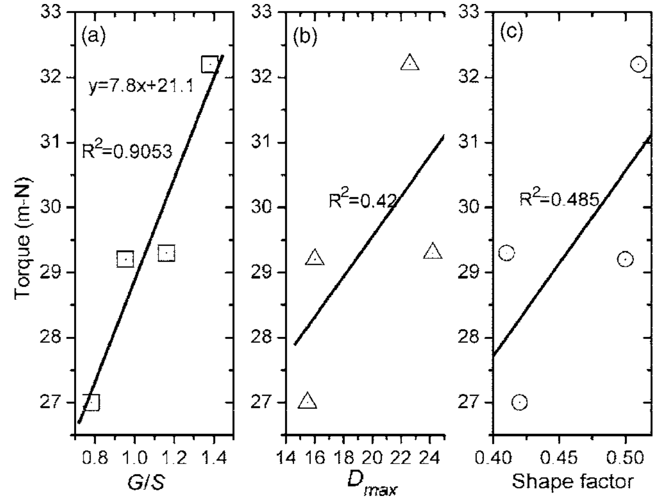

Fig. 11. Correlations on workability study results

The gradation-chart approach may be of help on this particular evaluation. The study by Kandhal and Cooley used Superpave mixes at NMAS 9.5 and 19 mm, prepared with crushed-gravel stone, sand, and compacted by gyrocompactor at 75 and 100 gyrations. The gradations of the above-cited work were fitted using Fuller's model (see Table 7) reaching R^2 values larger than 0.97. Data results were plotted on the point-ambit framework (see Fig. 12). In addition, G/S factor was computed for each mix. Rutting was normalized by multiplying APA deformation by the number of gyrations to compare all mixes. The results were plotted against G/S factor, shape factor, and D_{max}, respectively, in Figs. 13(a–c).

Table 7. Gradation Data and Rutting Values (with Data from Kandal and Cooley 2002)

HMA sieve (mm)	% passing			
	9.5-ARZ	9.5-BRZ	19-ARZ	19-BRZ
25.0			100	100
19.0			95	95
12.5	100	100	75	75
9.5	95	95	65	65
4.75	60	60	55	44
2.36	50	42	43	27
1.18	42	28	35	18
0.60	32	18	26	14
0.30	22	14	20	11
0.15	10	10	10	10
0.075	5	5	5	5
n	0.43	0.55	0.38	0.53
D_{max}	12.2	11.6	25.3	22.2
R^2	0.9797	0.9949	0.9884	0.9937
G/S	0.60	0.71	1.12	1.42
Ndes (gyrat)	100	100	75	75
APA rut (mm)	8.77	7.83	8.75	8.19
RutxNdes (mm gyrat)	877	783	656.25	614.25

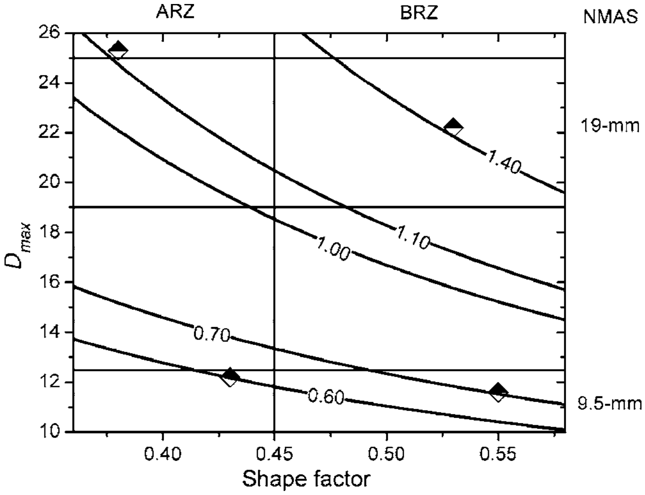

Fig. 12. Representation in gradation chart of gradations considered in rutting resistance study (with data from Kandal and Cooley 2002)

