NCAT Report No. 98-2

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ABSTRACT

Various studies have shown that the properties of mineral filler especially the material passing 0.075 mm (No. 200) sieve (generally called P200 material) have a significant effect on the performance of asphalt paving mixtures in terms of permanent deformation, fatigue cracking, and moisture susceptibility. However, researchers have employed different characterization tests for evaluating the P200 materials.

This study was undertaken to determine which P200 characterization tests are most related to the performance of asphalt paving mixtures. Six P200 materials representing a wide range of mineralogical composition and particle sizes were used. These P200 materials were characterized by six tests including Rigden voids, particle size analysis, and methylene blue test. Mixes were prepared with two fines/asphalt ratios (0.8 and 1.5) by weight. Mix validation tests included the Superpave shear test for evaluating permanent deformation and fatigue cracking, and the Hamburg wheel tracking test and AASHTO T 283 for evaluating moisture susceptibility of the 12 mixtures containing different P200 materials and fines/asphalt ratios.

The particle sizes in microns corresponding to 60 and 10 percent passing and the methylene blue test were determined to be related to the performance of asphalt paving mixtures.

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CHARACTERIZATION TESTS FOR MINERAL FILLERS RELATED TO PERFORMANCE OF ASPHALT PAVING MIXTURES

INTRODUCTION

According to various studies the properties of mineral filler especially the material passing 0.075 mm (No. 200) sieve (generally called P200 material) have a significant effect on the performance of asphalt paving mixtures in terms of permanent deformation, fatigue cracking, and moisture susceptibility. However, researchers have employed different characterization tests for evaluating the P200 materials. This study was undertaken to determine which P200 characterization tests are most related to the performance of asphalt paving mixtures.

REVIEW OF LITERATURE

Numerous studies have shown that the properties of mineral filler (especially the material passing No. 200 sieve) have a significant effect on the properties of the HMA mixtures. The introduction of environmental regulations and the subsequent adoption of dust collection system (baghouse) has encouraged the return of most of the fines to the HMA mixture. A maximum filler/asphalt ratio of 1·2 to 1·5, based on weight, is used by many agencies to limit the amount of the minus 200 material. However, the fines vary in gradation, particle shape, surface area, void content, mineral composition, and physico-chemical properties and, therefore, their influence on the properties of HMA mixtures also varies (1). Therefore, the maximum allowable amount should be different for different fines.

Fines can influence the performance of HMA mixtures as follows.

1. Depending on the particle size, fines can act as a filler or as an extender of asphalt cement binder (2, 3, 4). In the latter case an over-rich HMA mix can result leading to flushing and/or rutting. In many cases, the amount of asphalt cement used must be reduced to prevent a loss of stability or a bleeding pavement (5).
2. Some fines have a considerable effect on the asphalt cement making it act as a much stiffer grade of asphalt cement compared to the neat asphalt cement grade (1, 3, 6, 7), and thereby affect the HMA pavement performance including its fracture behavior (8, 9).
3. Some fines make the HMA mixtures susceptible to moisture-induced damage (1). Water-sensitivity of one source of slag baghouse fines has been reported in the United States (5), and the water-sensitivity of other stone dusts has been reported in Germany (10). Stripping of HMA mixtures as related to the properties of filler/asphalt combinations (fillers were obtained from operating HMA plants) has been reported in Japan (11).

It is very important to characterize the fines so that the performance parameters of HMA pavements (resistance to permanent deformation, stripping, and fatigue cracking) are not compromised.

MATERIALS, TESTS, AND TEST DATA

P200 Materials and Tests

Six aggregate sources (Table 1) were chosen to represent a wide range of mineralogical composition and particle sizes. These materials were obtained by dry sieving fine aggregate parent rock over a 75 µm (No. 200) sieve.

Table 1. P200 Aggregate Tests Results

Test	P-200 Type					
	P200-1 Natural Sand	P200-2 Lime-stone	P200-3 Dolomite	P200-4 Granite	P200-5 Blast Furnace Slag	P200-6 Limerock
Specific Gravity	2.558	2.760	2.955	2.872	3.043	2.798
Rigden Void (British Standard), %	39.3	35.4	32.3	41.4	40.6	34.3
Rigden Void (Penn State Modified), %	53.8	38.0	38.9	45.5	49.8	38.5
Fineness Modulus	3.67	2.46	4.99	4.50	4.47	2.81
D10 (micron)	1.54	1.26	4.18	3.30	2.41	1.38
D30 (micron)	6.45	3.27	22.58	15.64	12.67	4.23
D60 (micron)	26.92	9.98	51.95	40.89	43.41	14.60
Specific Surface Area (cm^2/ml)	12900	17968	6207	7206	8752	15603
Methylene Blue	18.7	1.3	0.3	2.1	2.0	9.5
Plasticity Index	29	NP	NP	NP	NP	NP
German Filler Test	35	70	80	60	55	75

The following tests were used to characterize the P200 materials.

- Rigden Voids (British Standard) - BS 812
- Rigden Voids (Penn State Modified) - Reference 13
- Particle Size Analysis
- Methylene Blue Test - Ohio DOT Procedure
- Plasticity Index - AASHTO T90
- German Filler Test - Koch Materials Company Procedure

Void content in fines (generally called Rigden voids) compacted to maximum density has been used by researchers for characterizing the fines. Void content is regulated by four basic properties of fines—particle shape, particle size, particle-size distribution, and particle surface structure (1). A sample of vacuum-oven dry sample of fines is either vibrated in a graduate cylinder (1) or compacted in a small mold by a compaction hammer (12, 13) to maximum packing. Mass (g) of the compacted fines is divided by the compacted volume (cm^3) to calculate bulk specific gravity (G_{fB}) of compacted fines. Apparent specific gravity (G_{fS}) of the fine solids is determined by AASHTO T 133 using kerosene. Void content (V) in the fines compacted to maximum density is then calculated as follows:

$$V,\ percent = 100\ (1 - \frac{G_{fB}}{G_{fS}})$$

Both British Standard BS 812 (12) and Penn State modified equipment (13) were used to determine Rigden Voids. They are based on the same concept but use a different compactive effort.

