Asphalt mixture performance and testing

Design and Performance Evaluation of Highly-modified Asphalt Concrete

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Abstract

The use of porous asphalt as surface course is a solution to help address the built environmental issues of both heat island and stormwater management in tropical countries. However, another form of moisture damage has been noted. Water enters the porous pavement and can become trapped between two layers. The asphalt pavements would fail as a consequence of traffic loading creating high hydraulic pressure gradients and movement of trapped water. A suitable binder course material is the highly-modified asphalt mixture conforming to the Taiwanese specification. The highly-modified asphalt concrete is being developed and is designed in terms of the pavement performance-related requirements. The objective of this study is to investigate the rheological properties of the polymer modified and conventional petroleum asphalt binders, and to assess the performance characteristics of the corresponding asphalt mixtures. The laboratory results show that the highly-modified bitumen (HMB) was less susceptible to temperature due to the highly polymeric modification effect in terms of the G* master curve. The HMB also possessed better delayed elastic response and had better rutting characteristic based on the MSCR test results. The performance-related characteristics of the asphalt mixtures could be well interpreted by means of the DSR master curves of the bituminous binders over a wide range of the temperatures. With regard to the wheel track testing, the highly-modified asphalt mixture with gap gradation generally had better resistance to rutting compared to the other asphalt concrete types based on the rut depth and mixture viscosity. In addition, the Burgers model was used to fit the rutting data and satisfactorily explained the durability of the asphalt mixtures. The asphalt mixture containing steel slag appeared to have better long-term rutting resistance in terms of the prediction obtained from the model.

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1. INTRODUCTION

With the long life asphalt pavements, the major pavement distresses can be confined within the asphalt surface layer. Thus, thin asphalt overlays used in mill-fill operations is one of the effective strategies for asphalt pavement rehabilitation. However, due to a dramatic growth of traffic intensities and higher axle loads than in the past, the premature failure of asphalt pavement rutting can be found on the newly rehabilitated thin surface layer in heavily trafficked areas [1-6]. Although the highway agency in Taiwan had adopted the maximum rutting depth of 12.5 mm as a threshold after the numbers of repetitive loads of 12,500 cycles on the basis of the wheel track testing results, limit studies have been conducted for evaluating the long-term permanent deformation properties of the asphalt mixtures.

The use of modified bitumen in asphalt concrete for surface course is expected to strengthen the existing pavements without increasing the structural thickness of the pavements. A substantial number of studies also revealed that the use of strong skeleton of coarse particles enhanced the resistance to permanent deformation of the asphalt mixtures. Muraya et al. [7] investigated the effect of gradation on permanent deformation by performing repeated triaxial test. The results showed that the skeleton mixtures were capable of being loaded at higher levels before the development of excessive deformation. The contribution of the aggregate skeleton toward permanent deformation resistance was important for skeleton mixtures. The characteristics of bitumen were of more importance for the dense-graded mixtures. Capitao and Picado-Santos [8] assessed permanent deformation property of high modulus asphalt mixture containing 10/20 penetration grade bitumen. They found that there were remarkable effects of asphalt content and air void content on the resistance to rutting. Tayfur et al. [9] investigated the effect of additive on rutting performance of SMA mixtures on the basis of the test results of rut depth using a French LCPC wheel tracker. The results showed that the SMA containing 5% SBS polymer modified bitumen were found as the most rut-resistant mixtures. Fontes et al. [10] evaluated the resistance to rutting of the rubber asphalt mixtures, and identified that gap-graded aggregate gradation and continuous blend asphalt rubber binder presented the best performance. Al-Khateeb et al. [11] compared the effect of aggregate source on rutting performance of Superpave dense-graded asphalt mixture containing PG 64-10 bitumen. The test results showed that the asphalt mixtures containing basalt aggregate exhibited superior performance relative to those incorporating limestone aggregate. Cao et al. [12] also indicated that the addition of SBS together with anti-rutting additive into the dense-graded asphalt mixture significantly improve the rutting resistance of the middle hot-mix asphalt layer in terms of the data obtained from uniaxial creep testing. However, the low-temperature performance and resistance to moisture damage appeared to be slightly declined. Brovelli et al. [13] investigated the effects of polymers on rutting performance of DGACs with a nominal maximum aggregate size of 20 mm using a wheel tracking device. The results showed that polymer modification improved rut resistance without compromising the stiffness and fatigue behavior.

