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Using the Primary Control Sieve Index to Define Gradation Type and As A Factor Related to Asphalt Mixture Properties

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ABSTRACT

Gradation is one of the most influential aggregate characteristics affecting asphalt mixture properties and performance. The aggregate size distribution influences almost every important property of asphalt mixes. In this study, the Primary Control Sieve Index (PCSI) is defined as the difference in percentage passing between the given gradation and the point on the maximum density line at the primary control sieve and represents the relative coarseness or fineness of the gradation. PCSI was used as a variable that correlated with other asphalt mixture properties and found to be a potential a surrogate for surface texture. The result of this study is the development of a simple way to quantify how fine or coarse a gradation is. The PCSI clearly shows the effect of varying gradations away from the maximum density line on the VMA. The PCSI has demonstrated to be a factor related to several other characteristics and properties of hot mix asphalt, such as compactability, permeability and pavement surface texture.

Key Words: Asphalt mixtures, gradation, primary control sieve, compactability, permeability, texture.

1 INTRODUCTION

Gradation is one of the most influential aggregate characteristics affecting asphalt mixture properties and performance. The aggregate size distribution influences almost every important property of asphalt mix including volumetrics, stiffness, stability, durability, permeability, workability, fatigue resistance, frictional resistance and resistance to moisture damage *(1).*

The simplest definition of fine and coarse gradations is based on the 0.45 power gradation graph. Fine gradations are those gradations that plot mostly above the maximum density line (MDL), and coarse gradations are those that plot mostly below the MDL.

Some research studies involving asphalt mixture gradations have identified fine-graded and coarse-graded mixtures based on the definition given by the National Asphalt Pavement Association NAPA *(2)*. The percent passing certain sieve sizes for a given nominal maximum aggregate size (NMAS) is used to define fine- and coarse-graded mixes as shown in Table 1.

Table 1 Definition of Fine- and Coarse-Graded Mixes *(2)*

Mixture NMAS	Coarse-Graded	Fine-Graded
37.5 mm (1 1/2")	< 35% Passing 4.75 mm Sieve	> 35% Passing 4.75 mm Sieve
25.0 mm (1")	< 40% Passing 4.75 mm Sieve	> 40% Passing 4.75 mm Sieve
19.0 mm (3/4")	< 35% Passing 2.36 mm Sieve	> 35% Passing 2.36 mm Sieve
12.5 mm (1/2")	< 40% Passing 2.36 mm Sieve	> 40% Passing 2.36 mm Sieve
9.5 mm (3/8")	< 45% Passing 2.36 mm Sieve	> 45% Passing 2.36 mm Sieve

Superpave volumetric mix design (AASHTO M 323) uses the primary control sieve (PCS) to classify gradations, with coarse-graded mixtures defined as having a gradation that passes below the PCS control point, and fine-graded mixes having a gradation that passes above the PCS control point. Other studies have used definitions based on the location of the gradation curve with respect to the restricted zone *(3).* Superpave gradations have been defined as BRZ, ARZ and TRZ, which stand for below, above and through the restricted zone, respectively. However, since the restricted zone has been eliminated from AASHTO specifications, coarse, fine, and intermediate-graded (medium-graded) mixtures are now more commonly used *(4)*.

Those definitions of gradation type can be used as qualitative variables only and present an important limitation in terms of statistical analysis. A simple or multiple regression analysis cannot be performed easily with qualitative variables. A quantitative parameter may lead to better analysis.

One quantitative parameter that has shown good results when it has been used as an indication of gradation type is the coarse aggregate (CA) ratio *(4)*. The CA ratio is defined as the percent retained on the sieve three sizes lower than the NMAS divided by the percent passing that sieve. For example, for a NMAS of 19.0 mm, 12.5 mm, and 9.5 mm, the associated sieve sizes are 4.75 mm, 2.36 mm, and 1.18 mm, respectively. A multiple linear regression analysis performed during the NCHRP 9-27 project showed that there is a good correlation between the natural log of permeability and the coarse aggregate ratio *(4)*. However, this definition is awkward, and the rationale is not intuitive.

Another parameter that can be used to describe gradation type is the fineness modulus. Fineness modulus is used in the design of Portland cement concrete mixtures to describe a weighted average for the aggregate being analyzed. It is defined as the cumulative percentages retained on each sieve divided by 100. An aggregate gradation with a higher percentage of coarse aggregate will have a higher fineness modulus.

2 OBJECTIVES

The main objective of this study was to determine a simple quantitative expression of the relative coarseness or fineness of a gradation as a variable that potentially correlates with other asphalt mixture properties. A second objective of this study was to evaluate the potential use of the Primary Control Sieve Index (PCSI) as surrogate for surface texture.

3 DEFINITION OF THE PRIMARY CONTROL SIEVE INDEX

The Primary Control Sieve Index (PCSI) is defined as the difference in percentage passing between the given gradation and the point on the maximum density line at primary control sieve. The primary control sieve (PCS) is defined in AASHTO M323 Standard Specification for Superpave Volumetric Mix Design. Table 2 shows the PCS for different aggregate nominal size and the percent passing the PCS.

In general, the PCSI represents the relative coarseness or fineness of the gradation. Figure 1 shows an example of the PCSI for 12.5 mm NMAS fine and coarse gradations. Coarse gradations have negative values (below maximum density line) and fine gradations will result in positive values of PCSI.

