method to determine the initiation of tertiary flow. Stepwise increase means gradually increase (increase step by step) in mathematical term. This approach utilizes the traditional method (minimum point of strain rate versus cycle number) and emphasizes the smoothing technique used to determine the flow number. Three easy steps and an assumption were applied in this method. The brief algorithm to identify the flow number is shown below:

Step 1: Smoothing the measured permanent deformation by re-allocating the measured results.

Step 2: Calculate the strain rate using the modified permanent deformation result.

Step 3: Determine the flow number by locating the minimum point of strain rate versus load cycle curve. It is notable that there is no flow number if the minimum point of strain rate versus load cycle curve is equal to maximum cycle number.

This method assumed the permanent strain will only same or increase over the load cycle number. In order to ensure the continuous increase in strain over load cycle number, the Stepwise method was used in Step 1. Figure 5 shows the direct measured result from the Universal Testing Machine. The non-uniform discontinuity data points that lead to the subjective analysis and miscalculation of the flow number are highlighted in Figure 5 as well.

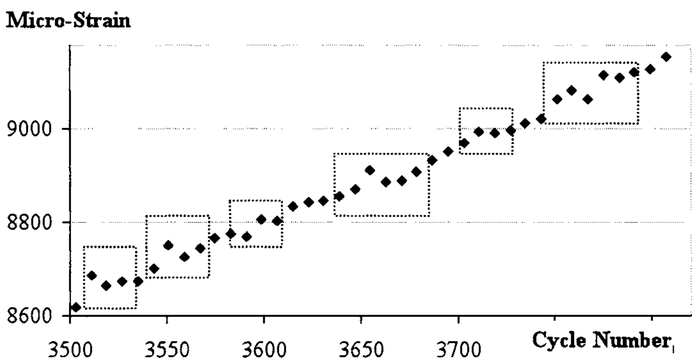

FIG. 5. Measured Permanent Deformations versus Cycle Number.

As mention previously, the proposed method emphasizes the smoothing technique and re-allocation method. Figure 6 shows the Stepwise method used in this approach. This method shifted the discontinuity data points forward along the x-axis (cycle number) by not changing the strain level to give a step wise increasing trend. For example in Figure 6, plot 3 will shift forward to replace plot 6, and plot 4, 5 and 6 will shift backward to replace plot 3; plot 8 will shift forward to replace plot 10, and plot 9 and 10 will shift backward to replace plot 8. The entire non-uniform discontinuity data point can be easily shifted using the excel function called "Sort Ascending." Figure 7 shows the shifted data point using the Stepwise method proposed. For step 2 and step 3, a traditional method used to find out the flow number was applied. Step 2 is to find out the strain rate using modified data set (data set modified in step 1). The strain rate was calculated by dividing the permanent strain by loading cycle number. Finally for step 3, the flow number can be found by locating the minimum point from the curve of strain rate versus cycle number.

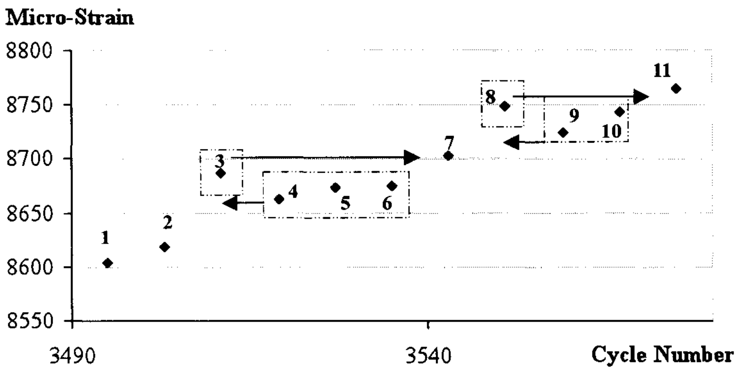

FIG. 6. Reallocation of the Deceptive Plots.

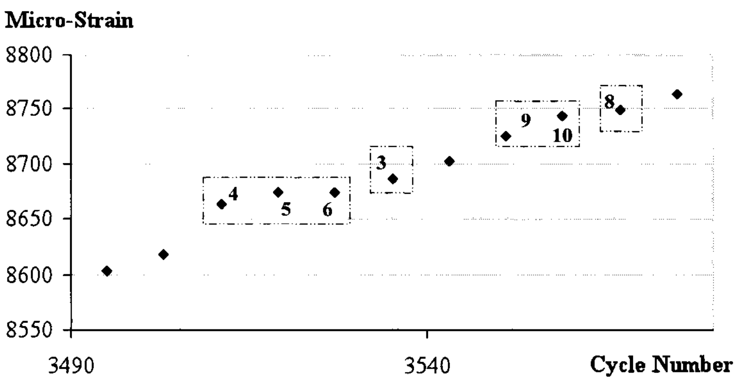

FIG. 7. Modified Permanent Deformation versus Load Cycle.