Previous studies clearly indicated the potential benefits of using strong aggregate skeleton or modified asphalt binder in hot-mix asphalt to improve rutting performance. However, as current specifications for asphalt mixtures have traditionally been based empirically on volumetric properties combined with additional performance-related requirements. In addition, most permanent deformation tests have been conducted for evaluating rutting behavior of asphalt mixtures within certain numbers of loading cycles. Little attention has been directed to evaluate the long-term permanent deformation of asphalt mixtures. It is imperative to design and develop rut-resistant and durable asphalt concrete for the thin asphalt pavements. Therefore, the study conducted here aimed at evaluating the conventional and long-term rutting characteristics of dense-graded and aggregate skeleton asphalt mixtures incorporating highly modified bitumen. The objectives of the study are as follows:

- Evaluate the linear viscoelastic of the HMB
- Assess the creep and recovery behavior of the HMB
- Investigate the pavement performance of the highly modified asphalt mixtures
- Predict the long-term rutting performance of the highly modified asphalt mixtures

2. MATERIALS

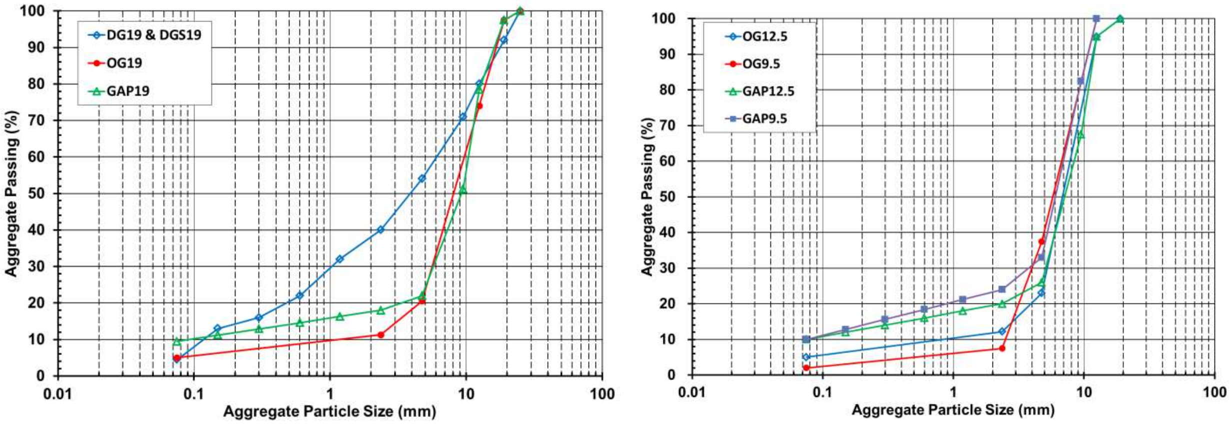
The laboratory experiment included eight combinations of aggregate gradations and aggregate types. One polymer modified bitumen, two aggregate types and seven aggregate gradations were utilized in this research. Bitumen rheological tests and asphalt mixture tests were conducted in this laboratory testing program. Triplicate specimens were tested for each asphalt material considered in this investigation.

2.1. Asphalt Binders

One type of polymer modified bitumen that supplied by an asphalt manufacturer was used in this study for producing asphalt mixtures with different gradations. This highly modified bitumen (HMB) contains 12% SBS polymer of 60/70 penetration grade bitumen (base bitumen) by weight. In addition, the 60/70 base bitumen (Pen 60/70) and the lightly modified bitumen (LMB) which contains 5% SBS were also included for rheological analysis in order to make comparisons.

2.2. Aggregates and Gradations

The natural aggregate including the coarse and fine particles was crushed limestone provided from one source. Figure 1 shows the aggregate gradations for producing dense-graded (DG) and aggregate skeleton mixtures with three nominal maximum aggregate sizes (NMAS) of 19, 12.5 and 9.5 mm. The aggregate skeleton mixture included gap-graded (GAP) and open-graded (OG) asphalt mixtures. The designation includes the mixture type followed by the NMAS. In addition, the steel slag used in this study was obtained from steel manufacturer and substituted for limestone aggregate in coarse portion. The dense-graded asphalt mixture containing the steel slag with NMAS 19 mm was labeled as DGS19. The specific gravity of 3.41 for the steel slag was higher compared to that of 2.63 for the natural limestone aggregate. In addition, the LA abrasion value for the steel slag is lower than that for the limestone.