Table 2 Primary Control Sieves from AASHTO M 323

Nominal Maximum Aggregate Size, mm	9.5	12.5	19.0	25.0	37.5
Primary Control Sieve, mm	2.36	2.36	4.75	4.75	9.5
PCS control point, % passing	47	39	47	40	47

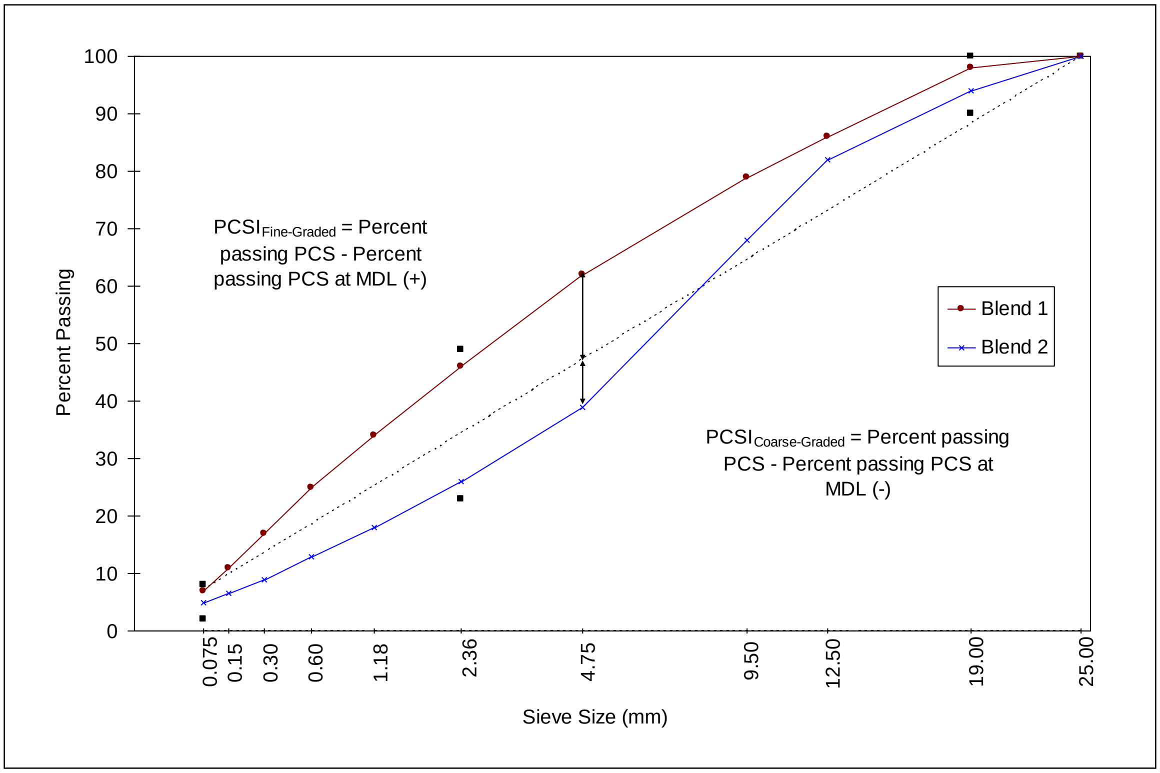

Figure 1 Illustration of the PCSI for 19.0 mm NMAS Gradations

4 ANALYSES AND DISCUSSION

Mixtures from Phase I and II of the NCAT Test Track, as well as from NCHRP Projects 9-27 and 9-9 were analyzed in this study. The PCSI calculated from these mixtures were compared to the coarse/fine definition given by AASHTO M 323 and the National Asphalt Pavement Association (NAPA) and the CA Ratio. The PCSI was also analyzed as predictor variable for a range of asphalt mixture properties. Surface texture measurements obtained from test track sections were also correlated to PCSI.

4.1 Comparison of the PCSI and Gradation Type Definitions

A total of 121 gradations were used to compare the PCSI and the definition of gradation type presented in Table 1. In this case, only 9.5, 12.5 and 19.0 mm NMAS gradations were used. Figure 2 shows the comparison between PCSI and type of gradation according to the definition given by NAPA. For 9.5 and 12.5 mm NMAS gradations, a straight line can be observed between PCSI and % passing the 2.36 mm sieve. However, for 19.0 mm gradations, the relationship was more scattered because of the different key sieve sizes used in the NAPA guide and AASHTO PCS definition.

In Figure 2, the horizontal lines at 35, 40 and 45% passing the 2.36 mm sieve separate coarse-graded and fine-graded mixes according to the NAPA guide. In all cases, negative values of PCSI for each nominal size were found below its respective separation line and positive values were always above this line. Thus, the numerical value of PCSI matches the different criteria shown in Table 1; at least for these three nominal sizes. Figure 2 also shows that PCSI does provide a simple, convenient quantification that can be used to further stratify/categorize (when compared to general Coarse/Fine separation, or even the CA ratio) when determining the impact gradation may have related to a property or characteristic that is being researched.

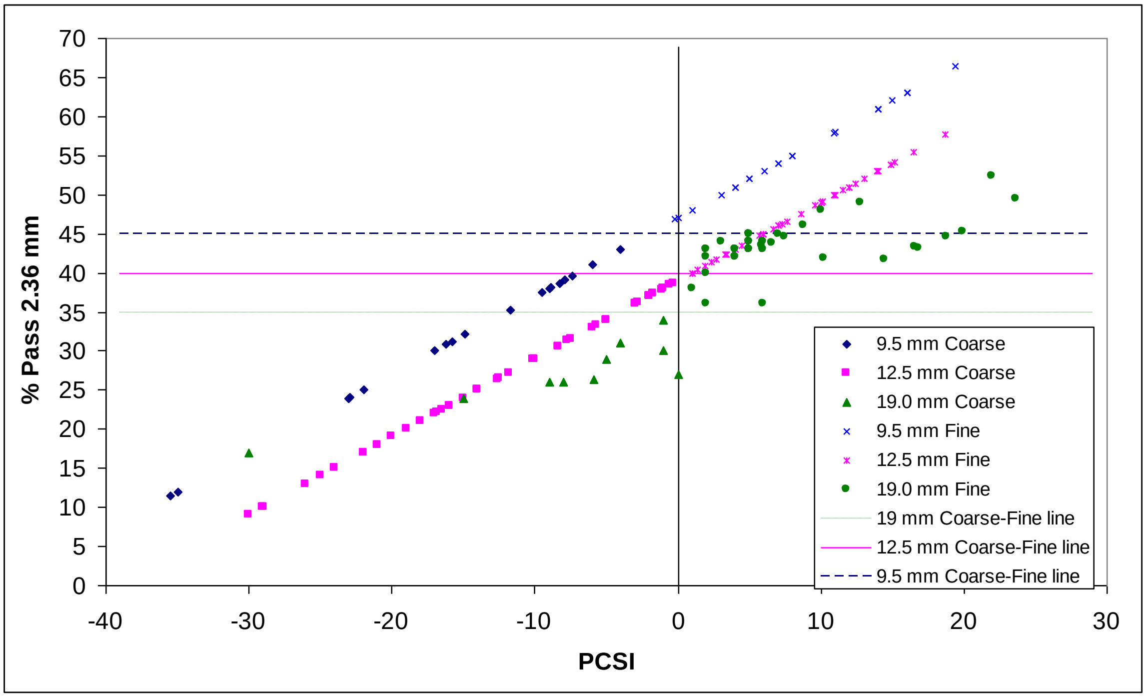

FIGURE 2 Comparison between PCSI and Type of Gradation According to the Definition Given by NAPA

