Technical Paper

ISSN 1997-1400 Int. J. Pavement Res. Technol. 6(5):576-581

Mechanical Properties of Filler-Asphalt Mastics

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Abstract: There has been an increasing awareness of the addition of ordinary Portland cement (OPC) rather than limestone filler into asphalt pavements in Taiwan. Filler interpaticle interaction and physicochemical interaction between cement filler particle and asphalt improved engineering properties of asphalt mixtures. Current Superpave parameters of G*/sinδ and G*sinδ were used to link the rheological properties of asphalt binders to the pavement performance of rutting and fatigue. However, the characteristics of asphalt binders were determined in the linear viscoelastic domain by performing frequency sweeps. The asphalt binder film might perform in the non-linear range due to the considerable difference between the stiffness modulus of aggregates and the modulus of binders. In addition, the filler-asphalt interaction might not be reflected by means of the Superpave parameters. Mechanical properties of stiffness, deformation and fatigue for filler-asphalt mastics may be more appropriate in terms of establishing a correlation with asphalt pavement performance. Oscillatory and creep tests using a dynamic shear rheometer (DSR) were performed to quantify the mechanical properties of cement and limestone filler-asphalt mastics at the same levels of filler contents by weight. The test results showed that the higher complex modulus and stiffening effect of the cement filler-asphalt mastics than those of the limestone filler-asphalt mastics within a linear viscoelastic domain. In terms of creep behavior, the addition of cement filler to base bitumen increases the viscosity at a steady state. The longer fatigue lives for the cement filler-asphalt mastics indicated the addition of active filler may provide a better pavement durability.

DOI:10.6135/ijprt.org.tw/2013.6(5).576

***Key words**: Fatigue; Mastic; Stiffness; Permanent deformation.*

Introduction

A change in asphalt strain is generally attributed to viscous flow as a function of the increase in temperature and loading time. Due to a considerable increase in traffic level, tyre pressure and heavier trucks, asphalt modification is a solution to overcome the distresses in flexible pavements. The aim of asphalt modifier is either to stiffen asphalt to reduce the total viscoelastic response of mixtures or to increase the elastic component of asphalt to reduce the viscous component. Various additives are used as asphalt modifiers such as mineral filler to form filler-asphalt mastic.

The mineral filler is defined as most of which passes the 0.063 mm sieve in accordance with BS EN 13043[1]. Many different types of fillers obtained by processing natural or manufactures or recycled materials can be used for asphalt pavements such as limestone, Portland cement, hydrated lime, sandstone, granite, fly ash etc. The voids of dry compaction are of importance for the behaviour of fillers. The volumetric proportion of filler including these voids was a main parameter for the rheological properties of bitumen-filler system [2]. Therefore, mechanical properties of asphalt pavements may be improved by the use of filler include strength, plasticity and resistance to moisture damage because of the filler surface area involved [3]. Harris and Stuart [4] indicated that a filler with high Rigden voids would result in a stiff mix that was difficult to lay-down and cause cracking, while a filler with low Rigden voids would not stiffen the mix enough and thereby cause asphalt drain-down after lay-down according to the performance of stone mastic asphalt (SMA). The influence of physical properties such as filler gradation, shape, surface texture and specific gravity on asphalt mixtures has been shown in literatures [4].

In addition to physical mechanism, the chemical mechanism of "active" mineral filler should be taken into account. Because of chemical compositions, filler might sever as an active material such as ordinary Portland cement. The activity can be manifested in the properties at the interface between the filler and the asphalt. Researchers [5-7] reported that active filler (hydrated lime) has a high relative concentration of reactive chemical functionality. The level of interaction between active filler particles and asphalt strongly affect high temperature rheology in certain compatible asphalt binders to a much higher degree than other inert fillers. The rheological results also showed that active filler (hydrated lime) had more considerable impact on the loss tangent (tan δ) of mastics than inert filler (limestone filler).

In addition, filler-asphalt mastics may not necessarily be characterized by empirical properties. Conventional specifications and tests only determine the characteristics of the asphalt binders at a particular temperature and a loading rate. It is essential to understand the stress-strain behavior of mastics over a wide range of temperature and loading time conditions. Fundamental tests using a dynamic shear rheometer (DSR) were introduced and developed to investigate rheological behavior of asphalt binders under different conditions [8, 9]. Although numerous studies have been conducted on the mechanical properties of stiffness, deformation and fatigue for asphalt binders using a DSR [10-12], little is known about the mechanical behavior of mastics. Thus, the objectives in this study are concerned with three areas: (1) to determine the stiffness modulus of the filler-asphalt mastics, (2) to analyze the viscosity of the filler-asphalt mastics at a steady state, and (3) to investigate the

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Note: Submitted January 23, 2013; Revised May 16, 2013; Accepted May 17, 2013.

fatigue behavior of the filler-asphalt mastics.