(a) Coarse Gradations (b) Fine Gradations

Figure 1: Gradations of Highly Modified Asphalt Mixtures

2.3. Asphalt Mix Design

The asphalt mix design results for the highly modified asphalt mixtures were determined by conducting Marshall mixture design procedure. Optimum bitumen contents for the dense-graded and gap-graded asphalt mixtures were determined to correspond with target air void content of 4%. For the open-graded asphalt mixtures, the design air void content was 20%. The specimens at optimum bitumen contents were then fabricated for further mechanical testing as required. The optimum bitumen contents are 4.8%, 5.1% and 6.1% for DG, OG and GAP mixes, respectively.

3. LABORATORY TEST

3.1. DSR Tests for Asphalt Binders

Dynamic oscillatory testing with frequency sweeps was conducted on the HMB using a DSR (dynamic shear rheometer) according to AASHTO M320 [15]. The values of complex modulus (G*) were measured over a range of test frequencies ranging from 0.1 to 20 Hz. The test temperatures were selected between 40 and 85^{o}C. The test results were fitted using the Christensen & Anderson model in order to interpret the linear viscoelastic behavior of the HMB [16]. To assess non-recoverable creep compliance (J_{nr}) and percentage recovery (R) of the HMB, the MSCR test was performed at 60^{o}C in accordance with ASTM D7405 [17]. 1 second shear stress was applied to the HMB, followed by a 9 seconds recovery period. The stress of 3.2 kPa was conducted and the test temperature was selected at 60^{o}C. J_{nr} was defined as a ratio of recovered strain to shear stress, while R was defined as the difference between strain at end of recovery period and peak strain after creep period.

3.2 Resilient Modulus

The resilient modulus (MR) test was employed to measure the modulus of elasticity of the asphalt mixtures. The test was conducted on 100 mm diameter specimens at 25°C and used a haversine loading followed by a rest period. The load was applied for 0.1 second along with a rest period of 0.9 second.

3.3 Cantabro abrasion test

The Cantabro abrasion test was performed at 25°C to evaluate the resistance to raveling of the asphalt mixtures. The compacted specimen was tumbled inside a steel drum without the charge of steel balls for 300 revolutions at a speed of 30 rpm. The percentage of weight loss during the abrasion process was used to represent the raveling resistance of the asphalt mixtures. The percentage of weight loss is ratio of specimen weight loss to initial specimen weight.

3.4 Indirect Tensile Strength and Moisture Susceptibility

The indirect tensile (IDT) test was used for evaluating the tensile strength and cracking potential of the asphalt mixtures. The test was carried out on the specimens at a deformation rate of 50.8 mm/minute and a temperature of 25°C. To evaluate moisture susceptibility, the indirect tensile strength was measured before and after water conditioning of specimens. The conditioned specimens were placed in a bath containing potable water at 60°C for 24 hours before being tested for indirect tensile strength. The retained tensile strength as a percent of the original tensile strength represented the performance of moisture damage for the asphalt mixtures.

3.5 Wheel Tracking Test

To investigate the rutting performance of the asphalt mixtures, the wheel tracking test was conducted at 60°C according to Public Construction Commission 02798 [14]. The asphalt slab was trafficked by a wheel under a loading pressure of 700 kPa. A loading frequency was selected at 42 cycles per minute. During 3,000 cycles, the values of permanent deformation induced at the middle of the asphalt slab were recorded. To determine allowable rutting levels and durability of the asphalt mixtures, the Burgers model was employed to fit the wheel track testing data. There are seven parameters of strain (ε_o), stress (σ_o), spring constant of Maxwell model (G_o), spring constant of Kelvin model (G_1), dashpot constant of Maxwell model (η_o), dashpot constant of kelvin model (η_1) and time (t). The equation for the total strain versus time is shown as follows:

$$\varepsilon_o(t) = \frac{\sigma_o}{G_o} + \frac{G_o}{G_1}\left(1 - e^{-tG_1/\eta_1}\right) + \frac{\sigma_o t}{\eta_o} \quad (1)$$

The parameter η_o, defined as mixture viscosity, is associated with the viscous flow of the asphalt mixture and can be used to obtain viscous strain within an asphalt mixture. The number of loading cycles was calculated using the Burgers model to correspond with the rutting depth of 12.5 mm.

