Enhancement of rutting resistance and fatigue behavior of asphalt mixtures modified by recycled waste polymer components

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Abstract: Rutting and fatigue of asphalt pavements, as two important distresses, are significantly influenced by the properties of binders. This study aims to improve the rutting resistance and fatigue behavior of asphalt mixtures by using two recycled waste polymer components of recycled crumb rubber (CR) and polyethylene (PE). Their contribution and mechanisms on enhancing the pavement performance were evaluated, in particular rutting and fatigue behavior of asphalt mixtures. The assessed pavement properties of the modified asphalt mixtures were evaluated by wheel tracking, uniaxial penetration and four-point bending (4PB) tests. The experimental results showed that the integrated modification technique by functionally incorporating PE and CR can improve the rutting resistance of asphalt mixtures, and the PE dosage was a key variable. The integrated modification method can enhance the shear strength of asphalt mixtures at a high in-service temperature, indicating the potential to reduce the flow rutting of asphalt pavements. Meanwhile, both the CR and PE can increase the cohesive behavior of asphalt mixtures, while the friction angle value was mainly determined by PE. The addition of PE reduced the fatigue life of asphalt mixtures, while CR was able to improve the fatigue properties of the PE modified asphalt mixture. The findings of this study are beneficial to develop sustainable and durable asphalt pavements, to tailor the reuse of different types of polymer wastes in asphalt pavements as well as to minimize the waste disposal at landfills.

Keywords: Asphalt mixture; Crumb rubber; Polyethylene; Rutting; Fatigue

1. Introduction

An asphalt pavement can be recognized as a multiple-layer structure, which is typically composed of an asphalt surface layer, road base and subbase. Based on this structure, each layer carries and spreads the loads from the above layer and passes these reduced loads to the next layer below (Wang, 2015). During the service life, the pavement may sustain heavy traffic loads and serious environmental conditions. In recent years, due to the considerable increase in axle loads, heavy traffic, severe climatic conditions and construction errors, serious damage of asphalt pavements has been recognized, especially in developing countries (Chen et al., 2016). It has been reported that rutting and fatigue are the two important distresses that significantly impact the service performance of asphalt pavements (Underwood et al., 2017; Yao et al., 2018).

Rutting, or permanent deformation in asphalt mixtures can be defined as the unrecoverable cumulative deformation that occurs in wheel paths as a result of repeated traffic loading (Muraya, 2007). The development of rutting is caused by the plastic and viscous movement of asphalt mixtures due to high in-service temperature or inadequate compaction during construction. It is generally accepted that the rutting behavior of asphalt mixtures is mainly influenced by the following factors: aggregate type and its gradation, air voids in asphalt mixtures, type and amount of bituminous binders, in-service temperature and traffic loading (Moghaddam et al., 2011). Among these factors, physical and rheological properties of bituminous binders play approximately 40% contribution to the rutting resistance of asphalt pavements (Sybilski et al., 2013).

Fatigue of asphalt pavements is a type of distresses associated with the weakening behavior of asphalt mixtures caused by repeatedly applied loads at certain stress levels (Fallon et al., 2016). The fatigue distress of asphalt mixtures is usually initiated in the form of microcracks and propagated to macrocracks due to repeated shear and tensile stresses in the asphalt surface layer (Moghaddam et al., 2011). Propagation of cracks in the pavement surface is related to the occurrence of adhesive fracture in thin mastic films and of cohesive fracture in thick mastic films (Lytton, 2004). Therefore, fatigue life of asphalt pavements is strongly affected by the type and amount of bituminous binders and the rheology, cohesion, adhesion and durable properties of the binders (Micaelo et al., 2015).

This study aims to improve the rutting and fatigue behavior of asphalt mixtures by adopting an integrated waste modification method. Two types of recycled materials, recycled crumb rubber (CR) and recycled polyethylene (PE), were functionally applied and tailored as admixtures to modify the pavement performance of asphalt mixtures.

The main objectives are to:

(1) Evaluate the relationship between dosage of admixtures (PE and CR) on the pavement performance of asphalt mixtures (rutting, cracking and fatigue).

(2) Determine the optimum amount of PE and CR in relation to the properties of the integrated modified asphalt mixtures.

(3) Predict the permanent deformation and fatigue life of the integrated modified asphalt mixtures in comparison with the SBS-modified asphalt mixtures.

2. Background

2.1 Utilization of PE in modified asphalt mixtures

PE is a semi-crystalline polyolefin material with excellent chemical resistance and good fatigue resistance (Awwad and Shbeeb, 2007). Fromn a chemical viewpoint, the molecule structure of PE has a long chain of carbon atoms with two hydrogen atoms liked to each carbon (Zhu et al., 2014). As one of the most important technical plastic materials in the world, large volumetric amounts of PE waste are being generated. The improper disposal of PE products not only pollutes the soils through atmospheric precipitation, water irrigation and fertilizer application, but also threatens human health through contamination of the food chain (Ma et al., 2015). Therefore, recycling and reuse of PE is becoming paramount and has been the focus of many research studies.

When PE waste is incorporated into bitumen, PE is swollen by absorbing the light components of bitumen and forms a biphasic structure with the polyolefin phase dispersed in the bitumen matrix (Pérez-Lepe et al., 2006). With the dosage increase of PE, these two interlocked continuous phases are formed in the modified bitumen and this intermolecular structure is responsible for the modification of bitumen performance. Punith found that the PE-modified asphalt mixtures obtained better pavement performance in comparison with conventional mixtures (Punith and Veeraragavan, 2007). The rutting resistance and temperature stability of asphalt mixtures can be enhanced by the inclusion of PE. Moatasim investigated the possibility of using high-density polyethylene (HDPE) as a modifier of asphalt mixtures (Moatasim et al., 2011). The results showed that the performance of HDPE-modified asphalt mixture obtained better properties, including Marshall Stability, tensile strength, tensile strength ratio and resilient modulus, in comparison with the conventional mixtures. The related research performed by Othman demonstrated a significant increase in both indirect tensile strength and compressive strength of modified asphalt mixtures by adding HDPE (Othman, 2010). Jeong et al. incorporated waste polyethylene film (WPE film) in asphalt mixtures and also found significant improvement in the performance of the mixtures (Jeong et al., 2011). Singh et al. studied the effects of the addition of PE on the properties of bitumen and asphalt mixture. They found that asphalt mixtures containing PE showed an improvement with respect to the Marshall strength, flow and volumetric properties. The frequency sweep tests indicated that PE improved the complex modulus while decreasing the phase angle of the recovered bitumen (Singh et al., 2017).