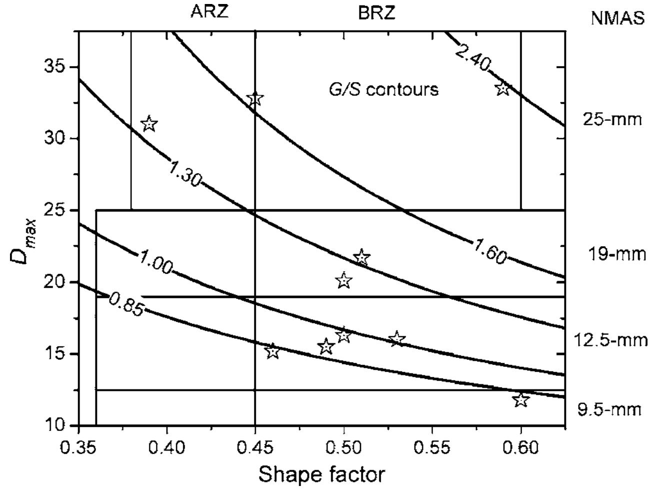

Fig. 14. Representation in gradation chart of gradations considered in permeability study (with data from Cooley et al. 2001)

Gradation Chart Approach on Permeability

HMA permeability has become an extremely important topic since the implementation of Superpave mixes because BRZ are expected to be more permeable than ARZ at the same NMAS (Choubane et al. 1998). Very permeable mixes could cause base-course, debilitation failures due to rainwater infiltration. Hence, designers should be aware of the differences of permeability at the same NMAS and when it is too permeable for a HMA to be able to take adequate measures to avoid potential failures. HMA permeability depends on factors such as total void proportion, maximum aggregate size, shape of gradation curve, lift thickness, among others (Cooley et al. 2002). The gradation-chart approach may be quite useful in evaluating the influence of gradation on permeability.

Data results from an investigation work (Cooley et al. 2001) performed on 11 highway projects throughout the United States were used to illustrate the above-noted affirmation. During the referenced research work, in-place permeability tests were carried out using a variable-head based device. A core drill was taken just aside every in-place test location to compute total void proportion. Total voids measured ranged from 3 to 12%. These highway projects included Superpave NMAS 9.5, 12.5, 19, and 25 mm and almost all BRZ. All gradations were fitted using Fuller's model in order to place them within the point-ambit framework, as shown in Fig. 14 where specification ambits for all Superpave mixes were also illustrated. Table 8 resumes data, Fuller's fit results, and G/S factor. Permeability values at air voids 4, 6, and 8% were obtained from correlation expressions presented by Cooley et al. 2001. While permeability increases with in-place total void proportion, the work cited also defined a critical value for permeability as the value of in-place total voids in which the increased rate of permeability became maximal. Critical values for voids and related permeability were obtained graphically in that study. Critical values for voids ranged from 4 to 8%. Related-to-critical permeability values were established as 100×10^{-5} cm/s for NMAS 9.5 and 12.5 mm mixes, 120×10^{-5} cm/s for 19 mm, and 150×10^{-5} for 25 mm, according to that study. In Figs. 15(a–c), permeability at air voids 4, 6, and 8% was plotted against G/S factor, shape factor, and $D_{\max}$.