4. RESULTS AND DISCUSSION

4.1 Linear Viscoelastic Behavior of HMB

Figure 2 gives the rheological properties of the HMB in terms of the G* at the reference temperature of 80°C. In addition to the HMB, the 60/70 base bitumen and the lightly modified bitumen (LMB) which contains 5% SBS were also included for rheological analysis in order to make comparisons. The Christensen & Anderson (CA) model fitted results were consistent with the DSR experimental measurements over a wide range of temperatures and frequencies. It is noted that the rheological results at low temperature were interpreted by CA model extrapolation due to limitation of the DSR used in this study. The HMB was found to have the lowest G* value at lower temperatures, whereas the highest G* was obtained for the HMB at higher temperatures compared to the LMB and Pen 60/70. The flatter master curve for the HMB showed that the HMB was less susceptible to temperature due to the highly polymeric modification effect. It can be interpreted that the difference in the modulus between bitumen and polymer becomes larger at higher and low temperatures. At high temperatures, base bitumen increasingly shows viscous flow while polymer modifier remains elastic. The HMB tends to have higher modulus because the polymer modifier predominates the rheological behavior of the asphalt binder. At low temperatures, base bitumen increasingly shows rigid solid as polymer modifier still remains elastic. Because the presence of the polymer modifier is more dominant on the rheological behavior of the asphalt binder, the modified asphalt binder possesses the lower G* value. However, it should keep in mind that additional data at low temperature should be required to confirm the trends. Similar trends of the master curves in terms of phase angle omit in this section for brevity.

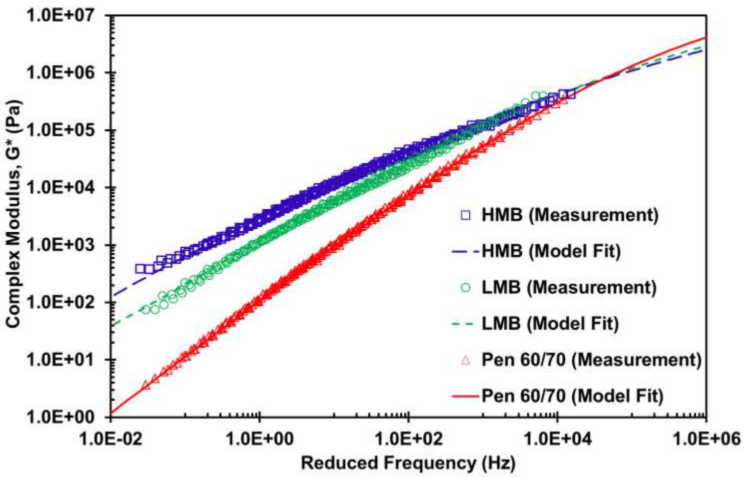


Figure 2: Linear Viscoelastic Behavior of Asphalt Binders

4.2. Creep and Recovery Properties of HMB

The non-recoverable creep compliance and recovery values were obtained by performing MSCR test using a DSR. Figure 3 shows that the HMB had the lowest J_{nr} values, reflecting the fact that the highly modified bitumen was the most resistant to permanent strain compared to the PMB and Pen 60/70. The HMB also appeared to have the highest R value, followed by the LMB and the pen 60/70 base bitumen. The data point of the HMB above the elastic response curve indicated that the highly modified bitumen possessed more sufficient delayed elastic response and would be able to recover to initial state before next loading compared to the pen 60/70 bitumen.