However, the addition of PE failed to significantly improve the low-temperature flexibility of bitumen (Isacsson and Lu, 1995). Due to its regular long chain structure, the molecule of PE is prone to have high tendency to pack closely and crystallize, which could lead to a lack of interaction between bitumen and PE and result in instability of the modified bitumen. Many researchers have found that PE failed to improve the elastic recovery and stress relaxation of the modified bitumen, and this indicates a potential for thermal and fatigue cracking at low in-service temperatures (Singh et al., 2013; Zhang et al., 2018). Additionally, due to its non-polar nature, PE is difficult to be miscible with bitumen and the compatibility of these two materials is poor (Polacco et al., 2006). Moreover, the density difference between PE and bitumen may cause the creaming of the polymer particles (Hesp and Woodhams, 1992). As a result, the PE-modified bitumen is prone to phase separation when stored at high temperature without constant stirring (Domingos and Faxina, 2015).

To sum up, although some properties, especially high in-service performance, of bitumen have been enhanced by the PE modification, two important limits still restrict its application. One is the fact that PE fails to improve the flexibility of bitumen and this reduces the resistance of the PE-modified asphalt mixtures to thermal cracking at low in-service temperatures. The other one is the phase separation of the PE-modified bitumen during storage at high temperatures.

2.2 Utilization of CR in modified asphalt mixtures

The increasing number of vehicles worldwide generates a huge amount of vehicle tire waste every year. It has been estimated that over 10 billion tires are discarded every year and their inadequate disposal poses a potential for fire risk, rodents, soil pollution and water pollution which eventually threatens human health and environment (Presti, 2013; Alamo-Nole et al., 2011). The development of recovery and recycling techniques as well as implementation of related regulations have led to the transformation of this waste into energy or new polymer products (Sienkiewicz et al., 2017; Guo et al., 2017).

The vehicle tire has a complex structure that is composed of three main components: elastomeric compound, fabric and steel. After the removal of the fabric and steel components, the rubber component has variable applications. It can not only be used as a cheap filler, but also primarily used as a source of valuable raw materials (Ismail et al., 2011; Leng et al., 2016). Since the 1960s, with the increasing number of scrap tires and the environmental awareness, large amounts of shredded tires have been recycled for reuse as a component of bituminous binder (Shu and Huang, 2014). Reusing the reclaimed tire rubber in asphalt mixtures can be briefly separated into two processes: dry and wet. In the dry process, crumb rubber is added to and blended with aggregates before the bituminous binder is added (Hassan et al., 2014). The first step of the wet process is to prepare the modified bitumen by mixing the base bitumen and CR for at least 45 min at a temperature of 180-210℃, followed by a maturation step for 3 hours at 180℃ without stirring. The obtained CR-modified bitumen is then mixed with aggregates to prepare asphalt mixtures. During the mixing process, light components of bitumen are absorbed by rubber granulates and this causes swelling of the CR particle to expand up to three times that of its original volume. When prolonging the mixing time, the rubber grains are decomposed under a high modification temperature. The change in the grain shape and size shortens the distance between particles and results in the increased binder viscosity (Airey et al., 2002). These two chemical reactions - depolymerization and devulcanization take place, which can break down part of rubber particles and dissolve them as the liquid phase of bitumen, causing a reduction in the bitumen's viscosity (Zanzotto and Kennepohl, 1996).

The CR modified bitumen and asphalt mixtures have been investigated by many researchers who have indicated that the CR modified mixtures can improve pavement performance. The CR-modified bituminous binders tend to have higher viscosity, higher softening point and lower penetration in comparison with unmodified binders (Liang et al., 2015). The CR modification can improve the rheological properties of bitumen with an increase in complex modulus G* and a decrease in the phase angle, which may contribute to the fatigue and fracture resistance of asphalt mixtures (Moreno-Navarro et al., 2016; Amini and Imaninasab, 2018). Moreover, chemical treatment techniques were also adopted by researchers to prepare the CR-modified bitumen, which resulted in improved elastic recovery and showed good properties both in the lab and in the field tests (Shatanawia et al., 2013). After being mixed, the addition of CR in asphalt mixtures improved the mechanical properties of asphalt pavements by reducing the fatigue cracking potential and thermal cracking. The effect of the CR-modified bitumen is nearly equivalent to a polymer-modified bitumen and CR-modified bituminous binder has been fouind be to an effective alternative to commercial SBS-modified bitumen (Huang and Mohammad, 2002; Presti and Airey, 2013; Subhy et al., 2015). Asphalt pavements constructed by using CR-modified bitumen showed reduced noise due to the contact of the tire with the pavement surface. In addition, the CR-modified asphalt pavement improved the adhesion of the vehicle wheels to the pavement layer, which shortens the braking distance and thus increases road safety (de Almeida Junior et al., 2012; Yu et al., 2014).

However, the CR-modified bitumen did not significantly improve the mechanical properties of asphalt mixtures at high in-service temperatures, which indicates its limited contribution to the rutting resistance (Pan et al., 2015). Researchers have found that the dynamic stability of the CR-modified asphalt mixture was slightly higher than that of conventional asphalt mixture but lower than that of SBS-modified asphalt and PE-modified asphalt mixtures (Zhang et al., 2018). This demonstrates that the CR-modified asphalt mixture cannot play a major effect on the anti-rutting asphalt mixture at high in-service temperatures.