In order to verify the applicability of the proposed approach, the proposed Stepwise method was compared with Three-Stage Deformation (Zhou et. al 2004) and Williams' method (2007). A total of 62 flow number data were compared. Figure 8 and Figure 9 show the comparison result of Stepwise method with Three-stage Deformations and Williams' methods, respectively. An R-square value of 0.97 and 0.992 were found from the comparison and this indicated that the proposed Stepwise method has shown a good correlation with these two methods.

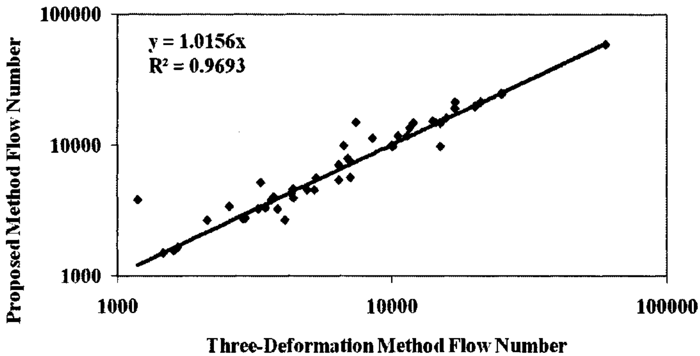

FIG. 8. Comparison of Stepwise and Three-Stage Deformation Method.

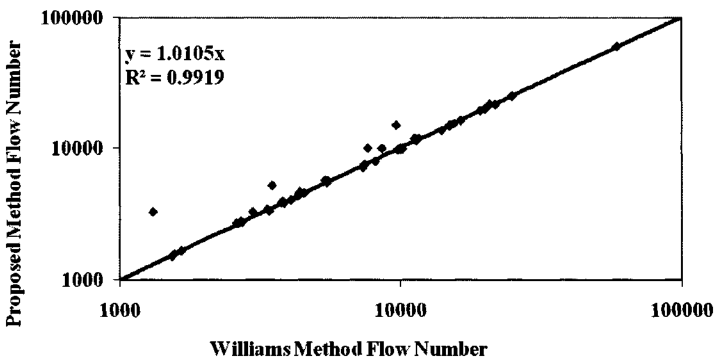

FIG. 9. Comparison of Stepwise and Williams' Method.

Even though the flow number can be well defined by all the methods mention previously (i.e. Three-stage Deformations and Williams' methods), the proposed Stepwise method was found to be more practical and easier to compute. The comparison using different approaches is ongoing to verify its consistency and applicability.

SUMMARY

This paper presents a new approach to determine the flow number of asphalt mixtures during dynamic creep test. The proposed approach provides a practical and consistent method to determine the initiation of tertiary flow. Stepwise method was used as smoothing technique in this approach to give stepwise increasing trend. In addition, the entire non-uniform discontinuity data point can be easily shifted using the excel function called "Sort Ascending." The flow number was defined at the minimum point of strain rate versus load cycle number using the new modified data point. In order to verify the applicability of the proposed approach, this method was also compared with Three-Stage Deformation (Zhou et al. 2004) and Williams' methods (Bausano and Williams 2007). The R-square value of 0.97 and 0.992 respectively were found from the comparison and this indicated that these methods have showed a good correlation with the proposed Stepwise method. In addition, the proposed Stepwise method was found to be more practical and easier to compute.

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Effects of Aggregate Gradation and Asphalt Binder on the Visco-elastic Behavior of Asphalt Matrix

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ABSTRACT: Asphalt matrix (AM) properties have been used for many years to relate the behavior and performance of Hot Mix Asphalt (HMA) mixture. The AM is commonly defined as the combination of asphalt binder and fine aggregates. Understanding the mechanics and rheological characteristics of AM can facilitate better mixture design, and provide an insight into the visco-elastic behavior of HMA mixtures. In this study, the effects of aggregate gradation and asphalt binders on the visco-elastic response of AM were studied. Two fine aggregate gradations and two asphalt types were used to make AM samples. Dynamic mechanical analyses were conducted to investigate the creep response and effect of rate of loading at various temperatures. The dynamic shear modulus (G*) and shear creep compliance (J[t]) were obtained over a range of temperatures to construct master curves at 25°C. The master curves for G* and J[t] were modeled using Sigmoidal function, and generalized visco-elastic model, respectively. The analysis of master curves and models showed that the finer gradation exhibited a lower G*, and higher J[t], for the neat binders. In general, the modified binders and coarser gradation produced a stiffer material for a range of frequencies, but the J[t] showed some variations in the AM creep response. In addition, rutting susceptibility of AM was evaluated using the Superpave® rutting parameter.