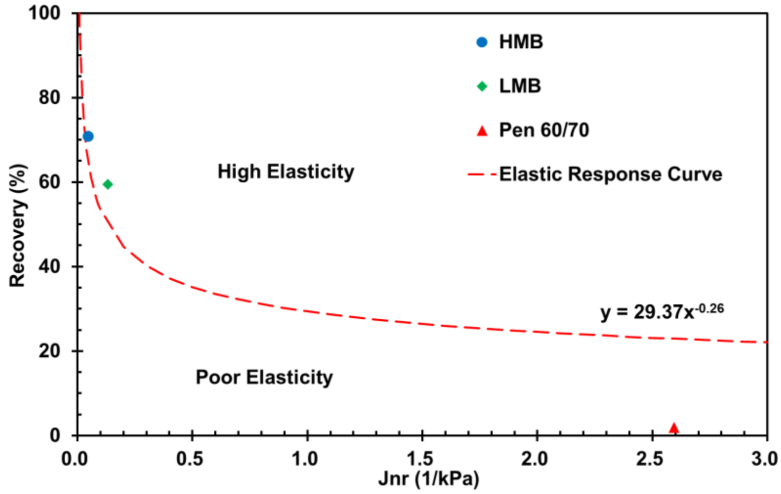


Figure 3: Elasticity of Asphalt Binders

4.3 Stiffness Modulus

Figure 4 gives the average test results (three replicates) of the resilient modulus testing for the asphalt mixtures. In terms of the asphalt mixtures with NMAS 19 mm, the dense-graded mixtures had higher M_R values compared to the aggregate skeleton mixtures, indicating that the dense aggregate gradation resulted in lower tensile strain under repeated loading conditions. Because the loading configuration develops a relatively uniform tensile stress perpendicular to the direction of the applied load and along the vertical diametral plane, a higher M_R value for the dense-graded asphalt mixture is attributed to the continuous gradation increasing the resistance to tensile stress. Although the dense-graded asphalt mixture with high M_R value decreases the strain at the bottom of the surface layer and reduces the stress in the underlying layer, the stiff mixture would increase the sensitivity of the fatigue life of the mixtures. The thin surfacing with a stiff mix would lead to the shorter service life of the asphalt pavements. In addition, the test results appeared to have little difference in stiffness between the DG19 and DGS19. It can be explained that these two dense-graded asphalt mixtures had similar M_R value regardless of aggregate type due to the similar volumetric parameters of VMA, VFA and air void.

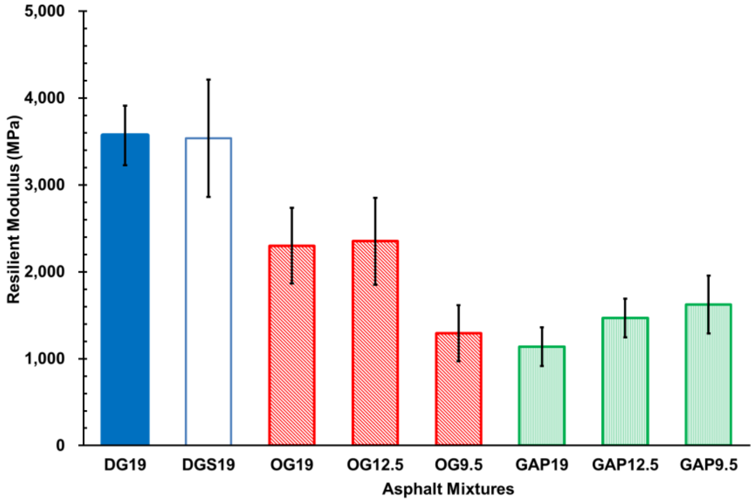


Figure 4: Resilient modulus for asphalt mixtures

4.4. Resistance to Raveling

The parameter of the Cantabro abrasion is employed to assess the resistance to raveling of the asphalt pavements. Figure 5 shows the average results of Cantabro abrasion testing against VMA values for the asphalt mixtures. There is an increase in VMA with increasing the abrasion loss value. For the NMAS 19 mm asphalt mixture, the OG19 was expected to have the highest percentage of weight loss, followed by GAP19 and dense-graded asphalt mixtures. In comparison with the other two types of asphalt mixtures, the open gradation mixture had the highest air void, leading to lack of binding characteristic. In general, low density in the open-graded asphalt mixture is unable to provide sufficient cohesion in the asphalt mixtures, thereby resulting in progressive disintegration of the asphalt pavements. Increase asphalt film without compromising other engineering properties would improve the resistance of raveling of the asphalt pavements with open gradation.