Particle size analysis was conducted with a Coulter LF200 Particle size analyzer. From this analysis, several parameters were determined. The relative fineness of an aggregate can be determined by the calculated fineness modulus (FM). Fineness modulus of the P200 material was calculated by dividing by 100 the sum of the percentages of P200 material coarser than 75, 50, 30, 20, 10, 5, 3, and 1 microns. The finer the aggregate, the smaller the fineness modulus. Parameters D10, D30, and D60 were also determined from particle size analysis. These parameters are the particle sizes that correspond, respectively, to 10, 30, and 60% of the material passing. The

specific surface area (cm^2/ml) or SA was the final parameter obtained from this analysis.

The methylene blue (MB) test is used by the International Slurry Seal Association (ISSA) to quantify the amount of harmful clays of the smectite (montmorillinite) group, organic matter and iron hydroxides present in fine aggregate (14). The principle of the test is to add quantities of a standard aqueous solution of the dye (methylene blue) to a sample until adsorption of the dye ceases.

The German filler test is a measure of the amount of mineral filler required to absorb 15 grams of hydraulic oil. The hydraulic oil is put in a small bowl, then 45 grams of mineral filler is added and mixed. An attempt is made to form a ball with the mixture. If a ball is formed and holds together, more mineral filler, in 5-g increments, is added. This process is continued until the mixture loses cohesion. At this point, all of the hydraulic oil is fixed in the voids of the P200 material and there is no excess to hold the particles together. The total amount of P200 added to the hydraulic oil is reported as the test value.

Table 1 contains the results of the P200 characterization tests. Each value is the average of three replicates.

Table 2 contains the correlation matrix between aggregate properties. The correlation coefficients (R values) are the first number in each cell. The second number in each cell is the statistical significance level (P) corresponding to the correlation coefficient.

Rigden voids, British method and Rigden voids, Penn State modified have a good correlation (R=0.78, P=0.06) with each other because both measure the voids in the compacted P200 material although with different compactive efforts. Rigden voids, Penn State modified, has

Table 2. Correlation Matrix of P200 Aggregate Properties[a]

	Rigden Void, BS	Rigden Void, PS	FM	D10	D30	D60	SA	MB	German Filler
Rigden Void, BS	1.0	0.784 0.065	0.235 0.655	-0.073 0.890	-0.051 0.923	0.186 0.724	-0.250 0.633	0.166 0.753	-0.749 0.086
Rigden Void, PS		1.0	0.326 0.529	-0.092 0.863	-0.013 0.980	0.277 0.595	-0.268 0.607	0.557 0.251	-0.949 0.004
FM			1.0	0.899 0.015	0.936 0.006	0.996 0.0001	-0.990 0.0001	-0.302 0.561	-0.058 0.913
D10				1.0	0.992 0.0001	0.907 0.013	-0.919 0.010	-0.538 0.270	0.321 0.535
D30					1.0	0.947 0.004	-0.942 0.005	-0.503 0.309	0.261 0.617
D60						1.0	-0.983 0.0004	-0.360 0.483	-0.001 0.998
SA							1.0	0.347 0.500	0.000 0.999
MB								1.0	-0.680 0.137
German Filler									1.0

[a] Top values are correlation coefficients R and bottom values are significance levels P in each cell.

an excellent correlation with the German filler test, whereas Rigden voids, British method, has only a fair correlation with the German filler test.

The German filler test is based indirectly on the Rigden voids concept. If the Rigden voids are high, the amount of P200 material needed to reach the end point of the test is relatively low because more hydraulic oil is fixed by the high voids. The German filler test does not require any special equipment and is very simple to perform and can potentially be substituted for Rigden voids, Penn State method.

The test parameters fineness modulus (FM), specific surface area (SA), D10, D30, and D60 are strongly related with each other as shown in Table 2. All correlations are significant at the 5% level.

Rigden voids, Penn State method, and Rigden voids, British standard, do not have any

correlation with the particle size parameters. As mentioned earlier, Rigden voids are regulated by particle shape and particle surface texture besides particle size.

Mixture Validation Tests

Twelve HMA mixes were evaluated in this study. The six P200 aggregates in both 0.8 and 1.5 F/A ratios were combined with limestone coarse and fine aggregate to produce validation mixes. All limestone was washed over a 75 µm (No. 200) sieve prior to batching to remove the P200 material. Limestone was chosen as the coarse and fine aggregate so that moisture susceptibility would not be caused by the base aggregate. Moisture susceptibility differences, if any, can then be attributed to the effect of the P200 material. Figure 1 shows the HMA mix gradation used for the 0.8 F/A ratio (5% passing 75 µm sieve). The HMA mix gradation for the 1.5 F/A ratio was same as that for 0.8 F/A ratio except it had 8% passing 75 µm sieve.

A Superpave PG 64-22 grade asphalt cement was used in all HMA mix testing. Optimum asphalt content was determined by Superpave volumetric mix design for a mix containing all limestone aggregate (including the P200 fraction) using the 0.8 F/A ratio. An asphalt content of 5.3% gave 4% air voids at N_{design} (119 gyrations, for intermediate design traffic level of 10^7 ESALs). This asphalt content and same compactive effort was used for all validation mixes. However, relatively low air voids (average of 2.8 percent) were generally obtained in validation samples. It is quite possible that in some cases it can be attributed to P200 material's potential action as an extender.

