## APPENDIX D: COMPARISON OF THE PERCENT PERMANENT STRAINS FROM VARIOUS TESTS

### 1. Test Data

Table 123 shows the average percent permanent strains provided by two asphalt binders based on binder, mixture, and pavement tests. Table 124 shows how the strains were calculated for the pavement tests. The permanent deformation measured at the 200$^{th}$ cycle of loading was divided by the asphalt pavement layer thickness of 200 mm to obtain the permanent strain at the 200$^{th}$ cycle of loading. The total strain at the 200$^{th}$ cycle of loading was not measured during the ALF pavement tests. It was calculated using the elastic equation $\epsilon_{total} = \sigma/E$ where $\sigma$ is the stress applied by the ALF (load divided by area of loading) and E is the dynamic modulus of the mixture measured in the laboratory using an unconfined repeated load compression test. Table 125 show how the strains were calculated for the repeated load compression test. Table 126 shows a comparison of the average total strains.

**Table 123. Percent permanent strain per cycle of loading at 58 °C.[1]**

| Asphalt Binder Grade | Binder Tests—Performed in the Linear Viscoelastic Range | | ALF Pavement Test at 200$^{th}$ Wheel Pass (Estimated) | Repeated Load Compression Test at the 200$^{th}$ Cycle of Loading[3] |
|---|---|---|---|---|
| | Standardized DSR Test at 2 to 10 rad/s, sinδ x 100 | Repeated Load DSR Test Using an Applied Stress of 500 Pa[2] | | |
| PG 59 (AC-5) | 99 % | 97.0 % | 2.9 % | 2.0 % |
| PG 77 (Novophalt) | 95 % | 83.5 % | 0.6 % | 0.6 % |

[1]Permanent strain x 100 ÷ total strain.

[2]The load duration was 1.0 s with a 9.0-s rest period, which allowed for the recovery of the time-dependant elastic strains.

[3]The load duration was 0.1 s with a 0.9-s rest period, which allowed for the recovery of the time-dependant elastic strains.

Table 124. Data from the ALF pavement tests at the 200th wheel pass.

| Asphalt Binder Grade | Permanent Def, PD, (mm) | Permanent Strain, $\epsilon_p$ = PD/200 mm (mm/mm) | Stress Applied by the ALF, $\sigma$, (MPa) | Dynamic Modulus,[1] E, (MPa) | Total Strain $\epsilon_{total} = \sigma/E$ (mm/mm) | Percent Permanent Strain, $\epsilon_p(100)/\epsilon_{total}$ |
|---|---|---|---|---|---|---|
| PG 59 AC-5 | 0.0225 | 0.0001125 | 0.690 | 176 | 0.00392 | 2.9 |
| PG 77 Novophalt | 0.0020 | 0.000010 | 0.690 | 427 | 0.00162 | 0.6 |

[1]Using a 0.1-s total load duration (the maximum load occurs at 0.05 s). The ALF load duration is greater than 0.1 s. It was estimated to be 0.4 s. However, the repeated load compression tests were only performed using a 0.1-s load duration.

Table 125. Data from the repeated load compression tests at the 200th cycle of loading.

| Asphalt Binder Grade | Permanent Strain, (mm/mm) | Total Strain (mm/mm) | Percent Permanent Strain |
|---|---|---|---|
| PG 59 AC-5 | 0.000016 | 0.00080 | 2.0 |
| PG 77 Novophalt | 0.0000022 | 0.00034 | 0.6 |

Table 126. Comparison of the total strains in the tests (mm/mm).

| Asphalt Binder Grade | Repeated Load DSR Test Using an Applied Stress of 500 Pa | ALF Pavement Test at 200th Wheel Pass | Repeated Load Compression Test at the 200th Cycle of Loading |
|---|---|---|---|
| PG 59 AC-5 | 1.64 | 0.00392 | 0.00080 |
| PG 77 Novophalt | 0.12 | 0.00162 | 0.00034 |

## 2. Comment

As expected, the average total strain and the average percent permanent strain are much higher greater for the DSR. The Superpave binder specification assumes that the ranking provided by the DSR for a set of asphalt binders does not change when the binders are added to a given aggregate gradation at the same volume. However, because of the large differences in the total strain and percent permanent strain, any interaction between the effects of the binders and the aggregate may lead to discrepancies in the rankings provided by binder, mixture, and pavement tests.