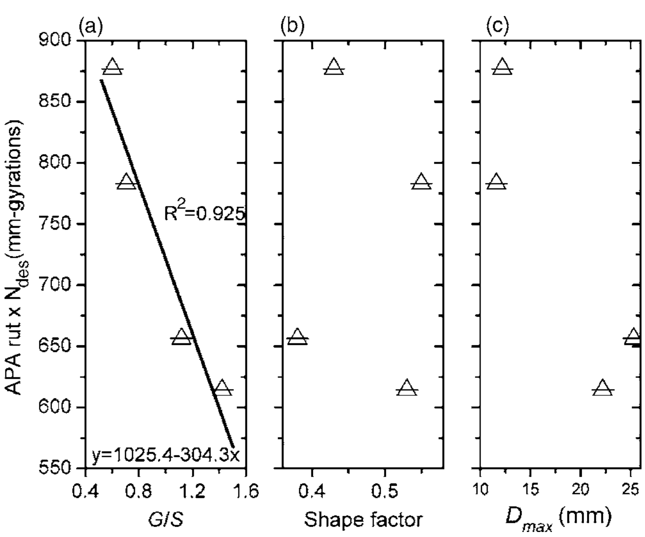

Fig. 13. Correlations on rutting resistance study results

Discussion

Generalities

According to RAMCODES Postulate 2, gradation is the main inherent factor to consider when classifying geomaterials with finer content less than 12% (e.g., HMA aggregate combination). Postulate 3 suggests that gradation should be quantified. One way of quantifying gradation is by fitting data through a mathematical model. The allometric or Fuller's model, composed of two parameters, namely characteristic factor (n) and maximum diameter size ($D_{\max}$), has reached acceptable coefficient of determination (i.e., R^2 larger than 0.97) when fitting well-graded gradations within the ambits of Superpave (see Tables 4 and 6–8) and Covenin (see Tables 2 and 3), but has reportedly no application on SMA and OGFC (Sánchez-Leal 2004b), both of the latter being poorly graded gradations. By means of original expressions developed in this work, Fuller's model can readily be used to express well-gradation conditions of ASTM D 2487-92 (a classification system for soils) for gravels and sands, and for computing the proportions of gravel and sand present in the aggregate. The gravel-to-sand

Table 8. Gradation Data and Permeability Coefficients for 11 Projects (with Data from Cooley et al. 2001)

Project sieve (mm)	% passing										
	1	2	3	4	5	6	7	8	9	10	11
37.5					100		100	100			
25.0			100		96		92	97			100
19.0	100		98	100	81		81	90	100	100	98
12.5	96	100	84	96	51	100	67	73	95	94	89
9.5	88	93	69	89	40	94	62	61	83	84	79
4.75	60	56	43	61	28	63	41	45	52	51	48
2.36	35	33	29	41	21	38	27	34	35	32	32
1.18	24	26	22	29	15	21	19	28	25	23	21
0.60	19	20	16	22	10	15	15	23	19	17	13
0.30	14	12	9	13	8	11	12	18	14	12	7
0.15	8	8	6	8	7	8	9	12	9	7	5
0.075	4.8	3.8	4.6	6.1	6	4.9	5	5	4.8	4.1	3.3
n	0.49	0.60	0.51	0.46	0.59	0.60	0.45	0.39	0.50	0.53	0.50
D_{max}	15.5	11.8	21.7	15.2	33.5	11.6	32.8	31.0	16.3	16.0	20.1
R^2	0.9764	0.9921	0.9864	0.9797	0.9715	0.9917	0.9912	0.985	0.9847	0.9821	0.9726
G/S	0.90	0.79	1.33	0.83	2.37	0.77	1.64	1.35	0.97	1.02	1.21
k at 4%	9	4	28	9	800	4	80	200	9	9	17
k at 6%	180	10	200	10	500	22	500	300	42	42	100
k at 8%	200	150	800	124	1,100	124	1,000	600	100	200	600

Note: k=coefficient of permeability at air voids 4, 6, or 6% (10^{-5} cm/s). These values were obtained from correlation expressions given in the source paper.

ratio (G/S) is proposed here as a factor to better explain the influence of gradation on HMA performance, which would allow the application of RAMCODES Postulate 1 (i.e., to apply criteria developed for soils to HMA). In point-ambit representation, defined as a graph with Fuller's parameters n on x-axis, and D_{max} on y-axis, any gradation would be a point, and any specification band would be a rectangle or ambit. In the present work, gradation bands that comprise both Covenin and Superpave specifications were fitted by Fuller's model and transformed into ambits. A gradation chart has been defined as an n-D_{max} plot where ambits for a family of specifications can be represented. Also, mathematical conditions developed here for good gradation and contours for G/S may be plotted in the chart. Up to now, a gradation-chart approach has an advantage overtraditional gradation-curve representation based up on the features. In a gradation-chart approach: (1) the gradation can be quantified; (2) responses for two or more gradations can be compared in the same graph; and (3) the influence of gradation factors such as maximum size diameter, shape factor, and gravel-sand ratio on HMA performance can be evaluated at the same time. A controversy arose with respect to which factor, among gradation structure (represented by shape factor), maximum size diameter, and G/S ratio, controls or better explains the influence of gradation on HMA performance.