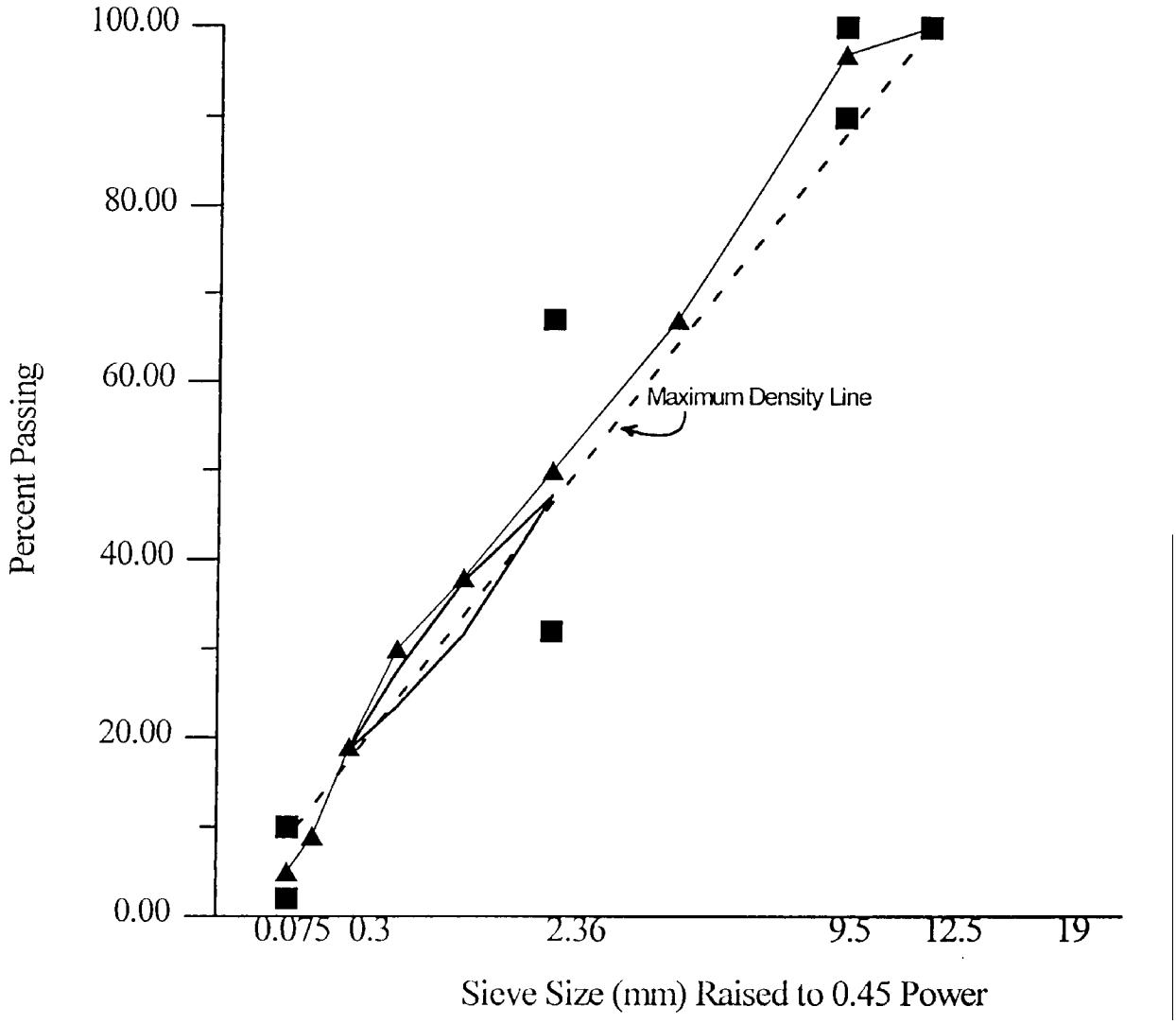

Figure 1. HMA Mix Gradation

Permanent Deformation and Fatigue Cracking

Specimens were made to be tested by the Superpave shear tester (frequency sweep at constant height and simple shear at constant height) and the indirect tensile tester for evaluating the HMA resistance to permanent deformation and fatigue cracking (15, 16). The testing of the compacted specimens was performed by the Asphalt Institute.

The following three individual test parameters which are used in the Superpave intermediate mix analysis were used to determine the propensity of the HMA mixtures to permanent deformation (rutting) and fatigue cracking.

1. G*/sinδ at 0.1 hertz.

   G*/sinδ of the HMA mix is similar to G*/sinδ (rutting parameter) of PG graded asphalt binder. It is a measure of HMA stiffness at high pavement temperature (40^0C) at a slow rate of loading (0.1 cycle/second). Higher values of G*/sinδ indicate increased stiffness of HMA mixtures and, therefore, increased resistance to rutting. G* is the complex modulus and δ is the phase angle when HMA is tested under dynamic loading.

2. Slope (m) of the frequency vs G* plot.

   The m value was obtained from the frequency sweep at constant height conducted by the Superpave shear tester (SST) at high effective temperature (40°C) for permanent deformation or T_{eff}(PD) with frequencies ranging from 0.01 hertz to 10 hertz. In other words, G* (stiffness) of the compacted HMA specimen is measured at different frequencies. The slope (m) of the best fit line on the frequency vs G* plot is calculated. This slope represents the rate of development of rutting for the tested mix and is used in the Superpave model as such. The lower the m slope, the better is the mix's resistance to rutting.

3. G*sinδ at 1.0 hertz

   G*sinδ of the HMA mix is similar to G*sinδ (fatigue factor) of the asphalt binder. It is a measure of the stiffness at intermediate effective pavement temperatures for fatigue cracking or Teff(FC). G*sinδ was measured at 1.0 hertz to represent fast moving traffic.

A T_{eff}(FC) of 20°C was used. High values of G*sinδ at 1.0 hertz indicate high stiffness at intermediate temperatures and, therefore, low resistance to fatigue cracking according to Superpave.

Moisture Susceptibility (Stripping)

Koch Materials Company performed the Hamburg wheel tracking test in their laboratory in Terre Haute, Indiana. The Hamburg wheel tracking device (HWTD) measures the combined effects of rutting and moisture damage by rolling a steel wheel back and forth across the surface of a HMA slab that is submerged in hot water maintained at 50°C (122°F). The testing duration is 20,000 cycles and deformation is recorded and plotted after each cycle. On the cycles versus deformation plot two distinct lines are generally observed. The first line (rutting line) indicates rutting in the HMA unaffected by stripping. The following second line (stripping line) with a steeper slope indicates rutting due to stripping. The point (number of cycles) where the slope of the rutting line and the slope of the stripping line intersect is called the inflection point. This is the point where stripping is assumed to have been initiated. Inflection point (expressed in terms of number of cycles) is the test parameter of interest for this study. The HMA slabs generally had an air void content of 7±1 percent.

AASHTO T-283 was also used to measure the moisture-susceptibility of the HMA mixes in terms of tensile strength ratio (TSR).