Materials and Testing Program

Materials

A combination of one straight-run penetration grade asphalt, two filler types and two filler concentrations of 35% and 65% by mass was selected to assess the filler effect on mechanical properties of filler-asphalt mastics. The 40/60 penetration grade asphalt originated from a Venezuelan crude was selected as a base material with a softening point of 50.2℃ to mix with mineral fillers in this test program. Two types of mineral fillers of limestone and ordinary Portland cement were added to the base asphalt. It is noted that the mineral fillers used in this study mostly pass the 0.063mm sieve. Limestone filler has shown to have little chemical reaction with asphalt [13-15], and therefore is considered to be relatively inert materials. Ordinary Portland cement is made primarily from limestone, clay and gypsum in a high temperature process. As water is present in the interface between asphalt and cement filler, carbon hydroxide is produced and thus cement filler chemically reacts with asphalt. Therefore, cement filler is considered to be an active filler. Rigden voids of 24.9 and 28.4% for the limestone and cement fillers were determined by dry compaction test in accordance with BS EN 1097-4 [16]. Thus, the four filler-asphalt mastics were labelled as 35LFAM (35% limestone filler-asphalt mastic), 35CFAM (35% cement filler-asphalt mastic), 65LFAM (65% limestone filler-asphalt mastic) and 65CFAM (65% cement filler-asphalt mastic)

In a filler-asphalt system with a filler volumetric concentration, the effective volume of filler consists of solid filler particles covered with asphalt. Therefore, the effective volume percentages of fillers in the mastics were calculated on the basis of Rigden voids, filler specific gravities and filler compositional concentration. The filler effective volume percentages are 22.2, 20.6, 54.4 and 52.1% for the 35LFAM, 35CFAM, 65LFAM and 65CFAM in this study.

Test Program

Frequency Sweep Test

The general principle of the dynamic oscillatory shear load test is to determine the dynamic rheological properties of asphalt mastic in a wide range of frequencies and temperatures using a DSR with a parallel plate test geometry. A hockey puck-shaped specimen is squeezed between two parallel plates. The specimen is subjected to a sinusoidal angular displacement of constant angular frequency during the test within the linear viscoelastic domain.

The frequency sweep testing was performed on the base asphalt and mastics under strain controlled conditions at temperatures between 5 and 85℃, and twenty frequencies between 0.1 and 20 Hz. The geometrics with gaps at test temperatures were utilized with 25-mm-diameter parallel plates with a 1-mm gap above 45℃ and 8-mm-diameter parallel plates with a 2-mm gap below 45℃. It is aware that the DSR gap width should be at least ten times bigger than the filler particle size. The stiffness characteristics of the filler-asphalt mastic were interpreted in the form of shifted master curves at a reference temperature of 25℃ based on time-temperature superposition principle (TTSP). In constructing a master curve using time-temperature superposition, dynamic data which consist of a series of curves for the test conducted at each temperature were first obtained over a range of frequencies and temperatures. The data are combined into a single master curve by shifting horizontally individual curves along the frequency axis to form a curve at a single reference temperature, as shown in Fig. 1.

Creep Test

Creep testing using a DSR was undertaken to determine the shear deformation behavior on the filler-asphalt mastics with increasing time of loading at a selected temperature of 60℃. The 25-mm diameter parallel plates with 1-mm gap was used to test samples. A constant shear stress was applied to an asphalt specimen for a long