As previously mentioned, the CA ratio was shown to be a significant predictor variable for permeability *(4)*. The NCHRP 9-27 project defined CA ratio as the percent retained on the sieve three sizes smaller than the NMAS divided by the percent passing that sieve. From this definition, it can be observed that higher CA ratios indicate coarser gradations. However, a particular CA ratio does distinguish between fine and coarse gradations.

Figure 3 shows that for each nominal size, a different value of CA ratio is needed to separate fine and coarse gradations. The CA ratios separating coarse and fine gradations using Figure 3 are shown in Table 3. Gradations with CA ratios lower than the criteria are fine-graded and gradations with higher values are coarse-graded.

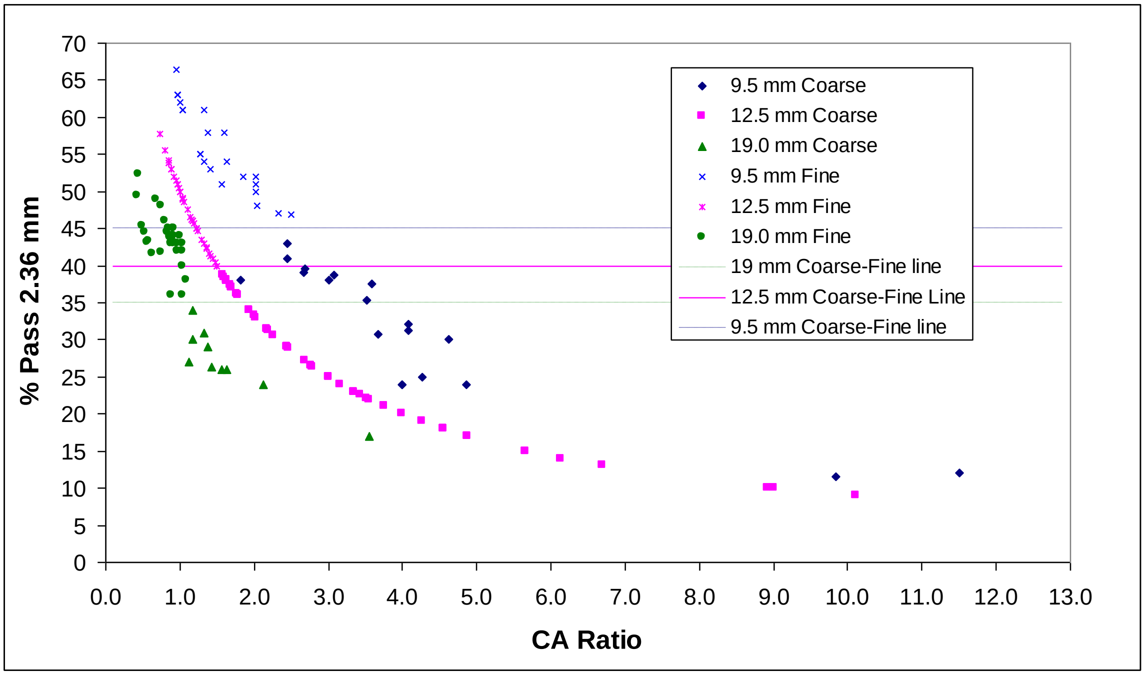

Figure 3 Comparison between CA Ratio and Type of Gradation According to the Definition Given by NAPA

Table 3 Criteria Used to Separate Coarse and Fine Gradations Based on CA Ratio

NMAS, mm	9.5	12.5	19.0
CA ratio	2.3	1.5	1.1

Figure 4 shows the relationship between these two parameters and it can be seen that lower values of the CA ratio correspond to positive values of PCSI (fine-graded) and higher CA ratios correspond to negative PCSI values (coarse-graded).

Figure 5 shows the relationship between PCSI and Fineness Modulus (FM). A strong correlation can be seen for every nominal size indicating that lower values of FM are associated to positive PCSI's (finer gradations) and higher values of FM correspond to negative PCSI values (coarser gradations). Even though it seems redundant to state that two methodologies of quantifying the relative coarseness/fineness of a particular gradation should arrive at the same conclusion. The PCSI is a simpler parameter to compute and provides a more intuitive way to visualize changes in other properties as shown in the following sections.