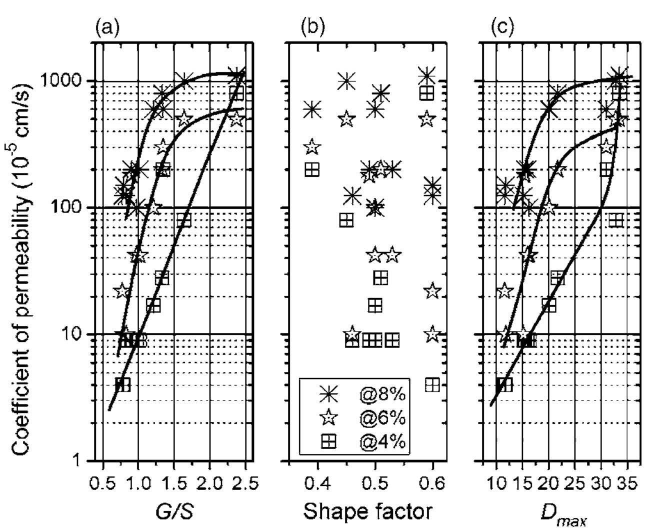

Fig. 15. Correlations on permeability study results

Workability

Gradations analyzed on workability topic belong to ambits NMAS 12.5 and 19 mm, exhibiting structures ARZ and BRZ, and G/S within 0.80–1.40 (see Table 6 and Fig. 10). Torque values were plotted against G/S factor, maximum diameter size, and shape factor in Figs. 11(a–c), respectively. A significantly larger coefficient of determination (R^2) for linear fit proves that G/S factor is notably more related to torque than to the maximum size diameter or shape factor alone. Fig. 11(a) shows a logical trend: The increase of gravel content diminishes HMA workability. Figs. 11(b and c) indicate that workability is controlled neither by maximum size diameter nor gradation structure alone. However, the original study performed by Gudimettla et al. (2003) concluded that there was no difference between ARZ and BRZ structures on workability response.

Rutting Resistance

Gradations analyzed on rutting resistance topic belong to ambits NMAS 9.5 and 19 mm, with structures ARZ and BRZ, and G/S

from 0.60 to 1.40 (see Table 7 and Fig. 12). Normalized rutting values were plotted against G/S factor, shape factor, and maximum diameter size in Figs. 13(a–c), respectively. Fig. 13(a) shows a good correlation between rutting resistance and G/S factor, and Figs. 13(b and c) evidence that rutting resistance has no correlation either with gradation structure or D_{max}. Fig. 13(a) indicates that the increase in gravel-to-sand ratio enhances rutting resistance. The original study by Kandhal and Cooley (2002) affirms that mixes have similar rut resistance at the same NMAS, with no consideration to structure.

Permeability

The study by Cooley et al. (2001), used here to evaluate the controversy between structure-D_{max} and G/S factor on permeability, covers up to 11 gradations at NMAS 25, 19, 12.5, and 9.5 mm, one ARZ, one through restricted zone (TRZ), and nine BRZ structures, and G/S ranging from 0.85 to 2.40. Some of these gradations belong to different specification ambits but to the same G/S level (see Table 8 and Fig. 14). That would be the case of Projects 2 ($G/S=0.79$; 9.5 mm BRZ) and 6 ($G/S=0.77$; 12.5 mm ARZ). And also, Projects 3 ($G/S=1.33$; 19 mm BRZ) and 8 ($G/S=1.35$; 25 mm ARZ). Coefficient of permeability values for compacted HMA at air voids 4, 6, and 8% were considered. Figs. 15(a–c) evidence a significant influence of both G/S and D_{max} on permeability, and definitely no influence of the gradation structure at any level of air void content. However, correlation with D_{max} observes some inconvenience because permeability coefficient increases dramatically at large maximum diameter size values [see Fig. 15(c)]. Approximate trend-lines in Fig. 15(a) show that permeability increases with G/S ratio. Also, the increase of air void content directly affects (increases) permeability within G/S range 0.8–2.4. However, that influence tends to be less important toward the frontiers of that range. At air void content of 4%, the relation between G/S and permeability is linear. Also, based upon trend-lines, at air void contents of 6 and 8%, that relation turns from linear to asymptotic from $G/S=1.5$ and beyond. Finally, as seen in Table 8, Projects 2 and 6 shown the same permeability values at all air void content level in spite of belonging to different NMAS ambits and structures. The same is true for Projects 3 and 8, with the exception of permeability at air voids of 4%, which is too high [considering the trend-lines in Fig. 15(a), this would have been due to an experimental error]. The original study by Cooley et al. (2001) concluded that permeability increased with both NMAS and in-place voids, but Choubane et al. (1998) affirmed that BRZ have larger permeability coefficient than ARZ. This confusion can be better explained by the G/S ratio because permeability depends on both maximum diameter size and structure together. Permeability is a very significant topic in HMA design but most times it is not evaluated by designers, much less by contractors. Permeability beyond a critical value produce compacted courses that could infiltrate considerable amount of rain water to the pavement base course which may produce considerable debilitation and consequent failure. Fig. 15(a) illustrates the implications on permeability of gradation and air voids level. Most quality control specifications allow a limit of 8% for in-place voids. Let 150×10^{-5} cm/s be a limit for a highly permeable pavement course. Thus, HMA at $G/S=0.9$ or larger would require that base course to be protected from water infiltration by placing a thin impermeable course between upper and base course.