Mixture Validation Data and Statistical Analysis

Table 3 contains all mixture validation test results. The main objective of the statistical

Table 3. P200 Mixture Validation Test Results

Mix Designation	Rutting Parameters		Fatigue Cracking Parameter	Moisture Susceptibility Parameters	
	High Temperature (40°C)		Intermediate Temperature (20°C)		
	G*/sinδ @ 0.1 hz, psi	m	G*sin δ @ 1.0 hz psi	TSR Percent	Inflection Point (Hamburg)
1A	8722	0.43373	98051	66.2	7000
2A	9830	0.40572	89829	64.6	8400
3A	11034	0.40931	97967	51.7	20000
4A	9682	0.43596	88811	55.0	8600
5A	11271	0.40282	85644	57.5	10000
6A	12934	0.39183	93707	64.1	10000
1B	21700	0.31559	109560	64.7	6000
2B	21752	0.30167	98782	59.9	14400
3B	10269	0.40396	93318	52.4	9800
4B	11872	0.37874	84319	54.7	6400
5B	9510	0.41171	86723	64.5	8000
6B	25900	0.29158	95502	68.1	5000

analysis is to correlate the P200 aggregate properties with HMA properties determined by the mix validation tests. Table 4 shows the correlation matrix between the P200 aggregate properties and the HMA properties at the 0.8 F/A gradation. Table 5 shows the correlation matrix between the P200 aggregate properties and HMA properties at the 1.5 F/A gradation.

G*/sin δ @ 0.1 hz and m (the slope of the best fit line on the frequency vs G* plot) were the two HMA parameters chosen to indicate the rutting potential, as mentioned previously. Neither of these parameters correlates to any of the P200 aggregate tests at a significant level ($P<0.05$) in the 0.8 F/A ratio gradation. However, good correlations were obtained between the

Table 4. Correlation Matrix Between P200 Aggregate Properties and HMA Properties (0.8 F/A Gradation)[a]

	Rutting		Fatigue	Stripping	
	G*/sin δ @ 0.1 hz	m	G*sin δ @ 1.0 hz	TSR	Inflection Point
Rigden Voids (British Standard)	-0.468 0.35	0.599 0.21	-0.556 0.25	0.033 0.95	-0.665 0.15
Rigden Voids (Penn State Method)	-0.526 0.28	0.599 0.21	-0.051 0.92	0.157 0.77	-0.463 0.36
Fineness Modulus	-0.094 0.86	0.365 0.48	0.039 0.94	-0.865 0.03	0.561 0.25
D10	0.007 0.99	0.248 0.63	0.110 0.84	-0.968 0.001	0.758 0.08
D30	0.01 0.99	0.228 0.66	0.113 0.83	-0.961 0.002	0.766 0.08
D60	-0.048 0.93	0.294 0.57	0.016 0.98	-0.886 0.02	0.606 0.20
Specific Surface Area	0.049 0.92	-0.367 0.47	0.009 0.99	0.896 0.02	-0.543 0.27
Methylene Blue	-0.255 0.63	0.306 0.56	0.534 0.28	0.693 0.13	-0.476 0.34
German Filler	0.657 0.16	-0.644 0.17	-0.003 0.99	-0.409 0.42	0.647 0.17

[a] Top values are correlation coefficients R and bottom values are significance levels P in each cell.

rutting parameters and the gradation indicators (fineness modulus, D10, D30, D60, and specific surface area) in the 1.5 F/A ratio gradation.

There were no significant correlations between P200 properties and G*sin δ (fatigue factor) in either 0.8 F/A ratio or 1.5 F/A ratio gradations. TSR correlated well with the gradation parameters at the 0.8 F/A ratio. However, with this exception, no significant correlations were seen between stripping parameters and P200 aggregate tests at either the 0.8 F/A ratio or the 1.5 F/A ratio.

Table 5. Correlation Matrix Between P200 Aggregate Properties and HMA Properties (1.5 F/A Gradation)[a]

	Rutting		Fatigue	Stripping	
	G*/sin δ @ 0.1 hz	m	G*sin δ @ 1.0 hz	TSR	Inflection Point
Rigden Voids (British Standard)	-0.293 0.57	0.251 0.63	-0.257 0.62	0.143 0.79	-0.355 0.49
Rigden Voids (Penn State Method)	-0.201 0.70	0.221 0.67	0.206 0.70	0.286 0.58	-0.465 0.35
Fineness Modulus	-0.901 0.01	0.926 0.008	-0.488 0.33	-0.584 0.22	-0.249 0.63
D10	-0.838 0.04	0.836 0.04	-0.560 0.25	-0.824 0.04	-0.032 0.95
D30	-0.871 0.02	0.881 0.02	-0.532 0.28	-0.771 0.07	-0.049 0.92
D60	-0.920 0.009	0.948 0.004	-0.511 0.30	-0.590 0.22	-0.192 0.72
Specific Surface Area	0.895 0.016	-0.915 0.01	0.572 0.24	0.609 0.20	0.288 0.58
Methylene Blue	0.615 0.19	-0.559 0.25	0.776 0.07	0.613 0.20	-0.559 0.25
German Filler	-0.05 0.92	0.060 0.91	-0.413 0.42	-0.361 0.48	0.359 0.49

[a] Top values are correlation coefficients R and bottom values are significance levels P in each cell.

The correlations are generally better for the F/A ratio of 1.5 (because higher amounts of P200 were used) than F/A ratio of 0.8. Therefore, P200 tests can be better related to HMA performance at F/A ratio of 1.5 which will be primarily used in this study to select the P200 tests which are related to HMA performance. It appears from Table 5 that the fineness of P200 material expressed by the test parameters D60, D30, D10, fineness modulus, and specific surface area is significantly related to permanent deformation of HMA at high concentration levels of

P200 in the mix.

As mentioned earlier, no significant relationships are observed between P200 aggregate properties and HMA rutting parameters (G*/sinδ @ 0.1 hz and m) or HMA fatigue parameter (G*sinδ) at a F/A ratio of 0.8. This indicates that at low concentration levels of P200, the effect on rutting and fatigue is not statistically significant.