## APPENDIX E: MASTIC TESTS ON ALF MATERIALS


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**Subject: PRELIMINARY MASTIC TEST RESULTS ON ALF MATERIALS**

Superpave uses the parameter G*/sinδ to grade asphalt binders according to high-temperature rutting resistance. G*/sinδ is measured using a dynamic shear rheometer (DSR). Rutting resistance should increase with an increase in G*/sinδ. Pavements tested for rutting resistance by the Accelerated Loading Facility (ALF) provided a discrepancy for the two modified binders used in the pavements, namely Novophalt and Styrelf. Novophalt had a G*/sinδ that was significantly higher than for Styrelf at temperatures of 58, 70, and 76 °C, but the pavement with Novophalt had a significantly higher resistance to rutting at these temperatures. The following binder properties provided the same discrepancy: G*, δ, sinδ, tanδ, zero shear viscosity, absolute viscosity, δ using RTFO/PAV residues, cumulative permanent strain after four cycles of repeated loading, and the G*/sinδ's of binders recovered from pavement cores after failure. The use of DSR angular frequencies ranging from 2.0 to 100.0 rad/s was not beneficial. Thus, it was decided to test mastics.

The G*/sinδ's of eight mastics were measured using the DSR. The mastics consisted of the AC-10, AC-20, Novophalt, and Styrelf (PG 58-28, 64-22, 76-22, and 82-22) binders used in the ALF pavements and two fine-sized materials: (1) No. 10 diabase aggregate passing the 75-μm sieve, and (2) a blend of 82-percent No. 10 diabase aggregate with 18-percent hydrated lime. These two materials are defined as "fillers" in this memorandum. The second filler is more representative of the filler in the mixtures being tested by the ALF, whose composition is given in table 127. The pavement performances provided by the four binders, from least to most resistant to rutting, was AC-10, AC-20, Styrelf, and Novophalt. This was based on ALF pavement performance at 58 °C using a single aggregate gradation and a single binder content.

Testing mastics that duplicate the actual mastics in the pavements tested by the ALF would be difficult because there may be variations in the following parameters from location to location within a given lane and from lane to lane: (1) the volume of the mastic, (2) the volume concentrations of the aggregate and binder that constitute the mastic, and (3) the gradation of the aggregate within the mastic. Furthermore, mastics cannot be prepared in the laboratory using fillers extracted from cores because a high percentage of the aggregate particles passing the 75-$\mu$m sieve will agglomerate in the super-centrifuge used to recover this material. Therefore, the dispersion of the extracted aggregate particles in laboratory prepared mastics may not be the same as in the pavements. The standardized extraction procedures also use paper filters which trap a small portion of the aggregate.

Aggregate samples passing the 75-$\mu$m sieve obtained by washing fully graded laboratory-batched aggregate samples also agglomerate upon drying. Therefore, either the fraction passing the 75-$\mu$m sieve has to be removed by an air system, or the dust has to be obtained by dry sieving. Dry sieving often leaves a significant portion of the finest aggregate particles clinging to the larger aggregate sizes, which means that the gradation of the minus 75-$\mu$m material may not be correct.

The two fillers used in this study were chosen as follows. Samples of the No. 10 diabase aggregate passing the 75-$\mu$m sieve were removed from samples of the stockpiled No. 10 diabase aggregate by both wet and dry sieving. Figure 86 shows that the gradations were similar. Therefore, it was decided to obtain subsequent samples by dry sieving. Agglomerates obtained by wet sieving were dispersed by the Horiba™ particle size analyzer used to measure the gradations.

The gradations of the No. 68 ands No. 10 diabase aggregates passing the 75-$\mu$m sieve were slightly different. However, if the No. 68 diabase aggregate were to be included in the mastic, its effect on the overall gradation would be minor. It constituted only 9.9 percent of the total filler by mass. Both the No. 10 and No. 68 stockpiled aggregates were produced by the same aggregate crusher at the same quarry. Therefore, the No. 68 diabase aggregate was eliminated in order to reduce the amount of work involved in the experiment. The natural sand was not included because it was less than 5 percent of the filler. These materials can be included in future tests if necessary.

The concentration of the diabase filler in the mastic was 26.8 percent by volume, while the concentration of the diabase filler with hydrated lime was 27.8 percent. The volume concentrations were slightly different because the filler to asphalt blend was fixed based on mass and the specific gravities of the diabase material and hydrated lime were different. The filler to asphalt blend by mass was 5.1 kg to 4.85 kg. Note that table 127 shows a value of 5.531 kg passing the 75-$\mu$m sieve. The composition of the filler to be used in the laboratory tests had to be determined using the gradations and blend percentages of the stockpiled materials. The gradation provided by these stockpiles had 5.531-percent material passing the 75-$\mu$m sieve by mass. Extractions performed on pavement samples provided an average of 5.1-percent aggregate passing the 75-$\mu$m sieve. Therefore, the latter percentage was used when formulating the mastics.