3. Materials and experimental methods

3.1 Materials

The 70# base bitumen used in this study was produced by Sinopec Qilu Petrochemical Company. Its properties as listed in Table 1 were tested in accordance with the Chinese standards JTG E20-

2011. Limestone aggregates supplied by Wenzu quarry in Shandong Province were used to prepare asphalt mixtures in this research. The physical properties of fine and coarse aggregates were measured according to the Chinese standards JTG E20-2011 and their results are shown in Table 2. The recycled polymer modifiers selected in this research were the reclaimed PE and the reclaimed CR. The reclaimed CR was produced from the end-of-life vehicle tires. The vehicle tires were first shredded and chipped to obtain rubber shreds, followed by an ambient grinding process to reduce the rubber particles in the range of 0.4-0.8 mm. The reclaimed PE was obtained by using the waste plastic greenhouse film. The waste plastic film was first cleaned, followed by extrusion and pelleting procedures to obtain the PE particles with the size of 2.0-3.0 mm.

Table 1. Physical and chemical properties of base bitumen

Bitumen tests	Results	Technical requirements	Test standards
Softening point (℃)	48.2	≧46	T0606
Penetration (25℃, 0.1mm)	68.3	60~80	T0604
Ductility (15℃, cm)	＞150	≧100	T0605
Flash point (℃)	295	≧260	T0611
Viscosity at 60℃ (Pa.s)	188	≧180	T0625
Relative density at 15℃(g/cm^3)	1.004	-	T0603
Solubility in C_2HCl_3(%)	99.75	≧99.5	T0607

Table 2. Physical properties of fine and coarse aggregates

Property	Results		Limits	Standards
	Fine aggregate	Coarse aggregate		
Specific gravity (g/cm^3)	2.734	2.738	≧2.6	T0304/T0328
Water absorption ratio (%)	0.82	0.44	≦2.0	T0304/T0328
LA Abrasion loss (%)	17.6	-	≦28	T0317
Crushing value (%)	14.5	-	≦26	T0316

3.2 Aggregate gradation and mixture design of asphalt mixture

An AC-20 type of asphalt mixture was considered in this study. This is a common mixture used in the middle layer of asphalt pavements in China. CR was first mixed with the base bitumen in the wet process before mixing with hot aggregates following the detailed procedures provided by Yao et al (Yao et al., 2018). In this research, three dosages of CR of 15%, 18% and 21% by weight of the base bitumen were used. The PE particles were mixed in a dry process by blending them directly with hot aggregates. The PE content of 0.2% and 0.3% by weight of asphalt mixtures was used. The three fractions of aggregates and the mineral filler were used for the aggregate gradation design as shown in Figure 1. The Marshall method was adopted to determine the best aggregate gradation and the optimum binder content. Targeting air voids of 4.0-4.5% and the highest Marshall stability, the optimum binder content determined as 4.3%.

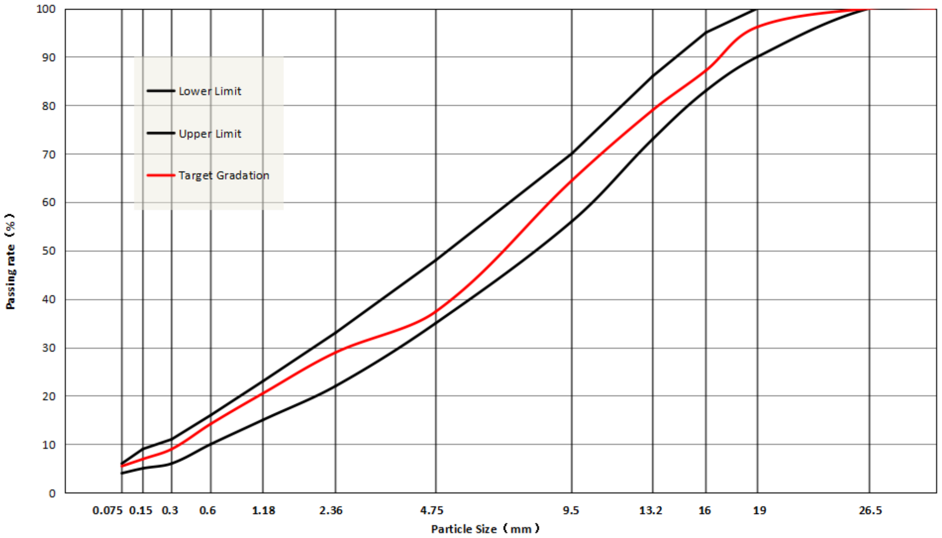

Figure 1. Aggregate gradation used in an AC-20 type of asphalt mixture

3.3 Experimental method

3.3.1 Wheel tracking test (WTT)

In order to evaluate the influence of recycled polymer components on the rutting resistance of asphalt mixtures, the wheel tracking test was carried out. As the stress state induced in an asphalt slab is similar to the actual axial loading, the wheel tracking test is considered as a suitable method for evaluating the rutting behavior (Javilla et al., 2017). The WTT slabs with dimensions of 300 mm x 300 mm x 50 mm were compacted in steel molds with a roller compactor. Before testing, they were conditioned at a predetermined testing temperature for at least 5 hours to obtain homogenous temperature distribution. During testing, the contact pressure between the rubber tire and slab surface was set at 0.7 MPa in order to simulate the traffic loading. The traveling distance of the rubber wheel was 230 mm with a revolution of 42 rpm and the rutting depth (RD) was recorded by using a linear variable differential transformer (LVDT). According to the JTG E20-2011 standard, the duration of the WTT test is 60 min with 2520 loading repetitions. The dynamic stability is finally calculated based on Equation 1. The dynamic stability is defined to represent the required number of wheel passes to yield 1 mm permanent deformation. A higher value can indicate better permanent deformation resistance.

$$\mathrm{DS} = \frac{15N}{RD_{60} - RD_{45}} \tag{1}$$

Where, DS is the dynamic stability (cycles/mm); N is the loading speed (42cycles/min); RD_{60} is the rutting depth at 60 min; and RD_{45} is the rutting depth at 45 min.