It appears from Table 5 that the fineness of the P200 material (especially D10) has a significant effect on the retained tensile strength (TSR). Since parent rocks (limestone) of the coarse aggregate and fine aggregate are the same in all mixes (only the P200 is different), the effect of binder stiffening (caused by the P200 material) appears to be dominant in these mixes. The smaller the size of P200 (especially D10), the more the binder is being modified and/or extended and thus gives increased resistance to stripping in AASHTO T283 test.

Surprisingly, no P200 aggregate tests has any significant relationship with stripping when measured by the Hamburg wheel tracking device. Methylene blue has the highest (although insignificant at the 0.05 level) relationship with the inflection point. Obviously, the Hamburg wheel tracking test, which is conducted with HMA slabs submerged in hot water (50°C) and subjected to mechanical action, is significantly different than the stripping process in AASHTO T283, which does not involve any mechanical action.

Again, similar to the results obtained in mixes with F/A ratio of 1.5, the fineness of the P200 material has a significant effect on the retained tensile strength (TSR) at a F/A ratio of 0.8 (Table 4).

As also observed in mixes with F/A ratio of 1.5, no P200 test has any significant relationship with stripping when measured by the Hamburg wheel tracking device. Methylene blue

is the only independent variable which has the highest (but not significant at the 0.05 level) correlation with inflection point (R= -0.48, P=0.34).

The forward selection multiple variables procedure given in the SAS program was used to select the P200 tests which are related to HMA performance parameters. The forward selection procedure begins by finding the variable that produces the optimum one-variable subset, that is, the variable with the largest coefficient of determination or R^2. In the second step, the procedure finds that variable which, when added to the already chosen variable, results in the largest increase in R^2 and so on. The process continues until no variable considered for addition to the model provides an increases in R^2 considered statistically significant at the specified level (P = 0.05 for this study).

Table 6 contains the P200 tests selected in the forward selection procedure and the corresponding regression equations relating the P200 aggregate tests to the HMA performance parameters.

The selection of the P200 aggregate tests that best relate to the HMA performance properties will be based solely on the information taken from the 1.5 F/A gradation testing. This is because 1.5 F/A ratio seems to correlate much better with the HMA performance properties compared to 0.8 F/A ratio due to an increased amount of P200 material in the mix. The models of 0.8 F/A ratio generally have low coefficient of determination or R^2 values and insignificant P values.

Permanent Deformation

G*/sinδ @ 0.1hertz at High Temperature High G*/sin δ values indicate increased resistance

Table 6. Regression Equations Between P200 Aggregate Tests and HMA Validation Tests

0.8 F/A Gradation

Performance Parameter	Step	Dependent	Independent	Equation	R^2	P
Permanent Deformation	1	G*/sin δ @0.1hz	German Filler	G*/sin δ=6845.29+59.737(German Filler)	0.43	0.16
Permanent Deformation	2	G*/sin δ @0.1hz	Rigden Voids (Penn State)	G*/sin δ=-8062.28+217.88(Rigden Voids, Penn State)+144.60(German Filer)	0.52	0.32
Permanent Deformation	1	m	German Filler	m=0.457-0.000699(German Filler)	0.42	0.17
Permanent Deformation	2	m	D10	m=0.450+0.0076(D10)-0.000876(German Filler)	0.65	0.21
Fatigue	1	G*sin δ @1.0hz	Rigden Voids (British Standard)	G*sin δ=120620.9-760.41(Rigden Voids ,British Standard)	0.31	0.25
Fatigue	2	G*sin δ @1.0hz	Methylene Blue	G*sin δ=123483.4--906.9(Rigden Voids ,British Standard)+457.7(Methylene Blue)	0.71	0.15

1.5 F/A Gradation

Performance Parameter	Step	Dependent	Independent	Equation	R^2	P
Permanent Deformation	1	G*/sin δ @0.1hz	D60	G*/sin δ=28961.36-387.56(D60)	0.85	0.09
Permanent Deformation	2	G*/sin δ @0.1hz	Methylene Blue	G*/sin δ=25596.17-338.18(D60)+321.94(Methylene Blue)	0.94	0.015
Permanent Deformation	1	m	D60	m=0.256+0.003(D60)	0.90	0.004
Permanent Deformation	2	m	Methylene Blue	m=0.275+0.0027(D60)-0.0019(Methylene Blue)	0.95	0.01
Fatigue	1	G*sin δ @1.0hz	Methylene Blue	G*sinδ=89153.7+981.26(Methylene Blue)	0.60	0.07
Fatigue	2	G*sinδ @1.0hz	Rigden Voids (British Standard)	G*sin δ=124586.23-965.21(Rigden Voids,British Standard)+1064.7(Methylene Blue)	0.75	0.12

to permanent deformation or rutting. The two-variable model (see Table 6 and Figure 2) gives D60 as the primary independent variable and methylene blue as the second independent variable. The coefficient of determination or R^2 value of this model is 0.94 (P=0.015) which is excellent. As the particle size (at 60% passing) decreases, the G*/sin δ (stiffness or resistance to rutting) increases. It appears that the finer the P200 material, the more it modifies the asphalt binder and