Each binder and mastic was tested using a minimum of three replicates. Four replicates were used for the Novophalt and Styrelf mastics because of low repeatability. Tests on the mastics with Novophalt and Styrelf were also repeated using four new samples to check reproducibility. All tests were performed on unaged binders and mastics.

Tables 128 and 129 provides the G*/sinδ's and sinδ's of the binders and mastics at 58 °C and the standard DSR frequency of 10.0 rad/s. Ninety-five-percent confidence limits ($\pm 2\sigma_{(n-1)}$) are included. Tables 130 and 131 provide the data at 58 °C and the ALF associated frequency of 2.51 rad/s. Statistical analyses of the data using *t*-tests at a 95-percent confidence level provide the following conclusions:

- The mastic consisting of Novophalt and diabase had a lower G*/sinδ than the mastic consisting of Styrelf and diabase based on the first set of tests, but a higher G*/sinδ based on the second set of tests.

- Both the first and second set of tests show that the mastic consisting of Novophalt, diabase, and hydrated lime had a higher G*/sinδ than the mastic consisting of Styrelf, diabase, and hydrated lime. The ranking provided by the four mastics using diabase and hydrated lime matched ALF pavement rutting performance.

- The hydrated lime significantly increased G*/sinδ even though the additional filler by volume was only 1 percent (26.8 vs. 27.8 percent). The increase using Novophalt was extremely high. A reason for this needs to be determined.

- The second set of tests on the Novophalt mastics provided significantly higher G*/sinδ's compared with the first set of tests. Therefore, the G*/sinδ's of the Novophalt mastics were not reproducible.

- DSR frequencies of 10.0 and 2.51 rad/s provided the same conclusions.

- The sinδ's, which are the decimal percentage of the total strain that is permanent, were all relatively high. They ranged from 0.738 to 0.998. (Note: The inverse of the Superpave rutting parameter sinδ/G* is equal to the maximum shear strain from a constant applied maximum stress times the sine of the angle ($\sin\delta/G^* = \gamma_{max}\sin\delta$). Although sinδ is the decimal percentage of $\gamma_{max}$ that is permanent, $\gamma_{max}$ can vary from binder to binder.)

Table 127. Composition of the filler in the ALF pavements.

| Material | Decimal Fraction of Material Passing the 75-μm Sieve[1] | | Blend for Stockpiled Materials Per 100-kg Mass | | Composition of Minus 75-μm Material by Mass, kg | Composition of Minus 75-μm Material on a Percentage Basis |
|---|---|---|---|---|---|---|
| No. 68 Diabase | 0.009 | x | 61 | = | 0.549 | 9.9 |
| No. 10 Diabase | 0.125 | x | 30 | = | 3.750 | 67.8 |
| Natural Sand | 0.029 | x | 8 | = | 0.232 | 4.2 |
| Hydrated Lime | 1.000 | x | 1 | = | 1.000 | 18.1 |
| | | | 100 | | 5.531 | 100.0 |

[1]For example, if 1.0-percent material passed the 75-μm sieve, then the decimal fraction is 1.0 ÷ 100 = 0.01.