In general, a relatively high rutting depth and rutting rate occurs during the first 45 mins of the test after which the rutting development tends to be stable in the next following 15 min (Peng, 2008). The dynamic stability calculated based on the rutting depth development between 45 to 60 min may obtain a higher value and overestimate the high-temperature performance of asphalt mixtures. In view of this restriction, the dynamic stability index was used to evaluate the rutting resistance:

$$\mathrm{DSI} = t_{60} \times N \times P / RD_{60} \tag{2}$$

Where, DSI is the dynamic stability index; N is the loading speed (42cycles/min); P is the applied loading (0.7 kN) and RD_{60} is the rutting depth at 60 min.

4.3.2 Uniaxial penetration test

The uniaxial penetration test is similar to the California Bearing Ratio (CBR) test, which is a penetration test for evaluation of the mechanical strength of unbound materials. This method was promoted by Bi and Sun to evaluate the shear behavior of asphalt mixtures (Bi and Sun, 2005). Cylindrical asphalt specimens with a diameter of 150 mm and a height of 100 mm were compacted by using the Superpave Gyratory Compactor. At least four specimens were prepared for each kind of asphalt mixture. Before testing, specimens were conditioned at 60℃ for 6 hours. During testing, a cylindrical steel pressure head with 50 mm in height and 42 mm in diameter was loaded on the asphalt specimen at a constant loading rate of 1 mm/min and the detailed procedure was described in the JTG D50-2017 standard. The penetration strength (R_τ), representing the shear resistance of asphalt pavements, was calculated based on the following equations:

$$R_\tau = f_\tau \sigma_P \quad (3)$$

$$\sigma_P = \frac{P}{A} \quad (4)$$

Where, σ_P is the uniaxial penetration pressure (MPa); P is the ultimate loading (N); A is the cross-sectional area of the loading head (mm^2); f_τ is the penetration pressure index (0.35).

The static unconfined uniaxial compression test was then performed by using cylindrical asphalt specimens with a diameter of 100 mm and a height of 100 mm. This test was carried out under the same conditions as the uniaxial penetration test. The peak load was finally obtained and used to calculate the first principle stress σ_u, based on Equation 5:

$$\sigma_u = \frac{P}{A} \quad (5)$$

Where, P is the peak load (N), and A is the cross-sectional area of the asphalt specimen (mm^2).

The cohesion (c) and the friction angle (φ) were finally calculated via the results of uniaxial penetration test and static unconfined uniaxial compression test, based on the following equations:

$$\sigma_{P1} = 0.765\sigma_P \quad (6)$$

$$\sigma_{P3} = 0.0872\sigma_P \quad (7)$$

$$\varphi = \arcsin\left(\frac{\sigma_{P1}-\sigma_{P3}-\sigma_u}{\sigma_{P1}+\sigma_{P3}-\sigma_u}\right) \quad (8)$$

$$\mathrm{c} = \frac{\sigma_u}{2}\left(\frac{1-sin\varphi}{cos\varphi}\right) \quad (9)$$

Where, σ_{P1} is the first principal stress of asphalt mixtures in the uniaxial penetration tests, and σ_{P3} is the third principal stress of asphalt mixtures in the uniaxial penetration tests.

4.3.3 Four-point bending (4PB) test

Fatigue cracking is one of the major types of distress observed in asphalt pavements and the addition of recycled polymer components can influence the pavement performance. The four-point bending test is commonly used to evaluate the fatigue life of asphalt mixtures according to the JTG E20-2011 standard. Figure 2 presents the basic processes for fatigue test. For the 4PB test, the beam specimens with dimensions of 380 x 63.5 x 50 mm were obtained from asphalt slabs with dimensions of 500 x 500 x 70 mm, which were compacted by the roller compactor. The fatigue test was conducted in a controlled strain mode with a target strain level of 200 μm/m at 15℃. The specimens were conditioned at the test temperature for at least 4 hours prior to the test. During testing, a sinusoidal loading pattern was induced to the specimen with a loading cycle frequency of 10 Hz. The failure life was defined when the flexural stiffness of the specimen reached 50% of the initial value. Original parameters such as the peak load (N) and the peak specimen displacement at the mid-span of the specimen (mm) were recorded automatically at each of the loading cycles. Several other parameters were calculated based on the following equations:

$$\sigma_t = \frac{L \times P}{w \times h^2} \tag{10}$$

Where, σ_t is the maximum tension stress (Pa); L is the span of the beam (0.357m); P is the peak load (N); w is the width of the beam (m); and h is the height of the beam (m).

$$\varepsilon_t = \frac{12 \times \delta \times h}{3 \times L^2 - 4 \times a^2} \tag{11}$$

Where, ε_t is the maximum tension strain (m/m); δ is the peak displacement at the mid-span of the specimen (m); a is the space of adjacent chuck (0.119m).

$$S = \frac{\sigma_t}{\varepsilon_t} \tag{12}$$

S is the bending stiffness modulus (Pa).

$$\varphi = 360 \times f \times t \tag{13}$$

Where, φ is the phase angle (°); f is the loading frequency (Hz); t is the time difference between leak strain and peak stress (s).

$$E_D = \pi \times \sigma_t \times \varepsilon_t \times sin\varphi \tag{14}$$

E_D is the dissipated energy in one cycle (J/m^3).

$$E_{CD} = \sum_{i=1}^{n} E_{Di} \tag{15}$$

E_{CD} is the accumulative dissipated energy (J/m^3); and E_{Di} is the dissipated energy in the i th loading cycle (J/m^3).