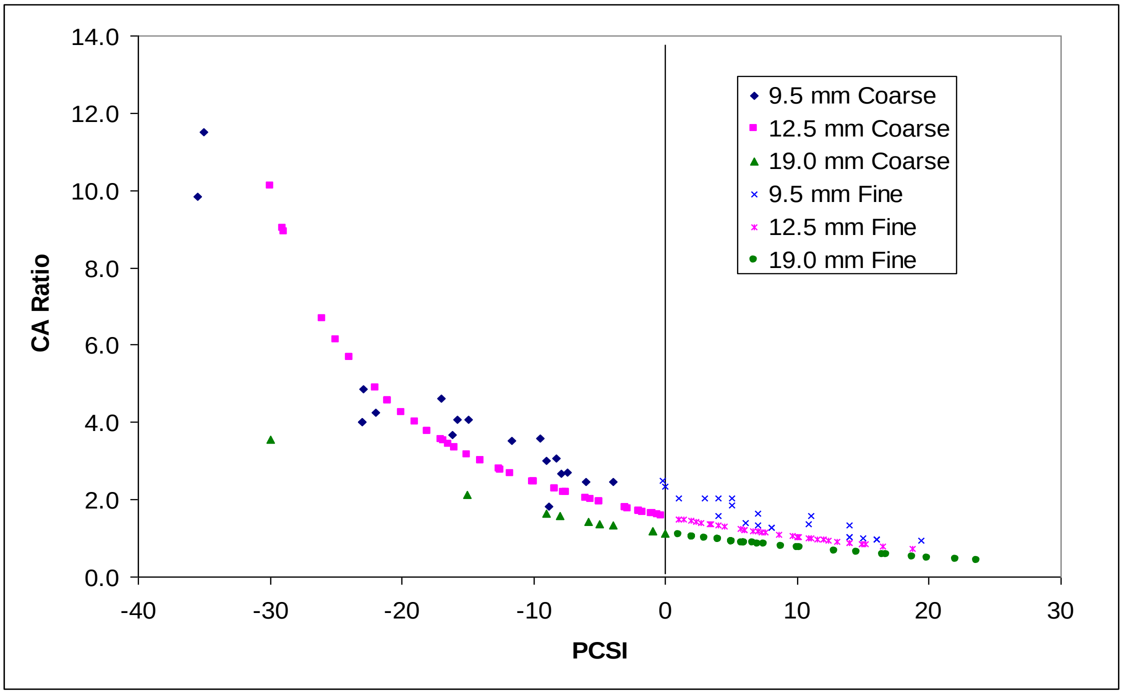

Figure 4 Relationship between PCSI and CA Ratio

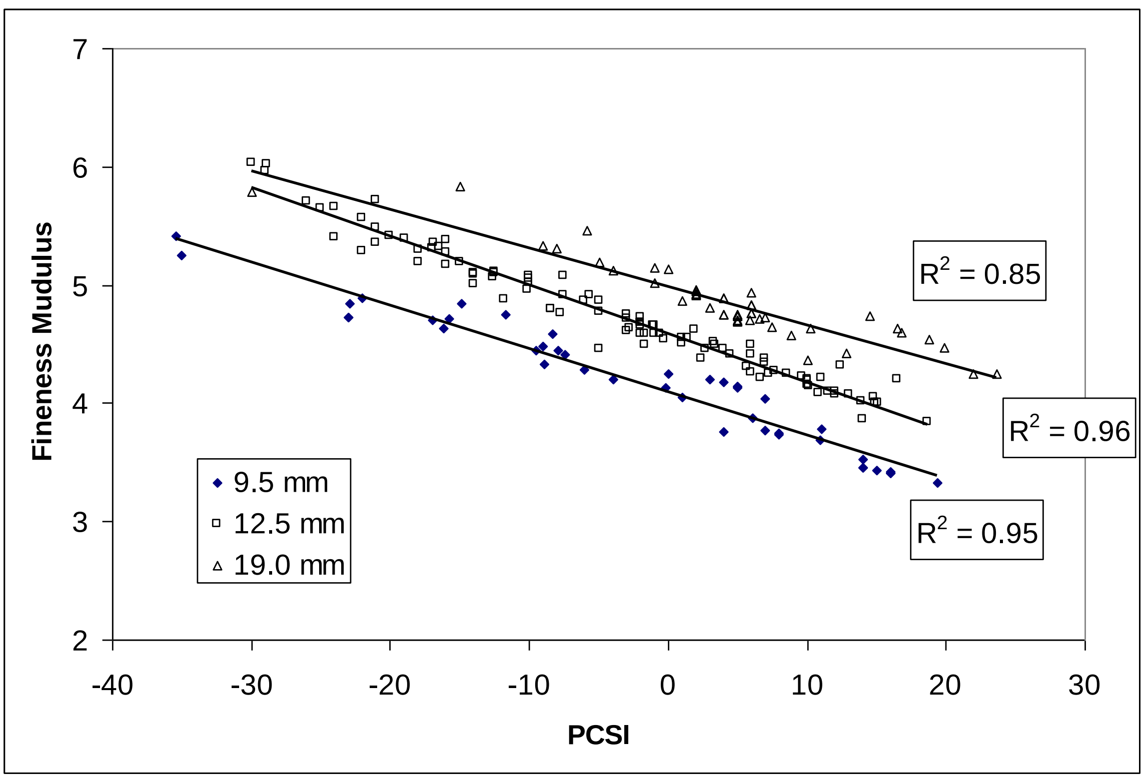

Figure 5 Relationship between PCSI and Fineness Modulus

4.2 Evaluation of the PCSI as a Predictor for Asphalt Mixture Properties

Seventy two mixtures were used to correlate PCSI and asphalt mixture properties. The dataset includes 9.5, 12.5 and 19.0 mm NMAS mixes designed with a variety of aggregate types and laboratory compactive efforts. The data used to determine the laboratory measured mix characteristics were obtained from quality control samples taken during the NCAT test track construction.

4.2.1 Voids in Mineral Aggregate

Figure 6 shows the relationship between PCSI and VMA. A second order correlation was obtained to describe this relationship. This relationship indicates that the PCSI can be used to quantify the impacts on VMA relative to the control sieve. Values of PCSI close to zero tended to have lower VMA. This result confirms the theory that deviating from the maximum density line in either the coarse or fine direction tends to cause an increase in VMA *(1)*.

The PCSI – VMA relationship is a simple illustration of a concept that many asphalt technologists have used for many years (deviation from MDL = higher VMA). When these data were sorted by nominal aggregate size, the results lead to the same relationship between PCSI and VMA.