INTRODUCTION

Hot Mix Asphalt (HMA) is a composite of graded aggregates and an asphalt matrix (AM), which is a combination of asphalt binder (AC) and fine aggregate passing No. 4 sieve. The AM is visco-elastic due to its time dependant response (Khattak et. al 2008). Understanding the mechanics and rheological characteristics of AM can facilitate better mixture design, and provide good insight into visco-elastic behavior of HMA mixtures. Little et al. (2004) studied the suitability of different micromechanically and rheologically based models to characterize the dynamic behavior of asphalt mastics (AC plus fines passing #200 Sieve). It was found that micromechanical models showed good agreement with testing data at low particle volume concentrations. The rheological model was successful in predicting the stiffening effect of limestone filler when added up to 25% by volume.

Khattak et al. (2008) studied the visco-elastic characteristics of moisture damaged AM mixtures. The results indicated that the generalized creep compliance mechanical model can effectively characterize the visco-elastic response of the AM mixtures, under both wet and dry conditions. The AM tests results clearly demonstrated that lime modification significantly improves the visco-elastic properties of moisture damaged AM. Understanding the AM, and its behavior, can allow researchers to relate its characteristics to the HMA mixtures. Studies have been conducted on the micromechanics of AM over several years through discrete element method. You and Buttlar (2004) practiced the use of AM mechanistic characteristics to relate its properties to its respective HMA. The AM was related by micromechanical properties through discrete element modeling. The micromechanical modeling of AM gave prediction tools based on the volumetric concentration.

In general, the visco-elastic characteristics and failure mechanisms of HMA are functions of: a) the asphalt binder's chemical, physical, rheological and adhesion properties, b) the type and distribution of the additive in the asphalt binder, and c) the coarse and fine aggregate gradation, type, and angularity, which govern the void size and distribution. This research study focuses on the effect of gradation and binder type on the visco-elastic behavior of AM.

LABORATORY TESTING

Test Materials and Sample Preparation

AM samples were constructed using limestone aggregate and asphalt binders obtained from a local contractor. Two asphalt types, neat asphalt AC30 (PG64-22), and the modified binder PAC40 (PG76-22), were used. The two aggregate gradations were extracted from the HMA gradations, and are shown in Table 1. The asphalt content used for both gradations was 22%. The mixing and compaction temperatures were the same as that of HMA.

Table 1. Gradations Data for AM Mixtures

US	Sieve Size	No. 16	No. 30	No. 50	No. 100	No. 200
Metric	mm	1.18	0.6	0.3	0.15	0.075
Gradation-1	% Passing	100	73	40	27	20
Gradation-2		100	57	34	23	17

Two types of AM samples were prepared for testing. At temperatures of 34°C and below, the sample was 10 mm in height and 16 mm in diameter. It was found that at higher temperatures (above 34°C), the taller samples were not stable, and became damaged during the testing. Consequently, the sample sizes were reduced to 6 mm in height and 22 mm in diameter. Efforts were made to make the sample homogeneous and consistent. However, there were still some variations in the results of the triplicate AM samples.

Dynamic Mechanical Testing

Bohlin's Dynamic Shear Rheometer (DSR) was used to conduct frequency sweep and creep compliance tests. All testing was conducted on triplicate samples of AM at 10, 20, 25, 34, 46, 58 and 64°C.

Frequency Sweep Test

The frequency sweep test was conducted to determine the G* of AM. The test was conducted at a range of frequency levels from 1 Hz to 60 Hz at logarithmic increments in a controlled stress condition. Prior to testing, a stress sweep was applied at each temperature to determine the visco-elastic range of stress. The visco-elasticity holds if the decrease in G* of the AM was within 10% (Khattak et al. 2008). Once the minimum and maximum stress levels were established, the actual samples were tested at 90% of maximum stress level. The samples were also conditioned for 100 cycles at 10Hz, at half the actual stress used for testing.