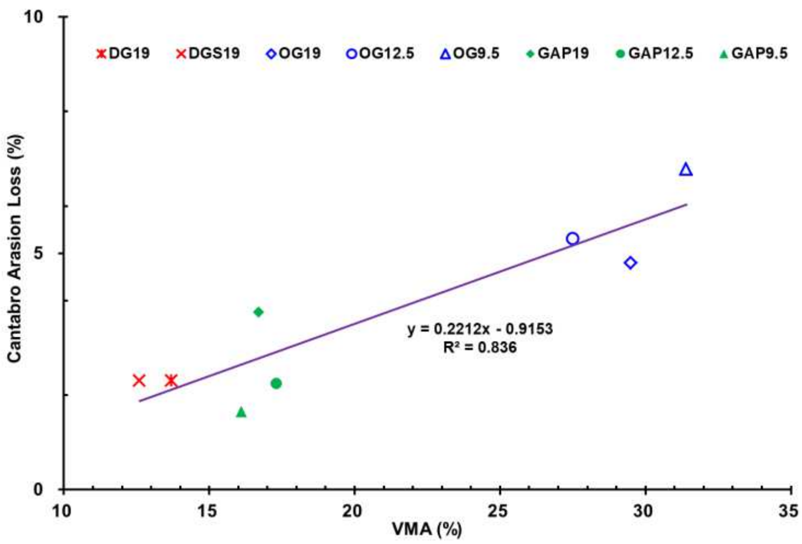


Figure 5: Cantabro weight loss for asphalt mixtures

4.5. Indirect tensile strength and resistance to moisture-induced damage

The indirect tensile strength is used to evaluate cracking potential and tensile strength of the asphalt mixtures. Figure 6 presents the average results of the indirect tensile strength against stability for each asphalt mix. The indirect tensile strength shows an increase with increasing stability. In addition, the tensile strength values of the dense-graded and gap graded asphalt mixtures appeared to be higher than those of the open-graded asphalt mixtures. It can be inferred that the dense-graded and gap-graded mixtures possessed better characteristics of cohesive strength due to lower air void, as compared with the open-graded asphalt mixture.

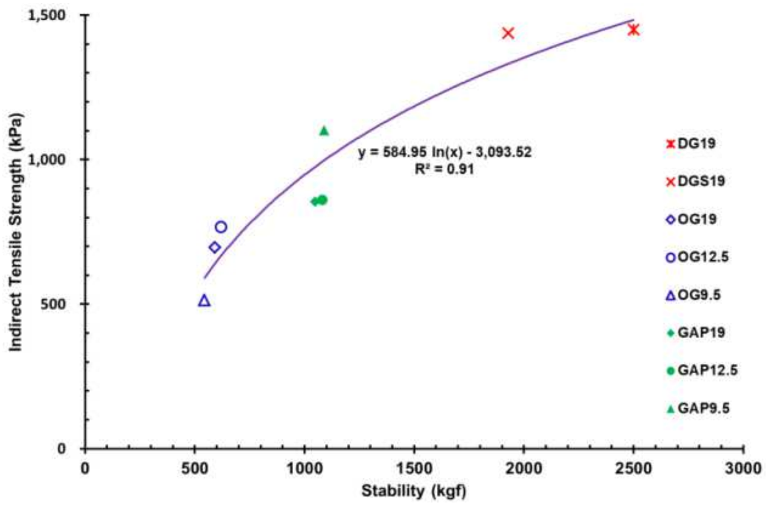


Figure 6: Indirect tensile strength for asphalt mixtures

Regarding the effect of aggregate size on tensile strength of the asphalt mixtures, the OG9.5 was found to have the lowest value compared to the OG19 and OG12.5 because of possessing the relatively higher air void content of 23%. For the gap-graded mixtures, the GAP9.5 appeared to have higher tensile strength in comparison with the GAP19 and GAP12.5, demonstrating that the cohesion for the finer gap-graded mixtures was higher than that for the coarse-graded mixtures. The GAP9.5 had higher tensile strength because it had a finer gradation, with its particles packed more closely together than the GAP19 and GAP12.5. Although the coarse gap-graded mixture had the stone-on-stone contact provided by the coarse aggregate fraction in the mix, the lack of fine aggregate fraction would result in the reduction of cohesive strength. Additionally, it can be interpreted that a reduction in VMA would increase characteristic of tensile strength for the gap-graded mixtures. Caution should be taken that the asphalt could be oxidized rapidly without adequate asphalt film thickness. As a result, the asphalt film is more easily penetrated by water, and the tensile strength of the gap-graded asphalt mixture is adversely affected.

When subjected to water, asphalt mixture would lose adhesion between the asphalt and aggregate surface. Figure 7 exhibits the resistance to moisture induced damage for the asphalt mixtures in terms of the retained strength ratio. The test results show that all asphalt mixtures investigated in this study met the minimum requirement of 75% regardless of mixture type. It is known that the aggregate type is primarily responsible for the moisture susceptibility. There existed little difference in DG19 and DGS19, reflecting that the steel slag and limestone aggregate utilized in this investigation were not prone to moisture damage. In addition, using the highly modified asphalt to make the mix impermeable to water minimized the moisture-induced damage. Overall, proper mixture design, compaction, aggregate type and asphalt type would enhance the resistance to moisture susceptibility of the asphalt mixtures.