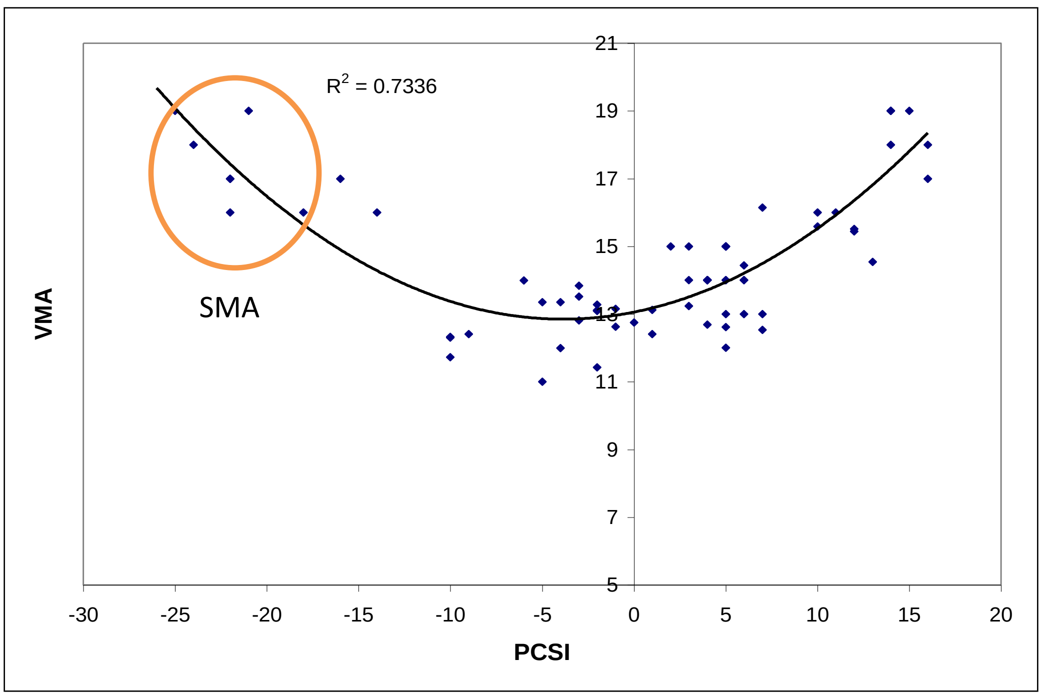

Figure 6 Relationship between PCSI and VMA

4.2.2 Mixture Compactability

PCSI was also compared with several laboratory parameters that have been suggested as indicators of compactability such as the compaction slope *(5)* determined from compaction in the Superpave Gyratory Compactor (SGC), the percentage of maximum theoretical specific gravity at N_{ini} ($\%G_{mm}@N_{ini}$), the number of gyrations to achieve 92% of G_{mm} ($N@92\%G_{mm}$), the compaction energy index (CEI) introduced by Bahia *(6)* and the fine aggregate coarse ratio (FA_C) defined in the Bailey Method *(7)*.

Several research studies have explored relationships between the SGC compaction slope and rutting resistance and evaluated the effect of mix proportions to compaction slopes. The Superpave mix design procedure *(1)* indicates that the compactability of a mixture can be estimated by the relative density at $N_{initial}$ (%G_{mm}@N_{ini}), which is an early point in the Superpave gyratory compaction process. The Compaction Energy Index (CEI) is defined as the area from the 8th gyration to 92% of G_{mm} in the Superpave densification curve. Bahia reasoned that this index is analogous to the work applied by the roller to compact the mixture to the required density during construction (*6*). According to the Bailey Method *(7)*, the fine aggregate coarse ratio describes how the coarse portion of the fine aggregate packs together and, consequently, how these particles compact the smaller aggregate particles that fill the voids between the larger particles. Typically as the FAc ratio increases, compactability increases, which is why VMA typically drops. But, there comes a point with the FAc if it gets high enough, that VMA stops decreasing and actually starts to increase.

Figure 7 shows the relationship between the SGC compaction slope and the PCSI. With the wide range of aggregate types and shapes in this dataset, the correlation is not strong, but there is a clear trend that lower PCSI values correspond to higher compaction slopes. Analyses with the other laboratory SGC compaction parameters indicated similar trends.

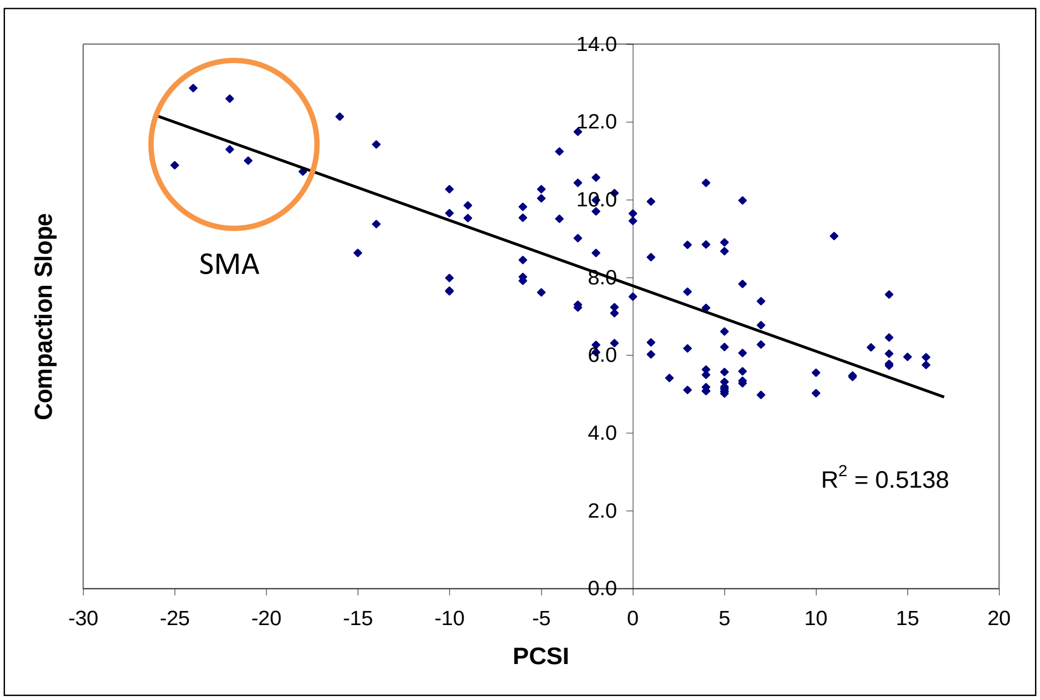

Figure 7 Relationship between PCSI and SGC Slope

Table 4 shows the single correlation coefficient (Pearson R-value) between PCSI and other mixture parameters. A positive R-value (proportional correlation) of 0.69 indicates that finer mixes tend to have higher values of %G_{mm}@N_{ini} than coarser mixes. In other words, fine mixes compact more quickly in the SGC. Table 3 also shows that PCSI is inversely proportional to the number of gyrations to achieve 92.0% of G_{mm}, the compaction energy index (CEI) introduced by Bahia *(6)* and the fine aggregate coarse ratio (FA_C) defined *(7)*.