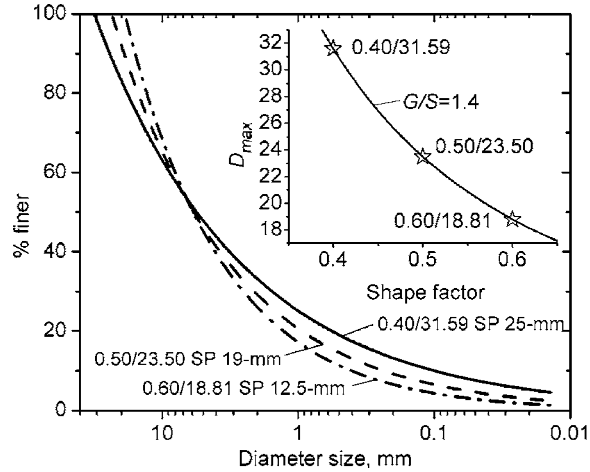

Fig. 16. Graphical representation of some Superpave gradations on both diameter-percent finer and n-D_{max} form

Superpave in Venezuela

Superpave implementation only with gradation specifications and consensus criteria began in recent years in Venezuela using mostly open-graded or BRZ mixes. These mixes are expected to have better strength performance compared to traditional dense-graded mixes. They have also shown an evidently different workability so that a great deal of adaptation has had to be done with contractors on fresh mix handling and placing work. Contractors are convinced—with not few inconveniences—that all this effort of adaptation is worthwhile due to superior performance mixes. However, Superpave mixes in Venezuela have been observed as highly permeable, in fact, several projects have been reported with base-course-debilitation failures due to rain water infiltration (G. Smith, personal communication, 2004). HMA has been placed directly on base course in those projects. A plot like Fig. 15(a) could prevent this kind of situation in the future.

Implications

The results of the application of the gradation-chart approach on Covenin and Superpave gradations indicate that the definitions for dense and fine (i.e., ARZ) structures coincide; and open and coarse (i.e., BRZ) structures, as well. Also, the analyses performed in this work narrow down to the fact that HMA response, at least on topics such as workability, rutting resistance, and permeability is influenced by both gradation structure and maximum diameter size at the same time (not alone). This would be an explanation as to why some research works reach contradictory conclusions on the influence of structure (i.e., ARZ, BRZ, and TRZ) and maximum size diameter on HMA performance. The allometric or Fuller's model, a mathematical model used to fit well-graded HMA gradations, regards both structure and maximum size diameter at the same time. This model was used in this work to develop an analytical expression to relate gravel-to-sand proportion (G/S) present within HMA to structure and maximum size diameter. Data analyzed here strongly suggest that G/S ratio has a remarkable correlation to HMA responses such as workability, rutting resistance, and permeability. In consequence, for instance, three HMA at the same G/S ratio would have similar mechanical and hydraulic behavior despite the fact that they are BRZ, TRZ or ARZ, or that they belong to different specification ambits. Fig. 16 shows a potential scenario, three HMA at G/S

=1.4, namely 0.40/31.59, 0.50/23.50, and 0.60/18.81, belonging to Superpave ambits 25, 19, and 12.5 mm, respectively. Despite the fact they have different gradations (from the traditional perspective), these HMAs would exhibit similar performance parameters. With all this, several questions arise in consequence. What good is a specification ambit if HMA behavior does not rely on it? Also, why would an agency specify a Superpave, for example, 25 mm BRZ if there were a 19 mm or a 12.5 mm BRZ with the same behavior? In Venezuela how many times (possibly in other countries as well) are projects put on hold for several weeks because the construction has run out of 25 mm gravel and they cannot produce the specified Covenin Type IV? What if they had known that they could produce a Type III with the same behavior? Why specify a Superpave 12.5 mm when there is a 19 mm that behaves the same but at less cost? (Often in Venezuela, HMA with low NMAS has a higher cost than HMA with high NMAS because the aggregate of the former requires more crushing).