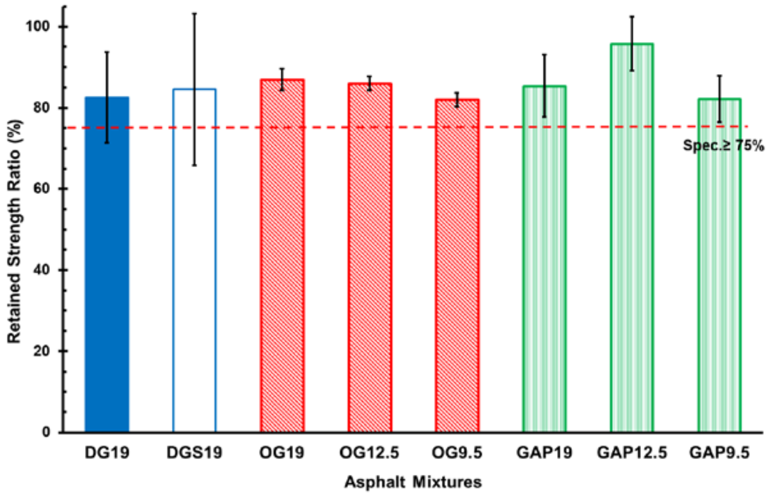


Figure 7: Retained strength ratio for asphalt mixtures

4.6 Resistance to Rutting of Highly Modified Asphalt Mixtures

Figure 8 shows that the OG19 was found to have the lowest rutting depth at the 3,000th cycle among these coarse-graded asphalt mixtures. It can be inferred that the aggregate skeleton of open-graded asphalt mixture controlled the densification within the mix. The asphalt mix with stone on stone was capable of being loaded at the initial number of cycles. However, the OG19 appeared to develop higher rutting depth rate after a certain number of cycles compared to DG19, DGS19 and GAP19. It was attributed to the insufficient amount of fine aggregate matrix to hold the coarse aggregate particles together, leading to a reduction in cohesive strength of the open-graded asphalt mixture.

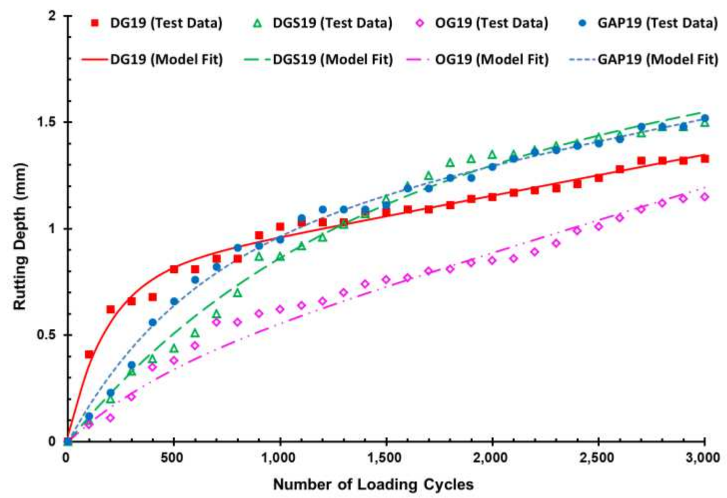


Figure 8: Deformation curves for coarse-graded asphalt mixtures

As compared to the DG19, the DGS19 had the lower values of rutting depth before 1200th cycles. The dense-graded asphalt mixture incorporating steel slag appeared to exhibit the stronger aggregate skeleton, thereby enhancing the resistance to permanent deformation within the initial number of cycles. It was due to the fact that the steel slag had angularity together with cubic shape as compared to the natural limestone aggregate. After 1200th cycles, the DGS19 exhibited the relatively rapid rate of rutting depth. The DGS19 was found to have the relatively lower VMA compared to the DG19, adversely affecting the resistance to deformation for a period of loading time. It was speculated that the cubic shape of the steel slag would contribute a reduction in VMA because of limited void content within the DGS19.

4.7 Long-Term Rutting Performance of Highly Modified Asphalt Mixtures

Because the wheel tracking test was only conducted on the asphalt mixtures for 3,000 cycles, the number of loading cycles was estimated using the Burgers model as the rutting depth reached 12.5 mm. Figure 9 gives the relationship between the mixture viscosity η_o and number of loading cycles at the rutting depth of 12.5 mm. The results show an increase in the number of loading cycles with increasing the mixture viscosity. The minimum numbers of repetitive loads of 12,500 cycles was employed to evaluate the rutting performance of the asphalt surface course required by the highway agency in Taiwan. The highly modified asphalt mixtures all met the requirements regardless of the aggregate gradations. The open-graded asphalt mixtures appeared to have the lower mixture viscosities due to the highest void content, leading to the more rapid rutting depth rate as compared to the dense-graded and gap-graded asphalt mixtures. The higher mixture viscosity represents the better cohesive strength within the asphalt mixture, resulting in the slower rate of rutting development.