These results also indicate that finer mixes require fewer gyrations to achieve 92% of G_{mm} and require less compactive effort according to the CEI theory. Finally, the relationship between PCSI and FA_C ratio indicates that fine gradations produce low FA_C ratios, which can be related to compactability of a mixture. Although these general relationships between gradation and mix compactability are understood by many asphalt technologists, the use of PCSI could also be used as potential indicator of compactability.

Table 4 Single Linear Correlation between PCSI and Some Laboratory Parameters Used to Measure Mixture Compactability

Lab Compactability Indicator	Pearson Correlation (R-value)
$\%G_{mm}@N_{ini}$	0.69
CEI	-0.64
$N@92\%G_{mm}$	-0.54
FAc Ratio	-0.83

4.2.3 Permeability

In the NCHRP 9-27 project *(4),* a multiple linear regression analysis was used to evaluate the relationship between permeability of field compacted cores to QC properties of the mixture**.** Based on results of 226 core samples the Mallow's C-p statistic and $R^2_{(adj)}$ values were used in a best subsets regression analysis, the best model was a combination of the natural log of air voids, coarse aggregate ratio and the natural log of VMA (Equation 1).

$$Ln\,(k) = -2.20 + 6.75Ln(CL) + 0.316(CAratio) - 3.05Ln(VMA) \quad (1)$$

Where,

Ln (k) = natural log of permeability;
Ln (CL) = natural log of air voids from the Corelok method;
CAratio = coarse aggregate ratio; and
Ln(VMA) = natural log of voids in mineral aggregate.

A multiple linear regression analysis similar to the one presented above was performed to evaluate the PCSI as a predictor variable instead of the CA ratio. The results of the same 226 core samples and the best subsets regression analysis is presented in Table 5. Based on the Mallow's C-p statistic and $R^2_{(adj)}$ values, the best model was a combination of natural log of in-place air voids based on the Corelok method, NMAS, sample thickness, natural log of voids in mineral aggregates (VMA) and PCSI. The five identified factors were then regressed versus the natural log of permeability and the following regression equation was obtained.

$$\ln(k) = -3.87 + 5.89 \ln(CL) - 0.0595\ PCSI - 1.81 \ln(VMA) - 0.0122\ Thickness + 0.0776\ NMAS \quad (2)$$

Where,

Ln (k) = natural log of permeability;
Ln (CL) = natural log of air voids from Corelok;
Ln (VMA) = natural log of voids in mineral aggregate;
PCSI = primary control sieve index; and
NMAS = nominal maximum aggregate size.

Table 5 Best Subsets Regression on Factors Affecting Permeability with PCSI

No. of Variables	R-Sq	R-Sq(adj)	C-p	NMAS	Thickness	lnCL	PCSI	lnVMA
1	68.5	68.4	53.0			X		
1	43.0	42.8	275.3					X
2	73.4	73.1	12.5			X	X	
2	70.2	69.9	40.1			X		X
3	74.1	73.7	8.1			X	X	X
3	73.9	73.6	9.7	X		X	X	
4	74.5	74.1	6.1	X	X	X	X	
4	74.5	74.0	6.9		X	X	X	X
5	74.8	74.2	6.0	X	X	X	X	X

There was a good correlation for the best subset equation with an R^2 of 0.75. The equation indicates that permeability increases as the air voids increase. Coarser gradations, expressed by negative PCSI values, tend to yield higher permeability. NMAS and lift thickness became significant variables with the use of the PCSI. The positive coefficient for the NMAS indicates that the permeability increases as the NMAS increases. The negative coefficient for the thickness indicates that thinner pavements are more likely to present higher permeability. In general, the use of the PCSI as a predictor variable produced not only an increment in the percent of variability explained by the model (a better R^2), but also the inclusion of two important variables that were found not significant in the previous analysis.

4.2.4 Pavement Texture, Skid Resistance and Noise

Another objective of this study was to explore the relationship between PCSI and pavement surface texture. Figure 8 shows the relationship between PCSI and initial Mean Profile Depth (MPD) measured using the Automatic Road Analyzer (ARAN) on the NCAT test track sections. As can be seen, coarse-graded and SMA mixtures had higher MPD's (i.e. greater surface texture) than fine-graded mixtures. A good linear correlation (R^2 = 0.8) indicates that the PCSI is a good indicator of initial pavement macro texture. Equation 3 shows the linear model obtained for this relationship.

For all the sections placed in 2003 the measurements of MPD were taken right after construction. For all the sections placed in 2000 the data correspond to values taken after one month of load application.