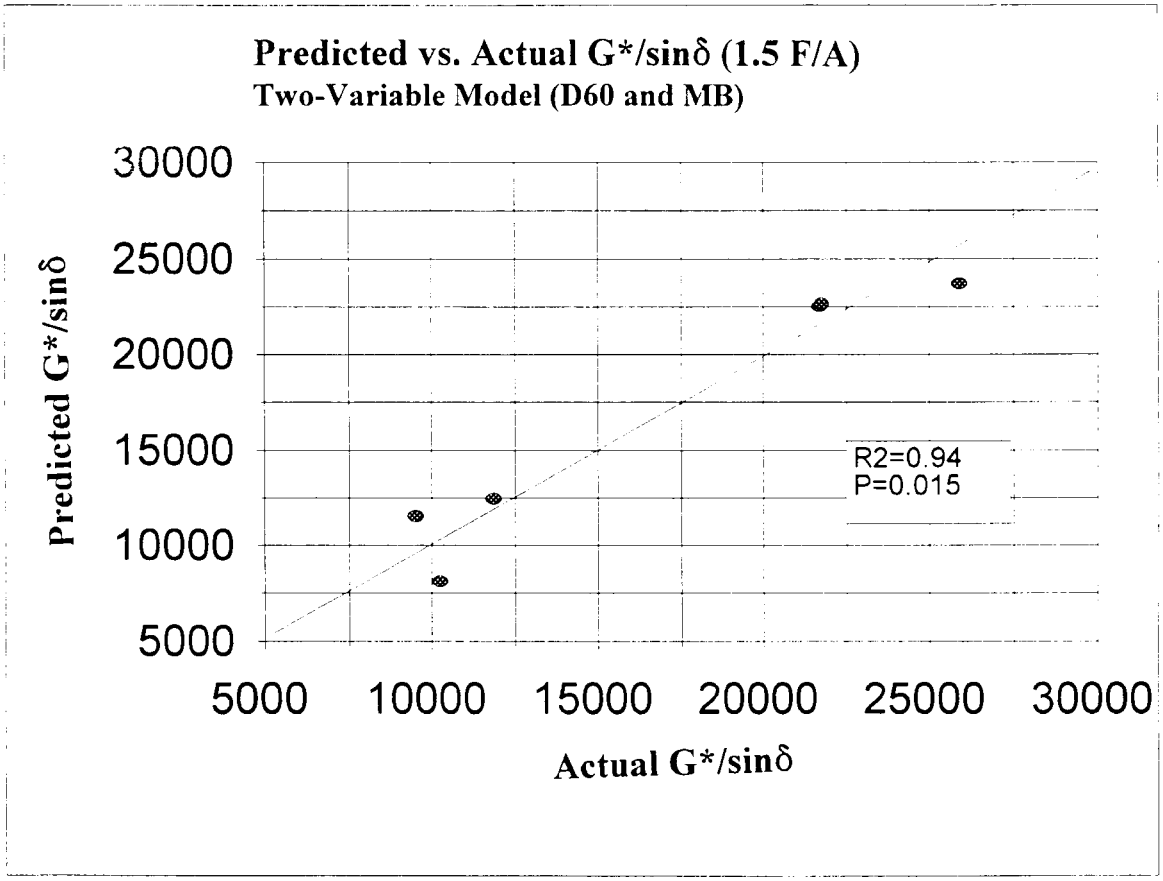

Figure 2. Predicted G*/sinδ Values vs. Actual G*/sinδ Using a Two-Variable (D60 and Methylene Blue) Model

stiffens the HMA mix. The model also indicates that the higher the methylene blue value (another indication of the presence of very fine P200), the higher is G*/sin δ.

m Value (Slope of the Frequency vs. G* Plot) at High Temperature High m values indicate increasing rate of rut development in HMA mixes. The two-variable model (R^2= 0.95, P= 0.01) gives D60 as the primary independent variable and methylene blue as the secondary independent variable affecting m (see Table 6 and Figure 3). This is similar to G*/sin δ @ 0.1 hertz.

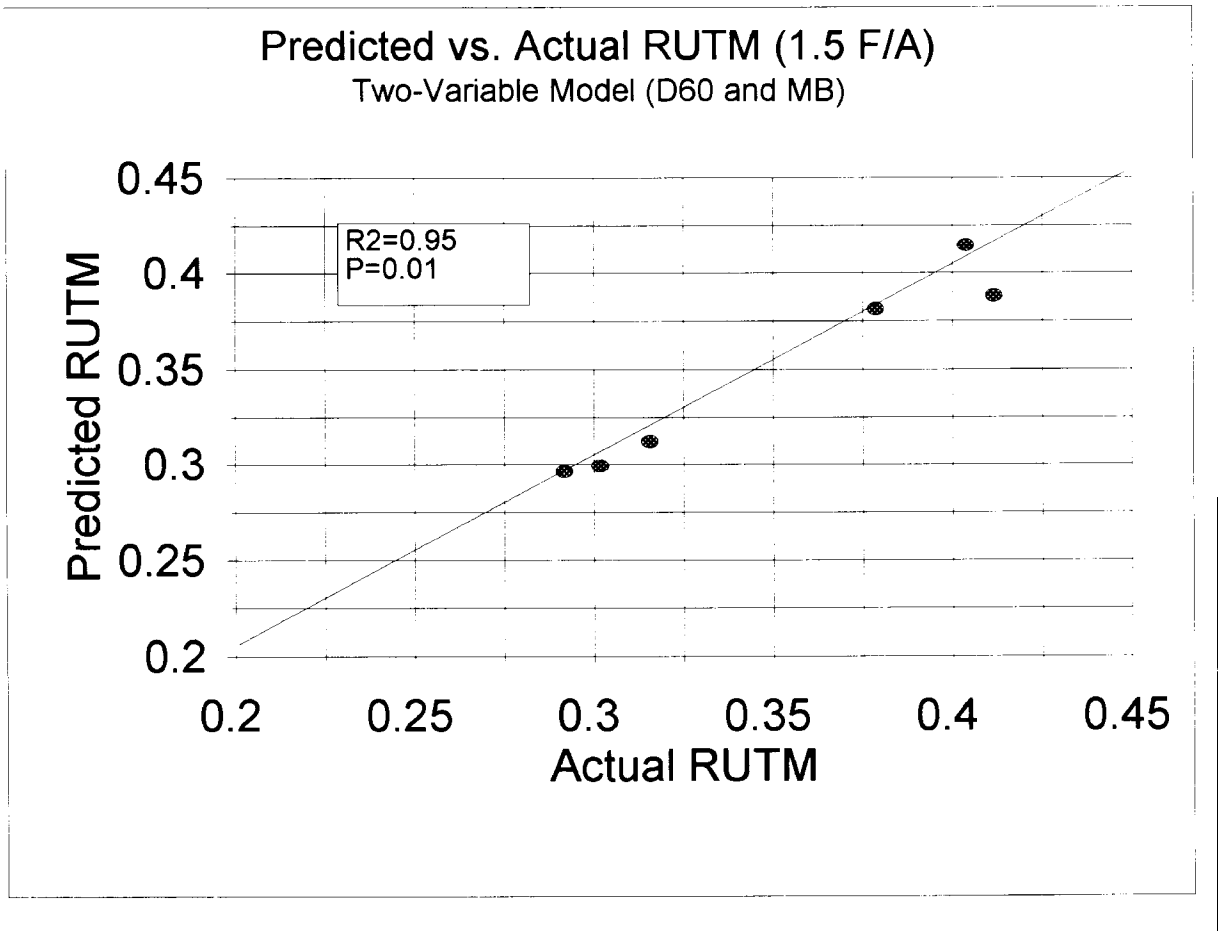

Figure 3. Predicted RUTM Values vs. Actual RUTM Values Using a Two-Variable (D60 and Methylene Blue) Model

It is recommended to use D60 and methylene blue as the P200 tests which are related to HMA performance in terms of permanent deformation.