It was found a positive linear correlation with the R2 value of 0.98 as including the dense-graded and gap-graded asphalt mixtures. It seems that there is no correlation between η_o and loading cycles for the open-graded asphalt mixtures. Although the aggregate interlocking is designed to have capacity to resist rutting at initial number of loading cycles, the highly modified bitumen also had great contribution to the cohesion within the asphalt mixture. It is noted that the development of rutting for the open-graded asphalt mixture is more sensitive to the asphalt binder viscosity rather than the aggregate gradation. As taking into account the bitumen viscosity, aggregate gradation and mix volumetric properties, the η_o can be considered as a good indicator to assess the durability potential of asphalt mixtures for thin asphalt overlay.

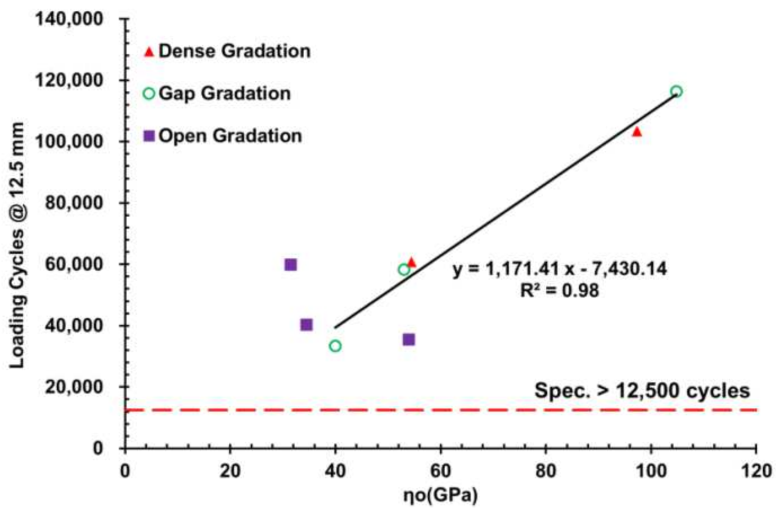


Figure 9: Relationship between η_o and Loading Cycles at 12.5 mm

5. CONCLUSIONS

This paper presents the effects of mixture type on rutting resistance and durability of the highly modified asphalt mixtures. It should be noted that the laboratory results described in this paper were confined to the materials, procedures and equipment used in this investigation. On the basis of the test results in this study, the following conclusions can be drawn:

- On the basis of the linear viscoelastic analysis, the use of highly modified bitumen made the bitumen less susceptible to temperature due to the highly polymeric modification effect. In addition, the highly modified bitumen possessed better delayed elastic response and had better rutting characteristic for thin asphalt overlay in terms of the MSCR testing.
- In terms of the stiffness modulus, the dense-graded asphalt mixtures had higher MR values compared to the asphalt mixtures with aggregate skeleton, indicating that dense gradation, lower air voids and lower asphalt contents reduce the tensile strain in the mixtures.
- The Cantabro test results indicated that the dense-graded asphalt mixtures had better performance in resistance to raveling compared to the aggregate skeleton mixtures. The aggregate skeleton asphalt mixture with insufficient amount of fine aggregate matrix to hold the coarse aggregate particles together would induce disintegration of the mixture.
- The aggregate skeleton asphalt mixtures possessed lower indirect tensile strength than the dense-graded asphalt mixtures, which was mainly attributed to the aggregate skeleton mixtures being subjected to compression without lateral support.
- In terms of moisture-induced damage, the test results concluded that proper mixture design, compaction, aggregate type and asphalt type would enhance the resistance to moisture susceptibility of the asphalt mixtures.
- In terms of the rutting prediction obtained from the Burgers model, the dense-graded asphalt mixture containing steel slag appeared to have better long-term rutting resistance due to the fact that the steel slag had angularity together with cubic shape.
- The mixture viscosity η_o can be considered as a good indicator to assess the durability potential of asphalt mixtures for thin asphalt overlay as it takes into account the bitumen viscosity, aggregate gradation and mix volumetric properties.

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