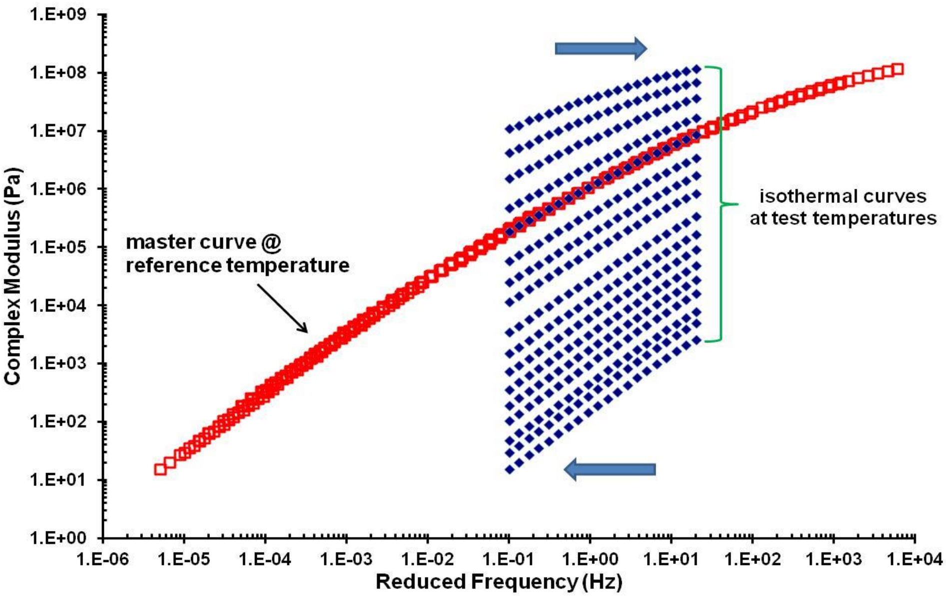

Fig. 1. Construction of Master Curve for Asphalt Binder at Reference Temperature.

time period. Under low shear stress levels between 300 and 1000 Pa, the effect of delayed elasticity decreased with time. The deformation behavior of the mastics was dominated by viscous flow after a sufficient long time to achieve a steady state. The viscosity determined in the form of steady state viscosity (SSV) was independent of shear strain rate. The SSV reflected dissipated motions in an equilibrium structure and it was suggested as a more appropriate rutting parameter [17, 18].

Fig. 2 shows that a typical creep test curve for an asphalt sample is divided into three regions. In the steady state creep region, the shear strain rate remains approximately constant with time and the asphalt behavior is dominated by viscous effect. As the shear strain is proportional to the loading time, the viscosity of the asphalt is independent of shear strain rate. The viscosity was calculated as a limiting viscosity value called SSV (steady state viscosity) in steady state creep region. The equation is shown as follows:

$$\mathrm{SSV} = \left[\frac{\mathrm{dJ_c}}{\mathrm{dt_c}}\right]^{-1} = \left[\frac{\mathrm{d}(\gamma/\tau)}{\mathrm{dt_c}}\right]^{-1} \tag{1}$$

where SSV is the steady state viscosity (Pa.s), Jc is the creep compliance (1/Pa), γ is the shear strain, τ is the shear stress (Pa) and tc is the creep loading time (sec).

Time Sweep Testing

Direct testing of filler-asphalt mastics in durability was employed to generate fatigue characteristics by means of time sweeps using a DSR. The measurements of complex modulus (G*) were obtained by performing a time sweep testing at different strain levels at 20℃ and with a loading frequency of 10 Hz. The failure criterion is defined as 50% reduction in initial G* for the tests, as shown in Fig. 3. This phenomenological approach (50% reduction in initial stiffness) has been traditionally used for the fatigue failure definition of asphalt binders and mixtures. In the controlled strain mode of testing, the specimen has a relatively longer crack propagation period because the strain is held constant and the resulting stress gradually decreases until the specimen is damaged. Fatigue results are presented with the data plotted against shear stress level. The straight fatigue lines for bituminous materials was used to represent the fatigue data generated by means of the following equation:

$$N_f = a\sigma_0^{-b} \tag{2}$$

where N_f was the fatigue life; σ_0 was the initial stress; and a and b were experimentally determined coefficients.

Results and Discussion

Stiffness Modulus

A frequency sweep covering the range of 0.1 to 20 Hz was obtained at each test temperature. In order to facilitate the analysis of the rheological results, the data are combined into a single master curve for each material using time-temperature superposition. The master curves of G* at a reference temperature of 25℃ for the base asphalt and the four filler-asphalt mastics are shown in Fig. 4. The smooth and continuous G* master curves are shown because of the base asphalt and mastics exhibiting simple rheological behavior.