G/S-versus-response plots would be very useful on HMA design. Just suppose that for a flexible pavement, a designer needs a HMA with APA rut of 6.5 mm or lower (if a study were available, it could be Young modulus, resilient modulus, or another permanent deformation parameter instead). In Fig. 13(a), at $N_{des}=100$ gyrations, a HMA with $G/S=1.2$ or larger would be needed. Figure 11(a) shows that such a mix would need significant placement effort. And, finally, Fig. 15(a) evidences that, at air void content of 8%, permeability would be as high as 500×10^{-5} cm/s so that a thin, impermeable, sandwich layer would be needed to protect base course from water infiltration. Hence, for that particular project, specifications would read, for instance: "Use HMA at $G/S=1.2$ or higher. Place a thin HMA layer at $G/S=0.8$, or lower, between upper course and base course." Of course, such specification would then be complemented by other factors apart from gradation that influence HMA behavior.

In the future, G/S-response correlations could also be developed for different aggregate characteristics such as consensus conditions (e.g., flat and elongated particles, sand equivalent, etc.), Los Angeles abrasion, etc., also for different binder characteristics, such as PG classification, modifiers, etc.

To wind up this discussion, the writer may recall the words of Professor Hveem (1941): "The best grading for any particular mixture can only be that which utilizes the available aggregates to give as many of the desired properties as may be possible." Certainly a gradation-chart approach helps the designer to meet this recommendation. Further, the gradation chart approach may lead to a "free design" where the designer may propose a gradation, based upon a combination of available aggregates, and then needs to prove desirable mechanical and hydraulic properties of compacted HMA.

Conclusions and Recommendations

The gradation-chart approach developed here is an original and useful tool to evaluate the influence of gradation on HMA performance superior to the traditional approach, based on maximum-diameter size and structure that can lead to contradictory conclusions.

Data evaluated in this work strongly suggest that gravel-to-sand ratio has a marked influence on HMA performance, and also neither maximum-diameter size nor structure have such influence alone. For Fuller's model and mathematical expressions developed here, gravel-to-sand ratio contains both maximum size diameter and structure.

Gravel-to-sand influence on HMA response was evaluated on considerations such as workability, resistance to rutting, and permeability by means of data collected from related NCAT published works. Results indicate that: (1) workability diminishes with gravel-to-sand ratio increase; (2) the larger the gravel-to-sand ratio, the greater the resistance to rutting; and (3) permeability increases with gravel-to-sand ratio.

Correlations between gravel-to-sand ratio and HMA response may be used for design, and designers may use these correlations to propose an aggregate combination based on available materials that comply with pavement structure requirements, and that would be called free design.

One of the most important implications of the present work is that, if the relationship between gravel-to-sand and HMA performance is so strong, then the specifications ambits, such as Superpave or Covenin, would no longer be needed because it would not make sense. As proved here, two HMA with the same gravel-to-sand ratio would behave the same (mechanically or hydraulically). However, the cost factor would not necessarily be the same because that consideration is quite dependent on very local conditions. The gradation chart itself would be a didactic bridge from specification ambits criterion, conformed by structure and maximum size diameter, to gravel-to-sand ratio criterion.

The objective of this work was totally satisfied, which was to present the development of a gradation-chart approach, its advantages and limitations, and to suggest possible applications for it. The conclusions of this work are based on data evaluated. Hence, more research needs to be done on this subject to consolidate this original approach. In respect to this, Part II of this work will use 2000–2002 design and performance data from NCAT's Test Track; and Part III will be devoted to design. The writer invites the reader to try out gradation chart approach on his/her own research results.

Notation

The following symbols are used in this paper:

- D_{max} = maximum size for geomaterial;
- D_{10} = diameter or size for which 10% of material is finer (mm);
- D_{30} = diameter or size for which 30% of material is finer (mm);
- D_{60} = diameter or size for which 60% of material is finer (mm);
- G/S = gravel-to-sand ratio;
- n = parameter describing gradation shape;
- p_i = cumulated finer proportion for particle diameter, D_i, in decimal; and
- R^2 = coefficient of determination.

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