Fatigue Cracking

G*sin δ @ 1.0 Hertz at Intermediate Temperature High values of G*sin δ indicate high mixture stiffness at intermediate temperature and therefore increased fatigue cracking. The two-variable model for G*sin δ @ 1.0 hertz indicates methylene blue as the primary independent

variable and Rigden voids, British standard as the secondary variable. This is similar to the rutting models in that higher values of methylene blue indicate stiffer HMA mixes. However, the model has a R^2 value of 0.75 and a level of significance of 0.12 (greater than the desired 0.05). Therefore, it appears that the effect of P200 material at the 1.5 F/A ratio is statistically not significant and, therefore, no P200 test is recommended for fatigue cracking.

Stripping

Two mix validation tests: AASHTO T283 (Modified Lottman) and Hamburg wheel tracking device, were used to determine HMA performance in terms of resistance to stripping or moisture susceptibility.

AASHTO T283 Higher retained tensile strength (TSR) obtained by this test indicates increased resistance to stripping. The two-variable model for TSR at a F/A ratio of 1.5 (R^2=0.82, P=0.08) consists of D10 (P200 size at 10% passing) as the primary independent variable (R^2=0.68, P=0.04) and specific surface area (SA) of P200 as the secondary independent variable (Table 7). TSR increases as the P200 becomes finer at 10% passing (D10 decreases). It appears that very fine size P200 at 10% passing level is stiffening the F/A binder and thus providing increased resistance to stripping. The literature review has indicated that high viscosity asphalt binders offer increased resistance to stripping compared to low viscosity asphalt binders, all other things being equal.

The two variable model (see Table 7) for TSR obtained at 0.8 F/A ratio is much better than that obtained at a 1.5 F/A ratio. It has a R^2 value of 0.98 (P=0.003) and it has D10 and

Table 7. Regression Equations Between P200 Aggregate Tests and Stripping

0.8 F/A Gradation						
Performance Parameter	Step	Dependent	Independent	Equation	R^2	P
Stripping	1	TSR	D10	TSR=71.21-4.844(D10)	0.94	0.002
Stripping	2	TSR	Methylene Blue	TSR=68.54-4.19(D10)+0.201(Methylene Blue)	0.98	0.003
1.5 F/A Gradation						
Performance Parameter	Step	Dependent	Independent	Equation	R^2	P
Stripping	1	TSR	D10	TSR=70.78-4.29(D10)	0.68	0.04
Stripping	2	TSR	Specific Surface Area	TSR=95.47-8.84(D10)-0.001(Specific Surface Area)	0.82	0.08
0.8 F/A Gradation						
Performance Parameter	Step	Dependent	Independent	Equation	R^2	P
Rutting	1	Inflection Point	D30	Inflection Point = 5496.7+478.4(D30)	0.59	0.076
Rutting	2	Inflection Point	Rigden Voids British Standard	Inflection Point = 35183.4+458.4(D30)-792.2 (Rigden Voids British Standard)	0.98	0.003
1.5 F/A Gradation						
Performance Parameter	Step	Dependent	Independent	Equation	R^2	P
Rutting	1	Inflection Point	Methylene Blue	Inflection Point = 9784.9-268.6 (Methylene Blue)	0.31	0.25
Rutting	2	Inflection Point	Surface Area	Inflection Point = 5792.6-359.9 (Methylene Blue) +0.39 (Surface Area)	0.58	0.28

methylene blue as the primary and secondary independent variables affecting HMA stripping. This indicates that the fineness (D10) of the material as well as the nature (methylene blue) of the P200 material affects HMA resistance to stripping (Figure 4). It appears that the two-variable model for TSR obtained at a 1.5 F/A ratio had a lower R^2 value and higher P value because large amounts of fines stiffened the asphalt binder too much and masked the effect of the nature of the fines.