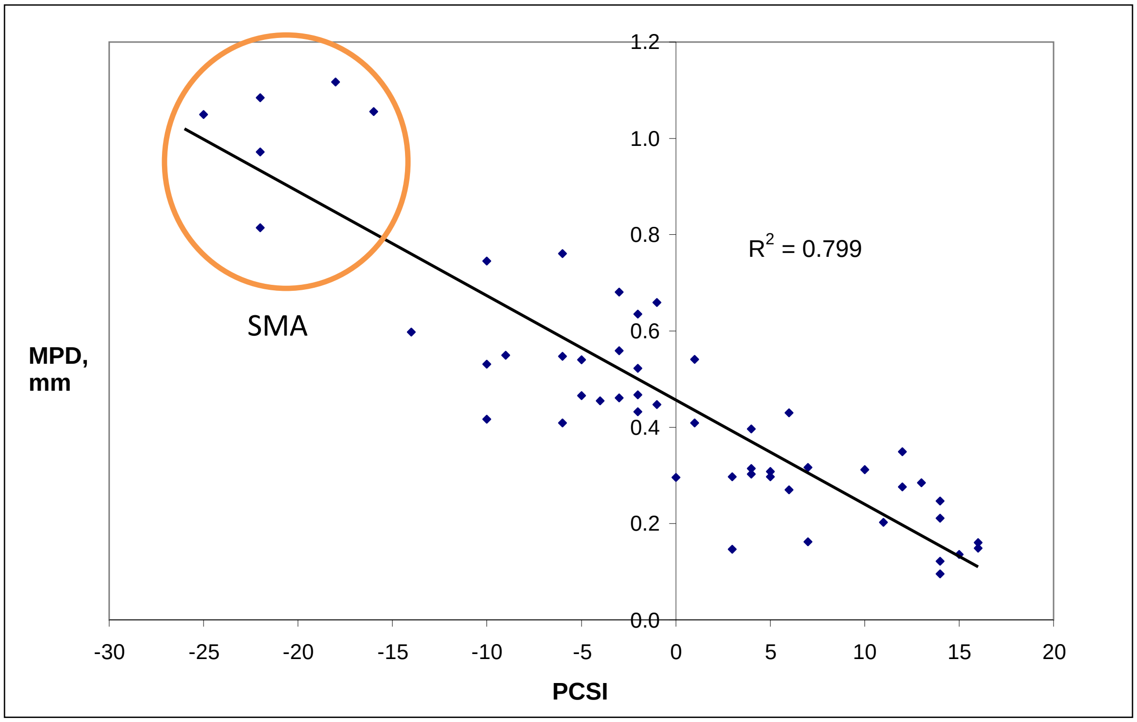

Figure 8 Relationship between PCSI and Surface Macrotexture

$$MPD = 0.449 - 0.0219PCSI \quad (3)$$

Where,

MPD = Mean Profile Depth, mm; and
PCSI = Primary Control Sieve Index.

Pavement texture affects most tire/road interactions including friction and noise. High macrotexture reduces the gradient of friction over speed, thus improving skid resistance at high speeds (*8*). Therefore, with the results presented in Figure 8, one intuitively can affirm that coarser gradations improve skid resistance.

Some studies have shown an increase in noise, generated by the tire/pavement interaction, due to an increase in texture (*9*). In addition, a fair correlation (R^2 = 0.51) was found between Fineness Modulus and noise level for dense-graded mixes placed at the NCAT Test Track *(10)*. These results suggested that finer mixes tend to reduce noise. However, it was also found that porous pavements (OGFC) with low nominal aggregate size (< 9.5 mm) and a high air void content (> 20%) may produce the same effect as finer mixes and even improve the results *(10, 11)*.

A process of optimization of skid resistance and noise levels can be addressed by the selection of the gradation. It was found that a porous mix with the characteristics described above may have a Fineness Modulus greater that 5.0 or a PCSI lower than -20. It can be seen in Figure 8 that mixtures with PCSI values below -20 tend to have an MPD of at least 0.8 mm. Some states have excellent skid resistance even with JMF of 60%+ passing the #8 sieve. Therefore, other parameters such as aggregate geology have to be considered in any efforts to establish requirement on skid resistance.

It was shown in the NCHRP 9-27 study that laboratory specimens can be used to estimate the surface texture. A difference in volume between dimensional and the SSD method (AASHTO T 166) or vacuum-sealing method (AASHTO T 331) was used in this study to approximate the surface texture *(4)*. Figure 9 shows a relationship between PCSI and the approximate value of the Mean Texture Depth (MTD). The MTD was defined as the difference from dimensional volume divided by the total surface area of the specimen.

Figure 9 indicates that the texture depth should be in the region between the fitted lines. The texture depth obtained from the difference in dimensional and SSD volumes has a strong correlation with PCSI (R^2 = 0.94). On the other hand, the texture depth from the difference in volume between the dimensional and vacuum-sealing methods has a lower correlation with PCSI (R^2 = 0.79). This second relationship is consistent with the range of texture depths and PCSI values observed in Figure 8 for NCAT Test Track mixes. As expected, for very fine mixes the difference in texture depth between the SSD and vacuum-sealing methods tends to zero and for coarser mixes the difference increases exponentially. Therefore, PCSI could be used in the mix design process to determine if the vacuum-sealing method will be more appropriate to conduct.