Shear Creep Compliance Test

A creep test was conducted to determine the shear creep compliance (J[t]) of the AM mixtures. A constant shear stress was applied on a sample for 5 minutes, and then the sample was allowed to recover for 10 minutes. Using the visco-elastic stress range the creep compliance test was performed at the maximum stress level. The sample conditioning was done similarly to the frequency sweep test.

RESULTS AND ANAYLSIS

Frequency Sweep

The G* values obtained at each temperature were plotted and shifted to a reference temperature to generate a master curve at 25°C. A typical master curve of G* of AM mixtures for a range of reduced frequencies along with the shift factor is shown in Fig. 1. The AM clearly displays the visco-elastic behavior at higher temperature with G* values representing lower frequencies, and at lower temperatures resulting in higher frequencies and more elastic response.

As reported earlier, it was not easy to mix and compact a homogenous samples of AM. This resulted in variations of G* values within the triplicate samples of AM tested at various temperatures. It was found that the variations in test results were a function of test temperatures and frequency. On average, the coefficient of variation (CV) ranged between 5 and 25 % at temperatures equal, or less than, 25°C, and frequency ranges of 10 to 60 Hz. On the other hand, the CV values were between 5 and 50% at temperatures higher than 34°C, and frequency of less than 10 Hz. The higher variations were more concentrated at temperatures of 58 and 64°C. Nevertheless, the average values of G* were calculated for the triplicate samples, and master curves were generated for all types of AM mixtures as shown in Fig. 2. The data in the Fig. 2 indicates that the modified binders and coarser gradation-2 produced higher G* values

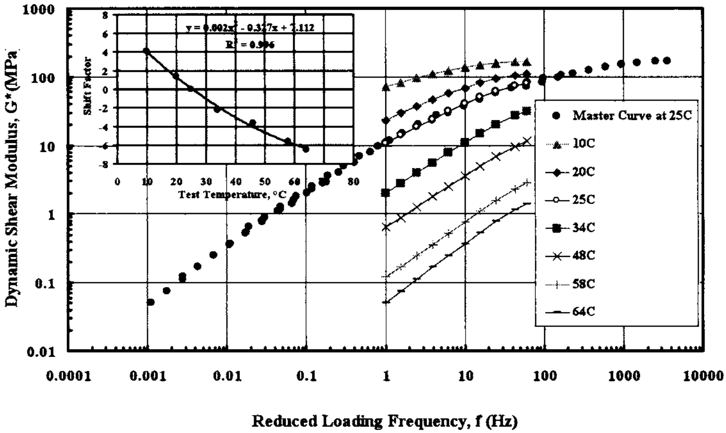

FIG. 1. Typical G* master curve at 25°C and shift factor for AM mixtures.

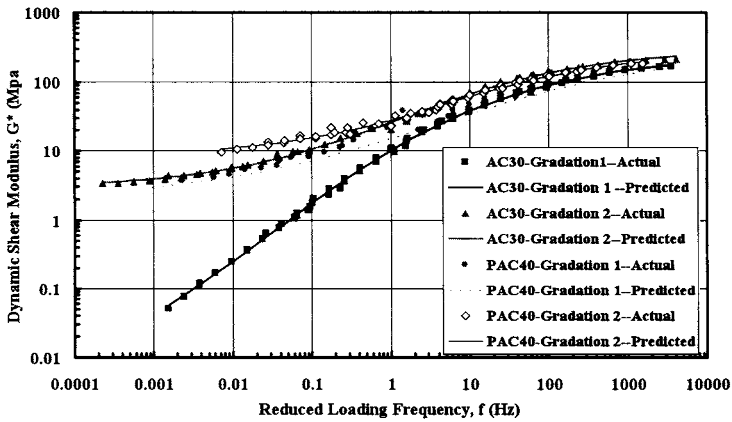

FIG. 2. G* master curves and Sigmoidal models for the four AM mixtures.

than the neat asphalt and finer gradation-1. A comparison was done between the asphalt binders and gradation at 0.01, 10, and 100 Hz. For gradation-1, the G* value of PAC40-AM mixture was 94 times higher than that of AC30-AM at 0.01 Hz. The differences in G* were drastically reduced at the higher frequency to 1.34 and 0.85 times greater, for 10 and 100 Hz, respectively. On the other hand, the differences in the gradation-2 were not as high as gradation-1 between the two types of binders. The PAC40 AM exhibited 2.74, 1.13, and 0.82 times greater G* than the neat binder at the three frequency levels. The effect of gradation was most deviated in the neat binder where the coarser gradation-2 showed about 76 times higher G* value than the finer gradation-1 at the low frequency of 0.01 Hz. This trend decreased at higher frequencies