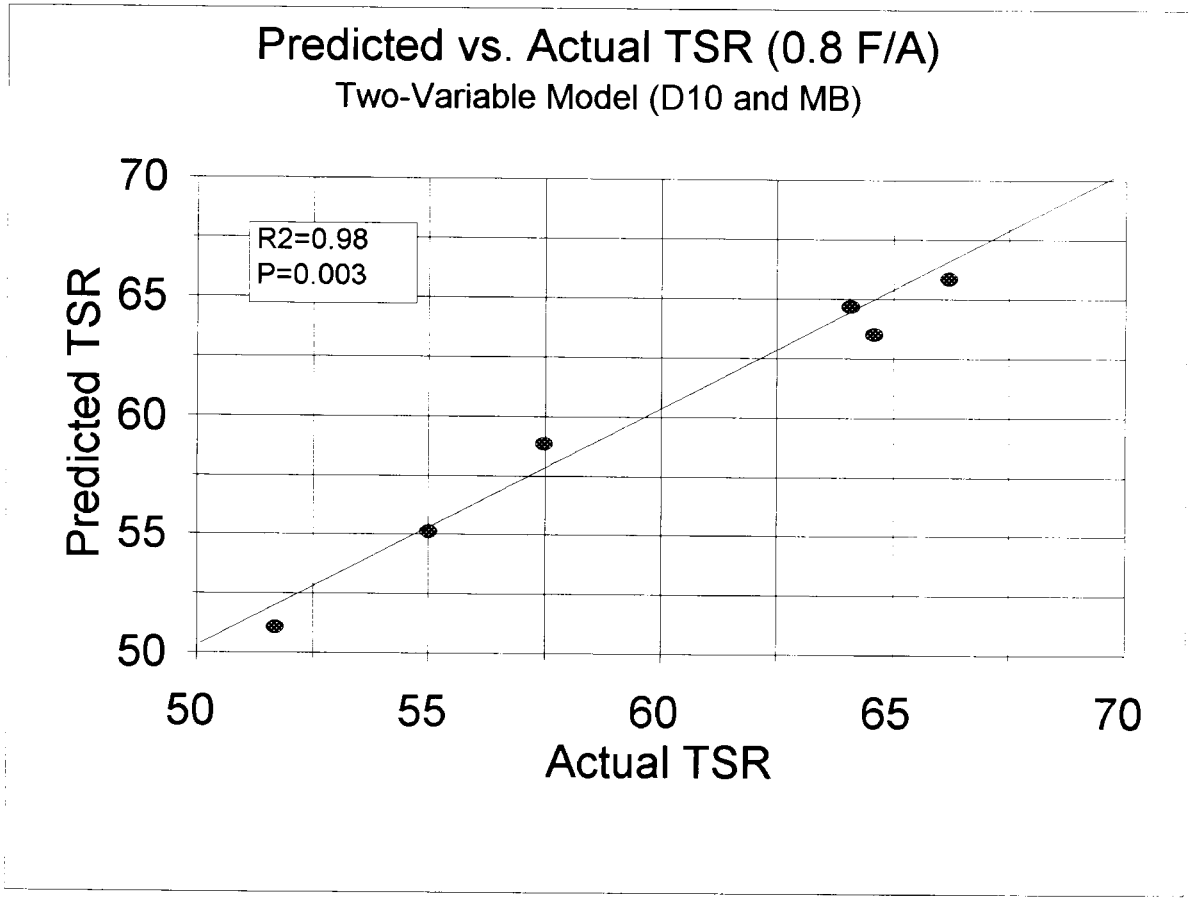

Figure 4. Predicted TSR Values vs. Actual TSR Values for the Two-Variable (D10 and Methylene Blue) Model

Based on the TSR obtained by AASHTO T283, D10 and methylene blue are the recommended P200 aggregate tests which are related to stripping of HMA mixes. As stated earlier, D10 indicates the fineness of the P200 material and methylene blue indicates both fineness and nature of the P200 material.

Hamburg Wheel Tracking The inflection point obtained in this test represents the number of passes at which stripping starts to occur in the HMA mix. The larger the inflection point (number

of passes), the higher is the mix's resistance to stripping. The two-variable model for inflection point at a 1.5 F/A ratio has a low R^2 (0.58) and high P value (0.28) and therefore, is not considered statistically significant (Table 7). This model has methylene blue and specific surface area as the primary and secondary independent variables affecting stripping. The higher the methylene blue value, the lower the inflection point and hence resistance to stripping. This is in agreement with the observation made in case of TSR obtained by AASHTO T283.

The two-variable model for inflection point at a 0.8 F/A ratio is significantly better than that at a 1.5 F/A ratio (Table 7). This is in agreement with the trend seen in the case of TSR. The two-variable model (R^2=0.98, P=0.003) has D30 as the primary independent variable and Rigden voids, British standard as the secondary independent variable affecting resistance to stripping. It should be noted that D30 has a high correlation (R=0.99, P=0.0001) with D10 which was selected as the primary independent variable in case of TSR. It is not understood why the Rigden voids, British standard was selected as the secondary independent variable by the statistical analysis. Normally, higher Rigden voids cause stiffer F/A systems and, therefore, should result in increased resistance to stripping (or higher values of inflection point). However, the model shows an opposite effect, because the slope of regression is negative.

It should be realized that AASHTO T283 and the Hamburg wheel tracking device are significantly different stripping tests, although the VTM values of the test specimens are comparable (7±1 percent). AASHTO T283 involves curing of the mix in a 60°C oven for 16 hours followed by vacuum saturation of HMA, then immersion in a hot (60°C) water bath for 24 hours, transfer to 25°C water bath for two hours, and then testing for tensile strength. Hamburg wheel tracking does not involve any vacuum saturation. It does involve immersion of the HMA in

a 50°C water bath. However, while immersed, the sample is subjected to the loaded wheel tracking device and rut depth measurements are taken. A repeated, dynamic mechanical load is applied to the HMA in Hamburg wheel tracking device whereas no such loading is applied in AASHTO T283. The conditioning and testing of HMA is significantly different in these two tests. Therefore, it is not surprising that different independent variables were selected in these two mix validation tests.

It is recommended that D10 and methylene blue be used for HMA performance in terms of stripping, taking into consideration both AASHTO T283 and Hamburg wheel tracking tests.

D10 is the primary independent variable in case of TSR. It has high correlation with D30 (R=0.992, P=0.0001) which was selected as the primary independent variable in Hamburg wheel tracking test.

Methylene blue is the secondary independent variable in case of TSR. This test indicates the nature and fineness of the P200 material.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions can be drawn from this study.

1. Permanent deformation. The permanent deformation data obtained by the Superpave shear tester in terms of G*/sin δ @ 0.1 hertz and m value (slope of frequency vs. G* plot) indicates that D60 (the particle size of P200 material at 60% passing) is the primary independent variable and the methylene blue value is the secondary independent variable affecting permanent deformation of HMA mixtures. It appears that the finer the P200 material, the more it modifies the asphalt binder and stiffens the HMA mix. Both lower

values of D60 and higher values of methylene blue indicate finer P200 material.

2. Fatigue cracking. The fatigue cracking data obtained by the Superpave shear tester in terms of G*/sinδ @ 1 hertz did not indicate any statistically significant correlation with any of the P200 properties evaluated in this study.

3. Stripping. The stripping data obtained by AASHTO T283 indicates that D10 (the particle size of P200 at 10% passing) is the primary independent variable and methylene blue is the secondary independent variable affecting the stripping potential of HMA mixes. D10 indicates the fineness of the P200 material and methylene blue indicates both fineness and nature of the P200 material.

The following tests that are related to HMA performance are recommended for evaluating aggregates for hot mix asphalt mixtures.

Performance Parameter	Recommended P200 Test
Permanent Deformation	D60 and Methylene Blue
Fatigue Cracking	None
Stripping	D10 and Methylene Blue

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