Figure 2. Sample preparation for 4PB fatigue test

4. Results and Discussion

4.1 Rutting resistance of modified asphalt mixtures

Figure 3 shows the rutting depth of modified and unmodified asphalt mixtures with time. It can be seen that the asphalt mixtures prepared with the base bitumen had the highest permanent deformation (4.4 mm) and the rutting curve still showed an obvious uptrend. After adding PE and CR, the rutting depth of the integrated modified asphalt mixtures had a dramatic decrease. The rutting curves showed relatively lower rutting slopes, indicating the decreased rutting development in comparison with the normal asphalt mixture. With respect to the modified asphalt mixtures, CR21PE0.3 obtained the lowest rutting depth with a final value of 0.75 mm. The rutting depth of the modified mixture containing 0.3% of PE was in the range of 0.75-0.82 mm, which was slightly lower than that of the asphalt mixture containing 0.2% PE with a final rutting depth of 1.01-1.22 mm (not shown in Figure 3).

Dynamic stability (DS), as one of the most widely used indicators for evaluating the rutting behavior of asphalt pavements, was calculated based on Equation 1, and the results are presented in Figure 4. The dynamic stability of the asphalt mixture prepared with the base bitumen was 1915 cycles/mm, which was the lowest value among these tested specimens. However, after adding PE and CR, the dynamic stability increased significantly and all of their values were over 10000 cycles/mm. This indicated that the rutting resistance of asphalt mixtures were obviously improved, which in turn contributed to the enhancement of the high-temperature performance of asphalt pavements. In terms of the same CR content, increasing the PE content in asphalt mixtures resulted in a 10% increase in the dynamic stability. It can be demonstrated that the PE, as a type of thermoplastic material, can enhance the binder stiffness which may reduce the pavement deformation under repeated loading. With respect to the same PE level, increasing the CR content from 15% to 18% resulted in a slightly reduced dynamic stability. This could be explained through the stiffness of the integrated modified mixture being reduced by the CR due to its much lower stiffness than that of PE. As the CR dosage increased from 18% to 21%, the dynamic stability experienced an increase and surpassed the specimen with 15% CR. The increased CR content can absorb more light phase components from bitumen and resulted in an increased bitumen stiffness and an increase elastic response. Furthermore, the combined effect of CR and PE increased the mixture stiffness and elastic response which finally improved its rutting resistance.

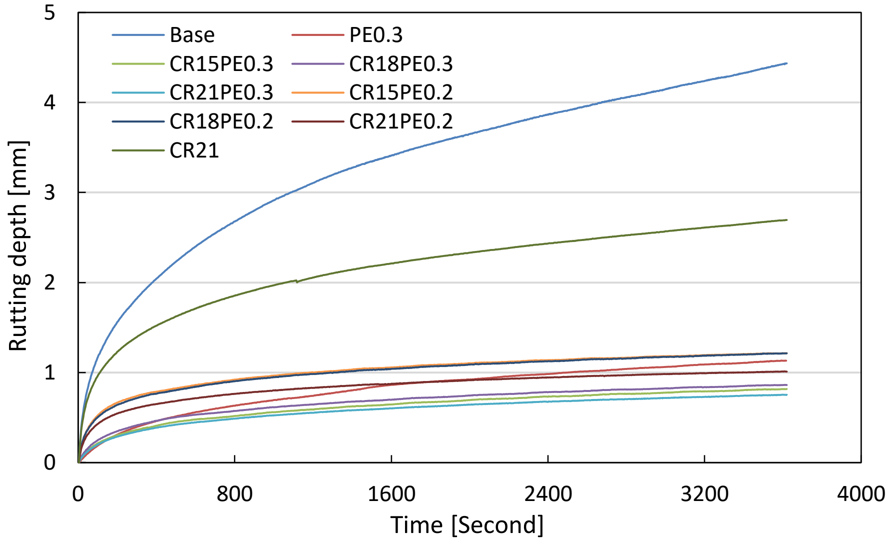

Figure 3. Development of rutting depth of asphalt mixtures under repeated loading

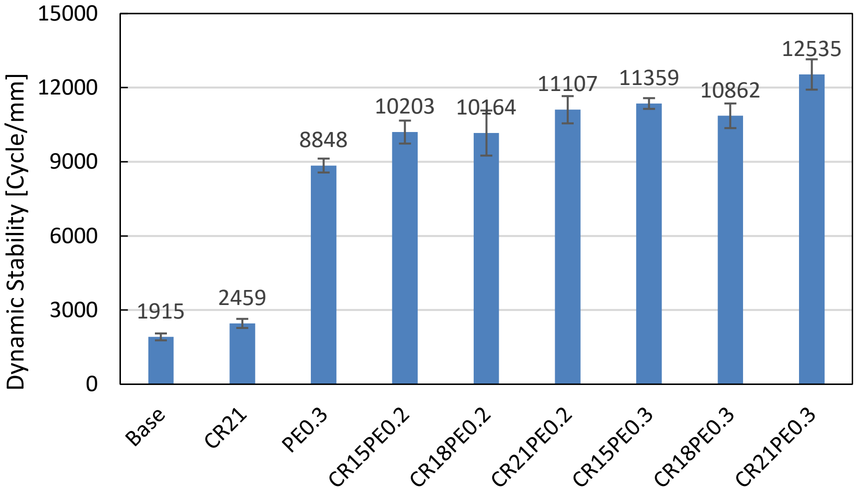

Figure 4. Dynamic stability of all asphalt mixtures after WTT test

The dynamic stability index (DSI) of all specimens was calculated based on Equation 2, and the values are presented in Figure 5. The normal asphalt mixture obtained the lowest DSI of 450. After using an integrated modification by adding CR and PE, the DSI results experienced a dramatic increase. Even though DSI showed a similar trend as that of DS, the DSI value seemed to be more sensitive to the PE content. Under the same CR content, the DSI values increased by approximately 50% when the PE dosage increased from 0.2% to 0.3%. This indicated the increased sensitivity of the DSI parameter in showing the influence of the PE dosage on the rutting resistance of asphalt mixtures. Therefore, DSI can be adopted as an auxiliary indicator to distinguish the rutting resistance of different asphalt mixtures.