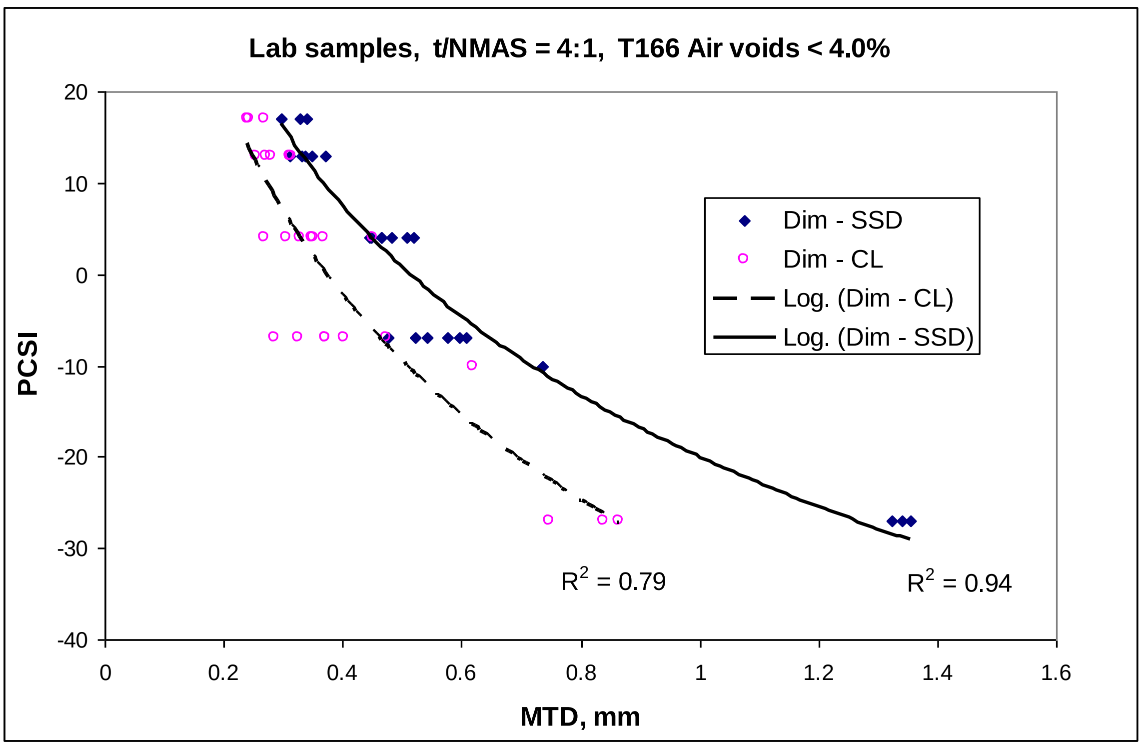

Figure 9 Relationship between PCSI and Estimated Surface Macrotexture

A simpler approach can be used to approximate the surface texture of gyratory samples. For specimens compacted at normal size (115 ± 5 mm) with similar dry weights, the difference from dimensional bulk specific gravity showed a strong correlation with PCSI. Figure 10 shows the relationship between PCSI and the difference from dimensional bulk specific gravity using the SSD and vacuum-sealing methods for specimens with air void contents between 3 and 5%. The fitted lines tend to be very close for finer mixes and tend to be separate for coarser mixes, which follows the same trend observed in the preceding figures.

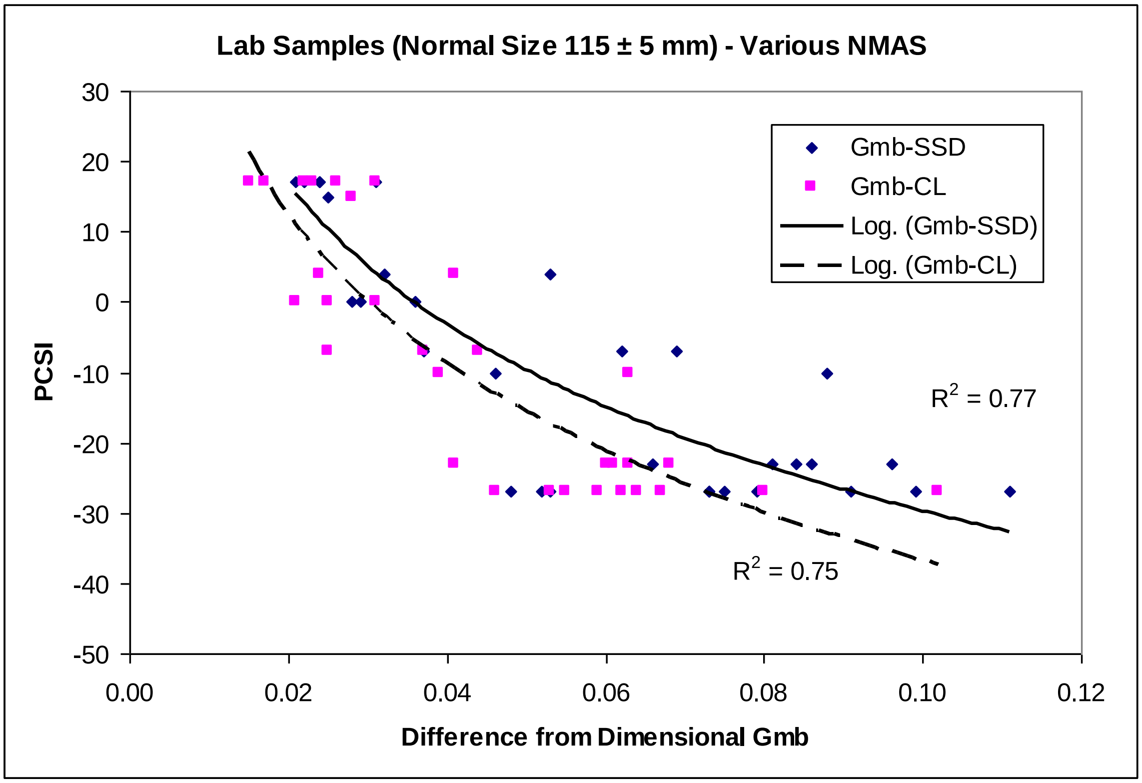

Figure 10 Relationship between PCSI and Difference of Bulk Specific Gravity of Gyratory Specimens

5 SUMMARY AND CONCLUSIONS

The Primary Control Sieve Index is a simple way to quantify the fineness or coarseness of a gradation. The PCSI is consistent with the definition of gradation types given by the NAPA pavement type selection guide and has strong correlations with other parameters used to describe gradation type such as coarse aggregate ratio and fineness modulus. Therefore, PCSI can be use in regression analyses to show the effect of gradation on a wide variety of mix characteristics.

It is important to mention that gradation by mass and by volume are virtually identical for blends where all of the aggregates are in a relatively narrow G_{sb} range (e.g. less than 0.2). But for blends that contain lightweight or heavyweight aggregates, relative to the other aggregates being used, there can be a fairly significant difference between gradation by mass and gradation by volume, which can impact the PCSI.

The PCSI clearly represents the effect of varying gradations away from the maximum density line on the VMA. In general, aggregate gradations that deviate from the maximum density line, either in the fine or coarse direction, tend to increase the VMA.

The PCSI is also related to several characteristics and properties of asphalt mixtures such as compactability, permeability and pavement surface texture. Compactability is expected to increase for positive PCSI values, permeability is expected to increase for negative PCSI values and texture is expected to decrease for positive PCSI values.

PCSI is based on the gradation at the primary control sieve. Although this is generally a key point in the gradation, there are certainly some gradations which have a low PCSI due to gaps or humps in the particle size distribution which cause the asphalt mixture mix to have different characteristics that do not follow expected trends.

Further analyses of the PCSI with other mixtures is recommended to verify and incorporate this parameter to represent the overall gradation and as a designing tool (i.e. changes in VMA). In addition, further investigation can be focus on using the PCSI for variability evaluation and acceptance since it has shown a significant correlation with volumetric properties.

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