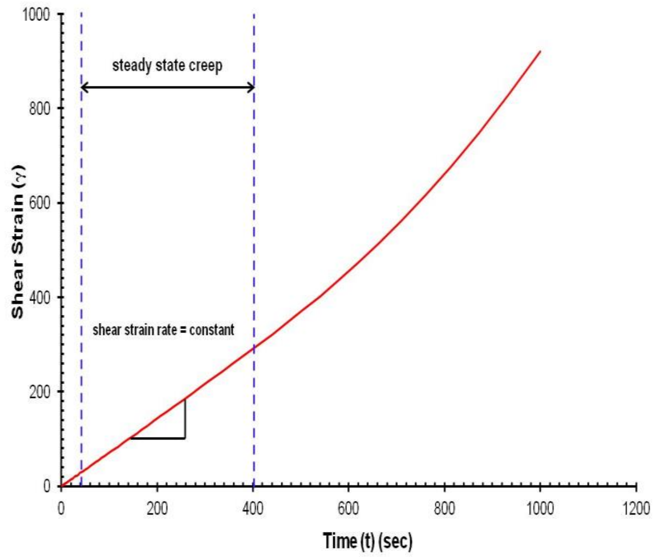

Fig. 2. Steady State Creep for Asphalt Binder.

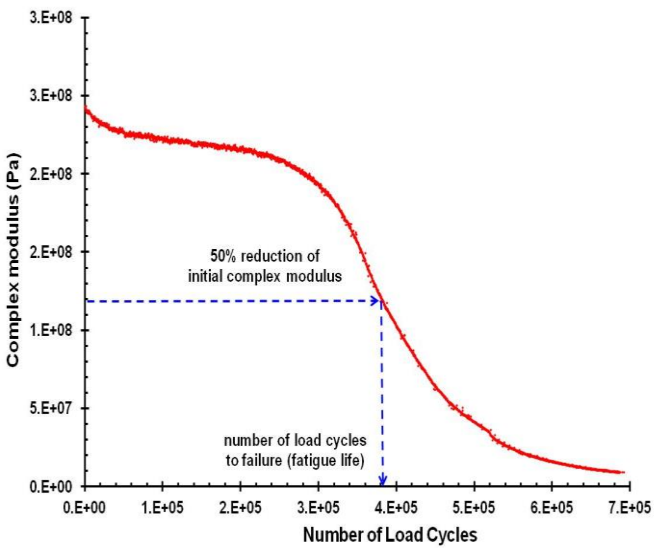

Fig. 3. Definition of Fatigue Criterion for Asphalt Binder.

The cement and limestone mineral fillers shifts up the master curves of the mastics vertically. The addition of the filler has an effect on the overall complex modulus at all test temperatures due to the stiffening effect of mineral filler. The filler-asphalt mastics with 65% filler content has the highest G*, followed by the 35% filler-asphalt mastic and 40/60 pen asphalt.

The relative increases in Superpave rutting parameter G*/sinδ at 60℃ and 1.6 Hz compared with the base asphalt are include as ratios in order to evaluate the stiffening effect of filler. Fig. 5 shows that there is a slight increase in G*/sinδ for the 35LFAM and 35CFAM compared to the base asphalt, while there is significant increase in G*/sinδ for the 65LFAM and 65CFAM. Although the limestone and cement fillers are additive added in the base asphalt, the stiffening ratios for the mastics are not directly proportional to filler content. The sharp increase in G*/sinδ is caused by the filler contributing such a large volume to the binder that it becomes the predominant component in the mastic and therefore has a dramatic effect on stiffness. A considerably higher complex modulus for the 65LFAM and 65CFAM might be caused by the filler-filler particle interaction being present in the filler-asphalt system.

In addition to effect of filler concentration on stiffness, effect of filler type is marginal on stiffness for the 35% and 65% filler-asphalt mastics although the G*/sinδ for the cement filler-asphalt mastic is somewhat higher than that for the limestone filler-asphalt mastics. There exists a interaction between cement filler and base asphalt, thereby increasing the rutting parameter. In terms of G*/sinδ data, the stiffening ratio (9.1) for 65CFAM is around 1.3 times higher than that (7.1) for 65LFAM on the basis of the effective volume of 50%.