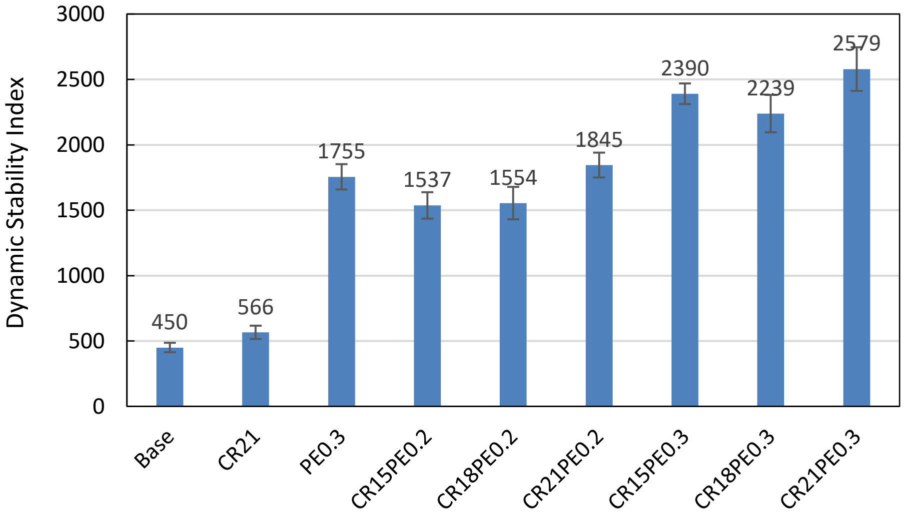

Table 5. Dynamic stability index of all tested asphalt mixtures

4.2 Uniaxial penetration strength of modified asphalt mixtures

The uniaxial penetration test was performed to evaluate the influence of the integrated modification on the shear behavior of asphalt mixtures. Figure 6 shows the loading curve of a representative specimen, by which the induced loading first increased gradually until the peak load, followed by a steady decline. The peak loading value of each asphalt mixture was obtained and used to calculate the penetration strength (R_τ) and the results are shown in Figure 7. It can be determined that the asphalt mixture prepared with the base bitumen had the lowest penetration strength. The incorporation of 21% CR resulted in nearly a 50% growth in terms of the penetration strength, and its value increased from 0.53 MPa to 0.77 MPa. The penetration strength of the PE modified mixture was more than doubled that of the normal asphalt mixture. With respect to the integrated modification, all of their specimens obtained relatively higher penetration strength than that of the normal asphalt mixture, and their values were in the range of 1.2-1.5 MPa. Under the same CR level, increasing the PE dosage from 0.2% to 0.3% resulted in approximately an increase of 0.2 MPa in terms of the penetration strength, except for the specimens prepared with 18% CR. In comparison, the variation of the CR content had limited effect on the penetration strength. It can therefore be concluded that the integrated modification by adding CR and PE can enhance the shear resistance of asphalt mixtures at a high in-service temperature, which in turn has the potential to reduce the rutting.

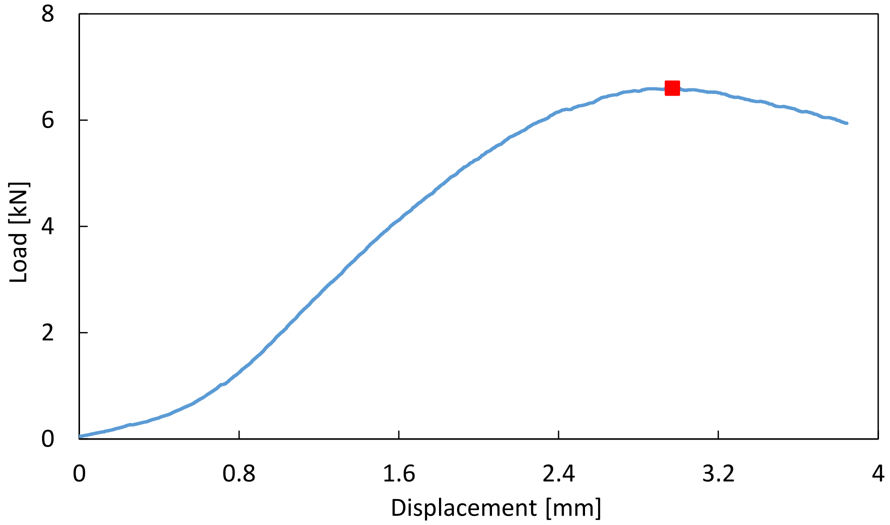

Figure 6. Applied compressive load versus displacement of pressure head for CR21PE0.3