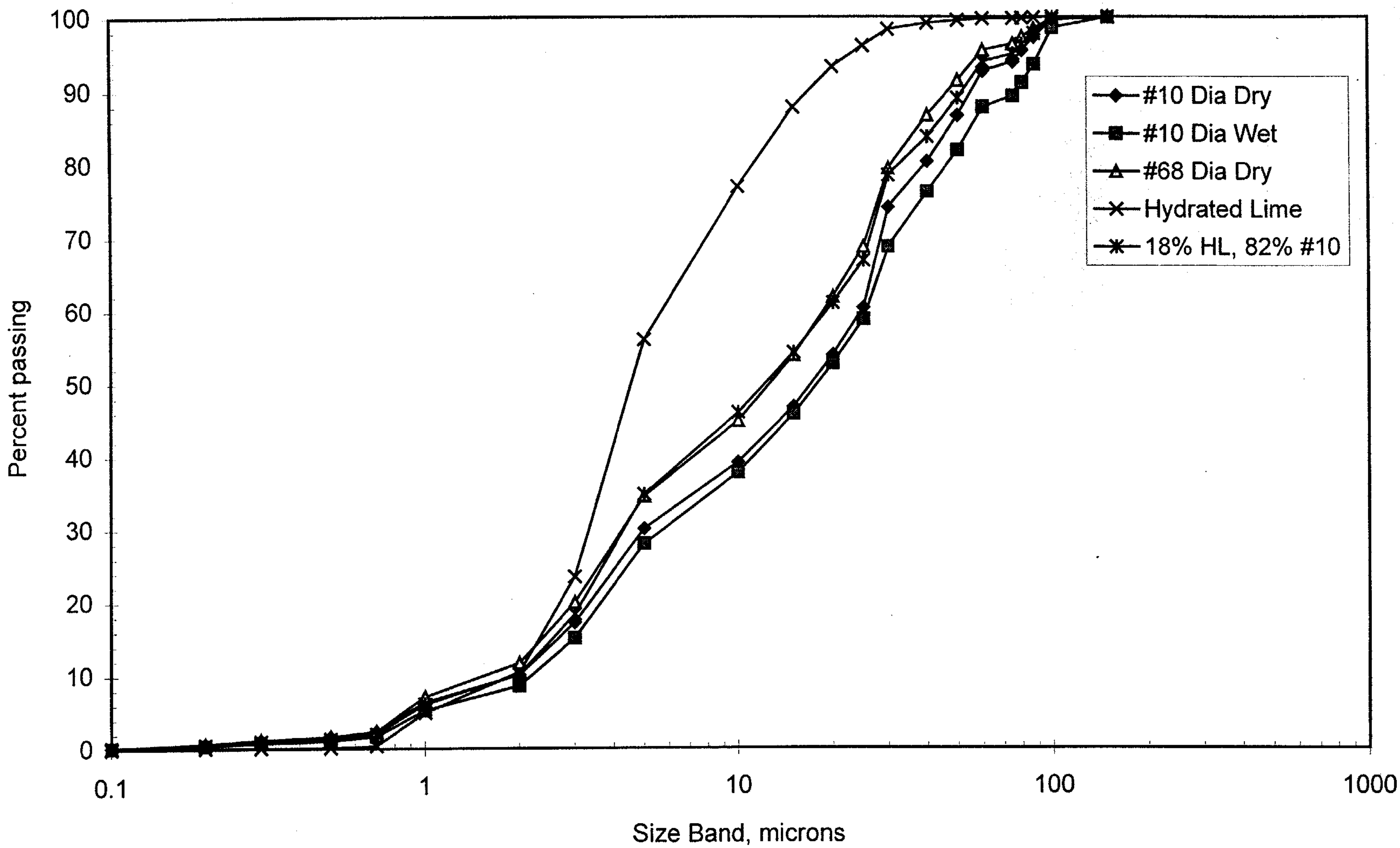


Figure 86. Gradations of the ALF aggregates and hydrated lime below 100 microns.

Table 128. G*/sinδ's of the unaged materials at 10.0 rad/s and 58 °C with 95-percent confidence limits ($\pm 2\sigma_{(n-1)}$).

| Asphalt Binder | Continuous High-Temp Performance Grade (PG) | Percent Filler by Volume | G*/sinδ at 10.0 rad/s and 58 °C (Pa) (First Test) | G*/sinδ at 10.0 rad/s and 58 °C (Pa) (Second Test) |
|---|---|---|---|---|
| Asphalt Binder Test Results | | | | |
| AC-10 | 65 | 0 | 2 030 ± 460 | |
| AC-20 | 70 | 0 | 4 780 ± 210 | |
| Styrelf | 88 | 0 | 17 450 ± 1 020 | |
| Novophalt | 77 | 0 | 13 870 ± 1 450 | |
| Asphalt Binder with Diabase Filler Test Results | | | | |
| AC-10 | 65 | 26.8 | 7 080 ± 540 | |
| AC-20 | 70 | 26.8 | 11 750 ± 570 | |
| Styrelf | 88 | 26.8 | 56 300 ± 7 100 | 53 800 ± 5 900 |
| Novophalt | 77 | 26.8 | 44 100 ± 2 800 | 62 300(1) ± 2 300 |
| Asphalt Binder with Diabase Filler and Hydrated Lime Test Results | | | | |
| AC-10 | 65 | 27.8 | 7 750 ± 345 | |
| AC-20 | 70 | 27.8 | 19 240 ± 3 670 | |
| Styrelf | 88 | 27.8 | 82 700 ±10 500 | 75 900 ±11 200 |
| Novophalt | 77 | 27.8 | 141 000 ±54 100 | 196 400(1) ± 9 900 |

(1)One outlier removed.