Special attention should be paid that the effective volume for the cement bitumen-filler mastic is smaller than that for the limestone bitumen-filler mastic. The cement filler-asphalts mastics have the higher effective volumes of 20.6 and 52.1% compared to the cement filler-asphalt mastics with the effective volumes of 22.2 and 54.4%. This is surely due to the fact that there exists a filler-asphalt interaction in the cement filler-asphalt mastics although the limestone filler contributes the larger effective volume to the binder compared to the cement fillers. As indicated in Fig. 4, the master curves clearly show the complex modulus values for the cement filler-asphalt mastics are slightly higher than those for the limestone filler-asphalt mastic, particularly as the filler concentration is up to 65% by mass. The cement filler-asphalt system is controlled not only by a mechanical filling effect of filler phase but also a physicochemical reinforcement.

Permanent Deformation Behavior

Superpave rutting parameter, G*/sinδ, have been used as a performance indicator for permanent deformation (Anderson et al., 1994). However, this parameter correlation is not particular good for specialist asphalt binders due to the inability of the Superpave parameter to account for the effect of delayed elasticity. As permanent deformation in an asphalt pavement is controlled by the asphalt binder's viscous flow and loading time, the viscosity at a steady state is a primary indicator of permanent deformation. As asphalt binders tend to show non-Newtonian behaviour at pavement service temperatures, the viscosity needs to be determined in the form of SSV, which is independent of shear stress and shear strain rate.

Fig. 6 shows the stiffening ratios in terms of steady state viscosity for the base asphalt and mastics. There is an indication that an increase in SSV is linear until a certain filler effective volume concentration, where the rate of increase becomes nonlinear and sharply reaches an asymptotic linear trend. The trend shows the effect of filler inter-particle interaction on the viscous property of the filler-asphalt mastics at higher filler concentration level (65% by mass). In addition, slight difference is obtained between G*/sinδ (shown in Fig. 5) and SSV stiffening ratios for the 35LFAM and 35CFAM, whereas there exists a considerable increase in SSV stiffening ratio for the 65LFAM and 65CFAM. In terms of SSV data, the stiffening ratio (32.6) for 65CFAM is approximately 2.3 times higher than that (13.9) for 65LFAM on the basis of the effective

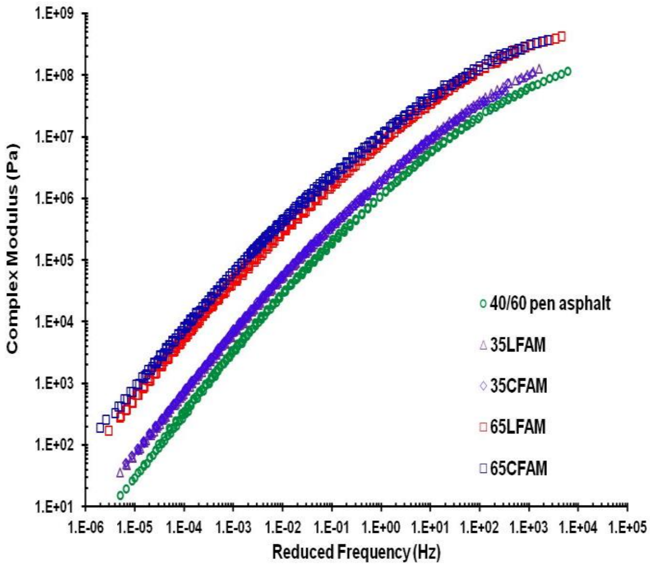

Fig. 4. G* Master Curves for Base Asphalt and Filler-asphalt Mastics.

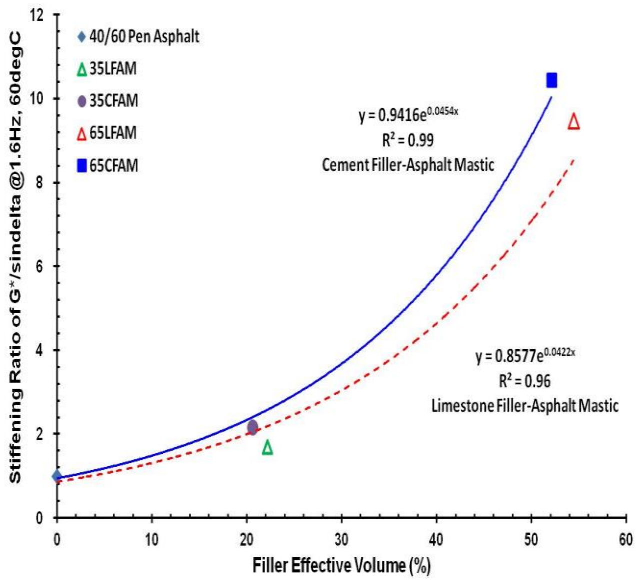

Fig. 5. Stiffening Effect of Fillers on G*/sinδ for Base Asphalt and Filler-asphalt Mastics.

volume of 50%. At high filler volume concentration level, the SSV ratio reflects not only the dominance of filler inter-particle interaction but also the physicochemical reinforcement between cement filler and asphalt, while the G*/sinδ ratio only shows the filler particle interaction.