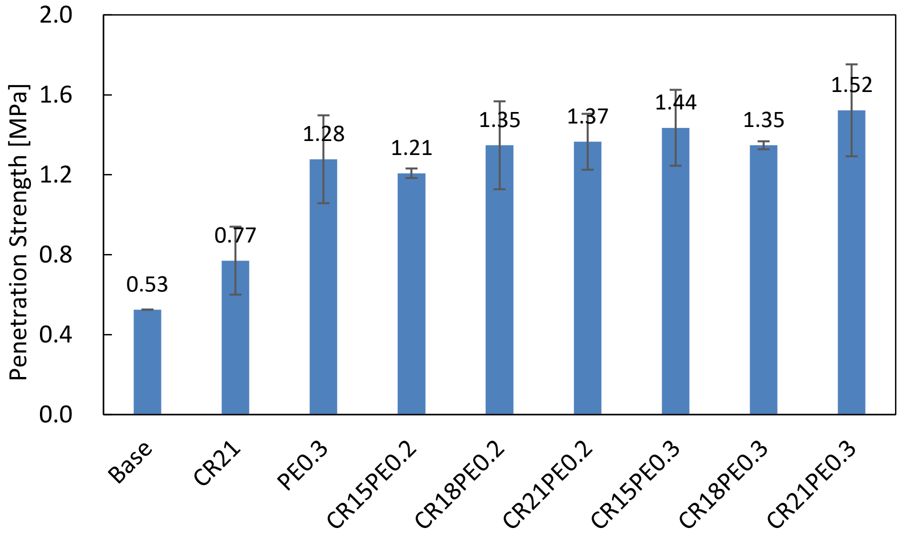

Figure 7. Penetration strength of all asphalt mixtures

Table 3 lists the uniaxial penetration pressure and the first principle stress of all asphalt mixtures measured by the uniaxial penetration test and the unconfined uniaxial compression test. These two parameters were then used to calculate the cohesion (c) and the friction angle (ϕ), according to Equations 6-9. Figure 8 shows the cohesion results of the normal asphalt mixture and the modified mixtures with the addition of CR and PE. It can be seen that the normal asphalt mixture obtained the lowest cohesion value being 0.122 MPa. Individually adding CR had limited influence on the cohesion value, while the addition of PE resulted in an obvious increase in this parameter. This could be due to the higher stiffness of PE than that of CR, by which the cohesive strength of the binder in the asphalt mixtures was significantly increased. As for the integrated modified asphalt mixtures, their cohesion values were relatively higher than that of the normal asphalt mixture and the single waste polymer modified asphalt mixture. The integrated modified mixtures prepared with the same CR content had similar cohesion values. As a result, the increment of the PE content from 0.2% to 0.3% had no contribution to the cohesion of the integrated modified asphalt mixtures. It can be explained that the addition of PE forms two interlocked continuous phases in the bitumen, which contributes to the cohesion value of mixtures. As the interlocked phases form, adding more PE into the mixture has limited influence on the cohesion value. With respect to the integrated modification, the addition of CR increased the cohesion value from approximately 0.17 MPa for the PE modified mixture to almost over 0.2 MPa for the integrated modified mixture. It implied that the rubbery behavior of CR improved the elastic property as well as the cohesive strength of binders, which in turn had a positive influence on the mixture cohesive behavior.

In terms of the friction angles as shown in Figure 9, the normal asphalt mixture had the lowest friction angle of 40.57°. The incorporation of CR and PE in the modified mixtures can increase their friction angles. The addition of PE resulted in a higher friction angle value than that of CR. The friction angle represents the internal friction between particles, including sliding friction due to the rough texture of particle surfaces and occlusal attrition due to the intergranular interaction between particles. As these mixtures used the same aggregate gradation, the occlusal attrition value of these specimens had no difference. So, the CR and PE improved the sliding friction and restricted the relative slip between particles, especially PE. In comparison with the PE modified mixture (PE0.3), the integrated modification had no further increase in the friction angle and even showed a slight reduction. This phenomenon was in good correlation with previous research, which showed that the CR and PE integrated modified bitumen yielded a lower complex shear modulus than that of the PE modified bitumen [0]. It demonstrated that the integrated modification cannot increase the sliding friction between particles, which in turn has no contribution to the resistance of asphalt pavement to flow rutting distress.

Table 3. Uniaxial penetration pressure (σ_P) and the first principle stress (σ_u) of all asphalt mixtures

Property	Mixture type								
	Base	CR21	PE0.3	CR15PE0.2	CR18PE0.2	CR21PE0.2	CR15PE0.3	CR18PE0.3	CR21PE0.3
σ_P (MPa)	1.5	2.2	3.65	3.45	3.85	3.9	4.1	3.85	4.35
σ_u (MPa)	0.53	0.59	0.75	0.84	0.89	0.96	0.87	0.98	0.99