Table 129. Sine of the phase angle (sinδ) at 10.0 rad/s and 58 °C.

| Asphalt Binder | Continuous High-Temp Performance Grade (PG) | Percent Filler by Volume | Sinδ at 10.0 rad/s and 58 °C (First Test) | Sinδ at 10.0 rad/s and 58 °C (Second Test) |
|---|---|---|---|---|
| Asphalt Binder Test Results | | | | |
| AC-10 | 65 | 0 | 0.995 | |
| AC-20 | 70 | 0 | 0.990 | |
| Styrelf | 88 | 0 | 0.865 | 0.865 |
| Novophalt | 77 | 0 | 0.942 | 0.957 |
| Asphalt Binder with Diabase Filler Test Results | | | | |
| AC-10 | 65 | 26.8 | 0.993 | |
| AC-20 | 70 | 26.8 | 0.991 | |
| Styrelf | 88 | 26.8 | 0.854 | 0.852 |
| Novophalt | 77 | 26.8 | 0.930 | 0.847 |
| Asphalt Binder with Diabase Filler and Hydrated Lime Test Results | | | | |
| AC-10 | 65 | 27.8 | 0.994 | |
| AC-20 | 70 | 27.8 | 0.988 | |
| Styrelf | 88 | 27.8 | 0.838 | 0.841 |
| Novophalt | 77 | 27.8 | 0.872 | 0.790 |

Table 130. G*/sinδ's of the unaged materials at 2.51 rad/s and 58 °C with 95-percent confidence limits ($\pm 2\sigma_{(n-1)}$).

| Asphalt Binder | Continuous High-Temp Performance Grade (PG) | Percent Filler by Volume | G*/sinδ at 2.51 rad/s and 58 °C (Pa) (First Test) | G*/sinδ at 2.51 rad/s and 58 °C (Pa) (Second Test) |
|---|---|---|---|---|
| Asphalt Binder Test Results | | | | |
| AC-10 | 65 | 0 | 543 ± 126 | |
| AC-20 | 70 | 0 | 1 320 ± 60 | |
| Styrelf | 88 | 0 | 7 000 ± 430 | |
| Novophalt | 77 | 0 | 4 260 ± 30 | |
| Asphalt Binder with Diabase Filler Test Results | | | | |
| AC-10 | 65 | 26.8 | 1 940 ± 150 | |
| AC-20 | 70 | 26.8 | 3 250 ± 150 | |
| Styrelf | 88 | 26.8 | 23 300 ± 3 000 | 22 200 ± 2 500 |
| Novophalt | 77 | 26.8 | 16 400 ± 3 500 | 27 900[1] ± 3 500 |
| Asphalt Binder with Diabase Filler and Hydrated Lime Test Results | | | | |
| AC-10 | 65 | 27.8 | 2 110 ± 93 | |
| AC-20 | 70 | 27.8 | 5 390 ± 1 040 | |
| Styrelf | 88 | 27.8 | 34 900 ± 4 700 | 32 200 ± 4 900 |
| Novophalt | 77 | 27.8 | 60 500 ±36 800 | 104 200[1] ± 8 200 |

[1]One outlier removed.

Table 131. Sine of the phase angle (sinδ) at 2.51 rad/s and 58 °C.

| Asphalt Binder | Continuous High-Temp Performance Grade (PG) | Percent Filler by Volume | Sinδ at 2.51 rad/s and 58 °C (First Test) | Sinδ at 2.51 rad/s and 58 °C (Second Test) |
|---|---|---|---|---|
| Asphalt Binder Test Results | | | | |
| AC-10 | 65 | 0 | 0.998 | |
| AC-20 | 70 | 0 | 0.996 | |
| Styrelf | 88 | 0 | 0.866 | |
| Novophalt | 77 | 0 | 0.945 | |
| Asphalt Binder with Diabase Filler Test Results | | | | |
| AC-10 | 65 | 26.8 | 0.997 | |
| AC-20 | 70 | 26.8 | 0.996 | |
| Styrelf | 88 | 26.8 | 0.850 | 0.849 |
| Novophalt | 77 | 26.8 | 0.929 | 0.808 |
| Asphalt Binder with Diabase Filler and Hydrated Lime Test Results | | | | |
| AC-10 | 65 | 27.8 | 0.998 | |
| AC-20 | 70 | 27.8 | 0.995 | |
| Styrelf | 88 | 27.8 | 0.838 | 0.835 |
| Novophalt | 77 | 27.8 | 0.864 | 0.738 |