Fatigue Property

Attempts have been made to include a binder parameter in asphalt mixture fatigue prediction with the Superpave fatigue criterion, G*sinδ, determined in the linear viscoelastic region by means of frequency sweeps. Fig. 7 shows the stiffening ratios in terms of G*sinδ at 20℃ and 10 Hz for the base asphalt and filler-asphalt mastics. Little difference in G*sinδ is shown between the 35LFAM

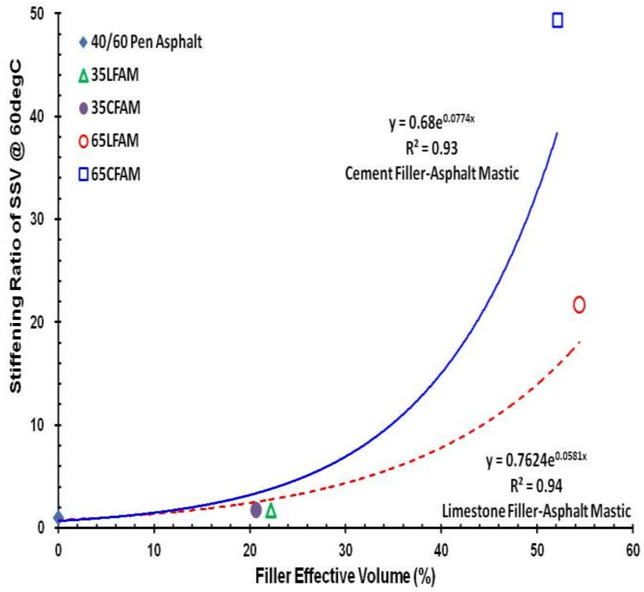

Fig. 6. Stiffening Effect of Fillers on SSV for Bbase Asphalt and Filler-asphalt Mastics.

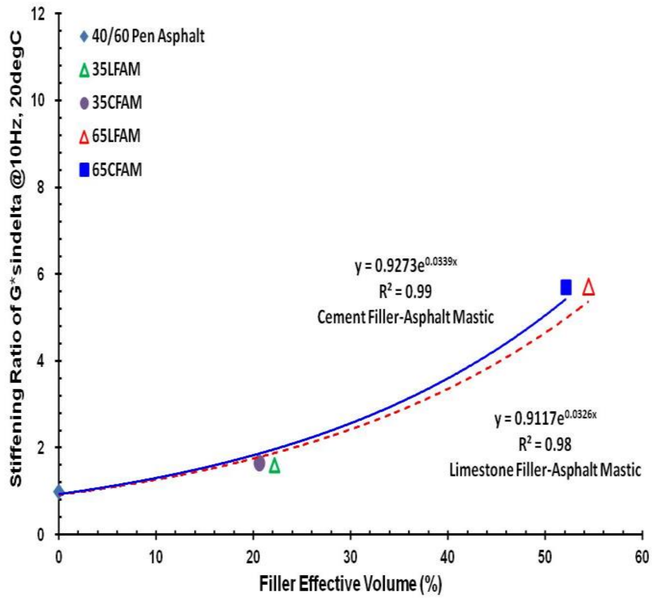

Fig. 7. Stiffening Effect of Fillers on G*sinδ for Base Asphalt and Filler-asphalt Mmastics.

and 35CFAM. On the basis of the effective volume of 50%, the 65LFAM and 65CFAM have similar stiffening ratios of 4.7 and 5.0, respectively. The G*sinδ stiffening ratio for 65CFAM is only 1.1 times higher than that for 65LFAM.

In attempt to make the comparisons with the influence of filler type on fatigue relationships based on the time sweep data, the fatigue lines of the cement and limestone filler mastics have been plotted against shear stress in Fig. 8. The fitted lines of power law fatigue indicate that the fatigue lives for the cement filler-asphalt mastics are slightly longer compared to those for the limestone filler-asphalt mastics. It appears that the filler concentration by mass is important rather than the actual filler type. 35% mastics generate steeper fatigue lines compared to 65% mastics. Much flatter fatigue lines are obtained from the 65LFAM and 65CFAM . This indicates that the 65% mastics is more sensitive to shear stress developed inside the specimen as shown in Fig. 7.

The values of shear stress after one million load cycles of testing are determined using the fatigue equation as reported above. 65CFAM has a highest value of 466 kPa, followed by the 65LFAM (454 kPa), 35CFAM (152 kPa), 35LFAM (151 kPa) and 40/60 pen asphalt (114 kPa). The inclusion of the filler particles into the base asphalt as solid bodies forces the strain to occur around the solid particles, which enables the mastic to take higher stress as the crack surface area necessarily increases.

It is noted that the filler effective volume percentages of the 35CFAM (20.6%) and 65CFAM (52.1%) are lower compared to those of the 35LFAM (22.2%) and 65CFAM (54.4%) on the basis of the 65% filler concentration by mass. Results confirm the extended fatigue life obtained by the addition of cement filler as the filler effective volume concentrations are at the same level. The

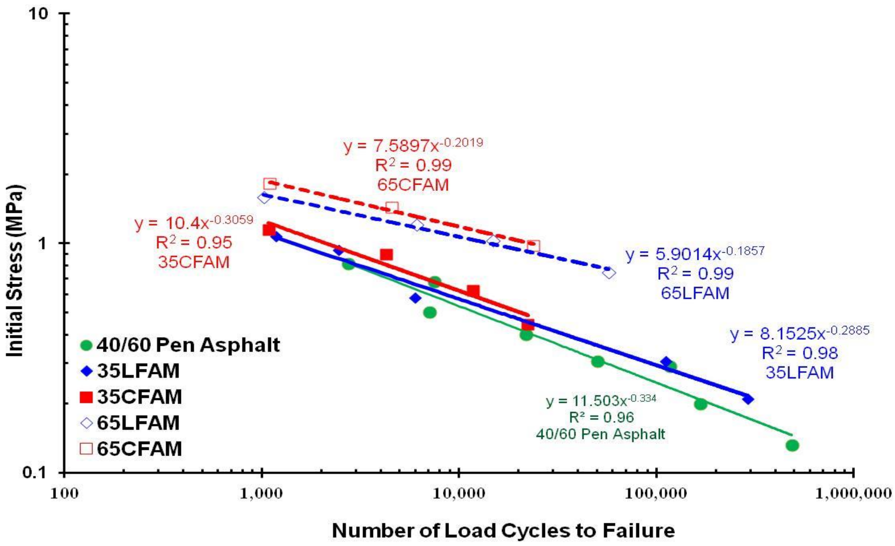

Fig. 8. Effect of Filler Type and Content on Fatigue for Filler-asphalt Mastics.

physicochemical reinforcement between cement filler particles and asphalt should improve the fatigue property of the mastic.

Conclusion

In this investigation, the DSR oscillatory and creep tests were used to determine the mechanical properties of a range of filler-asphalt mastics at pavement service temperatures. It should be noted that the findings drawn in this paper are only applicable to the 40/60 penetration grade bitumen and the specific mineral fillers tested in this study. The following conclusions can be made from the data presented in the paper:

- In terms of G*/sinδ data, the stiffening ratio (9.1) for 65CFAM is around 1.3 times higher than that (7.1) for 65LFAM on the basis of the effective volume of 50%. The cement filler-asphalt system is controlled not only by a mechanical filling effect of filler phase but also a physicochemical reinforcement.
- In terms of SSV data, the stiffening ratio (32.6) for 65CFAM is approximately 2.3 times higher than that (13.9) for 65LFAM on the basis of the effective volume of 50%. At high filler volume concentration level, the SSV ratio reflects not only the dominance of filler interparticle interaction but also the physicochemical reinforcement between cement filler and asphalt, while the G*/sinδ only show the filler particle interaction.
- The G*sinδ stiffening ratio for 65CFAM is only 1.1 times higher than that for 65LFAM. Time sweep results confirms the extended fatigue life obtained by the addition of cement filler as the filler effective volume concentrations are at the same level. The physicochemical reinforcement between cement filler particles and asphalt should improve the fatigue property of the mastic.

Acknowledgment

The authors gratefully acknowledge the support for this research from Nottingham Transportation Engineering Centre.

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