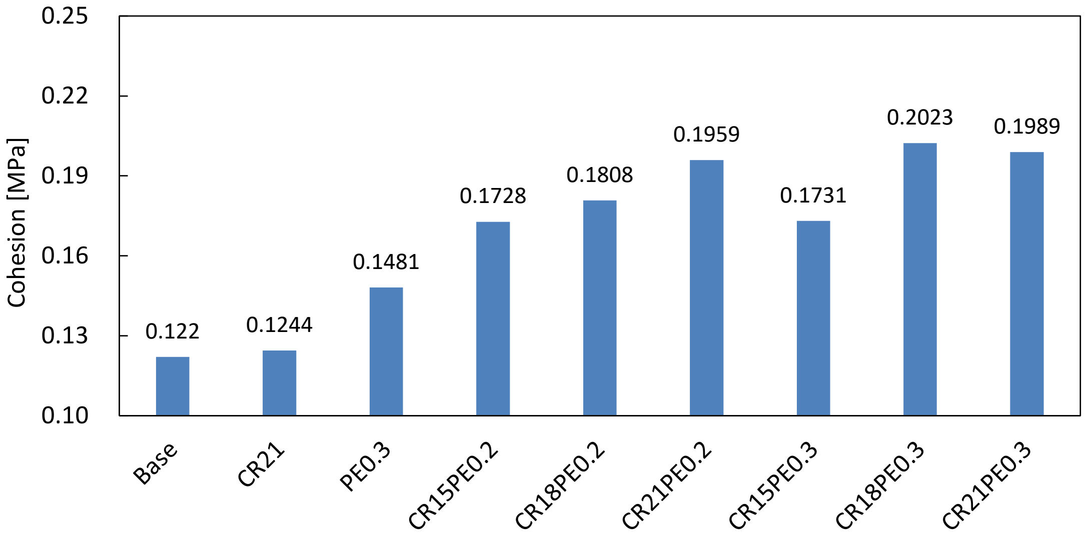

Figure 8. Cohesion of asphalt mixtures before and after modification

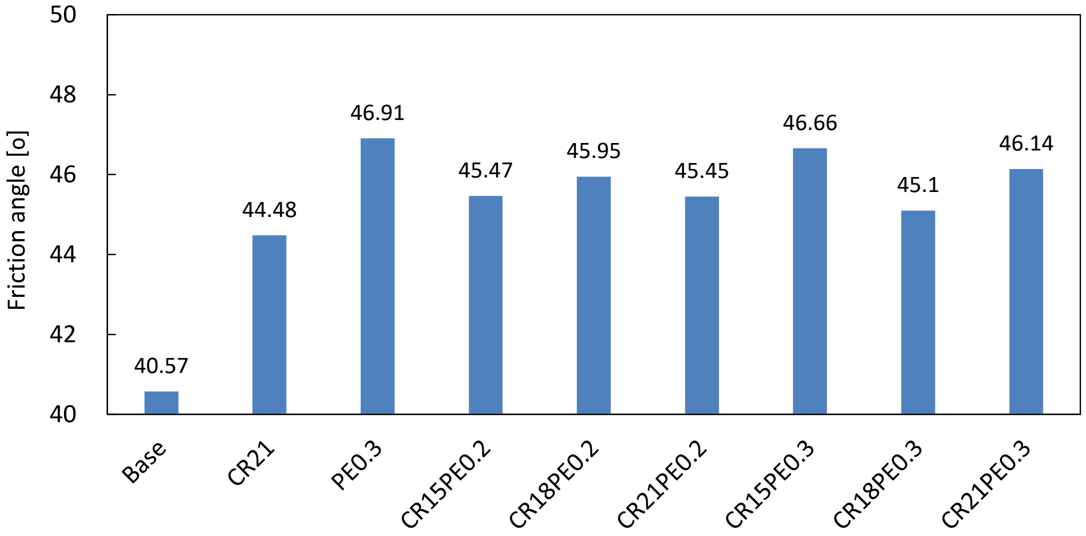

Figure 9. Friction angle of asphalt mixtures before and after modification

4.3 Fatigue behavior of modified asphalt mixture

The four-point bending (4PB) test was conducted to investigate the influence of CR and PE on the fatigue performance of asphalt mixtures. Four asphalt mixtures (Base, PE0.3, CR21PE0.2 and CR21PE0.3) were selected for comparison. Figure 10 shows a typical flexural stiffness development curve with loading cycles. The reduction in the flexural stiffness reflects the development of the internal structures with the repeated loading, and three damage stages can be briefly classified. In stage Ⅰ, the flexural stiffness experienced an obvious decrease at the beginning. This represents the initial development of fatigue damage and the rapid reduction in the flexural stiffness is mainly because of the temperature increase inside the mixture specimen during the repeated loading (Benedetto et al., 1996). In stage Ⅱ, the reduction in the flexural stiffness was in a relatively low rate. This represents a low level of damage and a constant ratio of dissipated energy in the previous loading cycle is transformed into damage due to the formation of micro-cracks. Finally, micro-cracks are developed to macro-cracks and this results in an obvious reduction in the flexural stiffness in StageⅢ[0]. In this section, four parameters were produced from the 4PB test results: initial flexural stiffness, phase angle, fatigue life as well as accumulative dissipated energy.

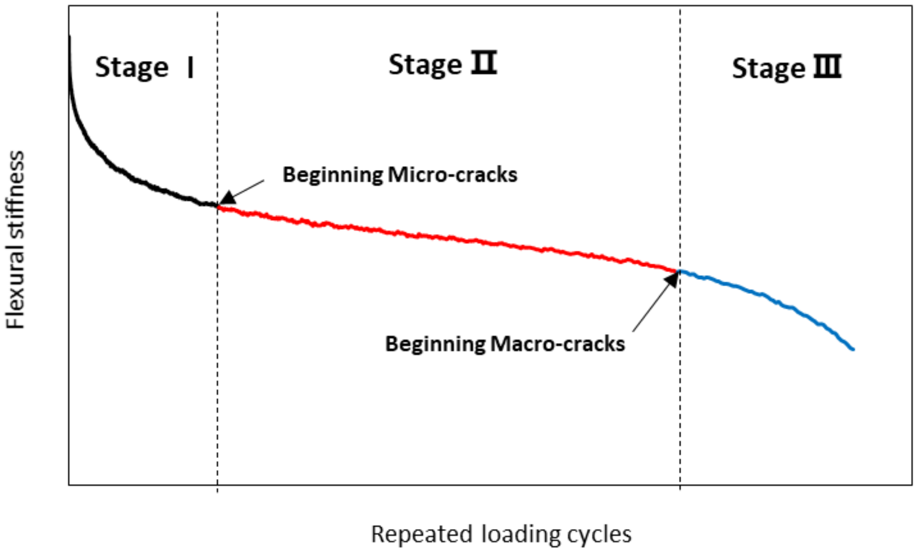

Figure 10. A curve of flexural stiffness versus loading cycles

In this research, the flexural stiffness at the 100th cycle of repeated loading was defined as the initial flexural stiffness. This parameter reflects the capability of the asphalt beam to resist the flexural deformation. Figure 11 presents initial flexural stiffness of asphalt mixtures before and after modification by adding CR and/or PE. It can be found that the initial flexural stiffness of asphalt mixtures decreased from 3561 MPa to 3157 MPa after incorporating PE with a dosage of 0.3%. It is well known that the addition of PE can increase the stiffness of bituminous binders. However, many light components of bitumen would be absorbed by the PE and this results in the reduced adhesion between aggregates and binders, which in turn decreased the initial flexural stiffness of the PE modified asphalt mixture. The integrated modification by adding CR and PE resulted in an increased initial flexural stiffness with values of 3781 MPa and 4098 MPa for CR21PE0.2 and CR21PE0.3, respectively. This indicated that CR was the dominant component for improving the initial flexural stiffness of asphalt mixtures. The incorporation of CR improved the toughness and tenacity of the bituminous binders, by which the cohesive and/or adhesive properties of asphalt mixtures can be reinforced and finally contributed to the initial flexural stiffness modulus.

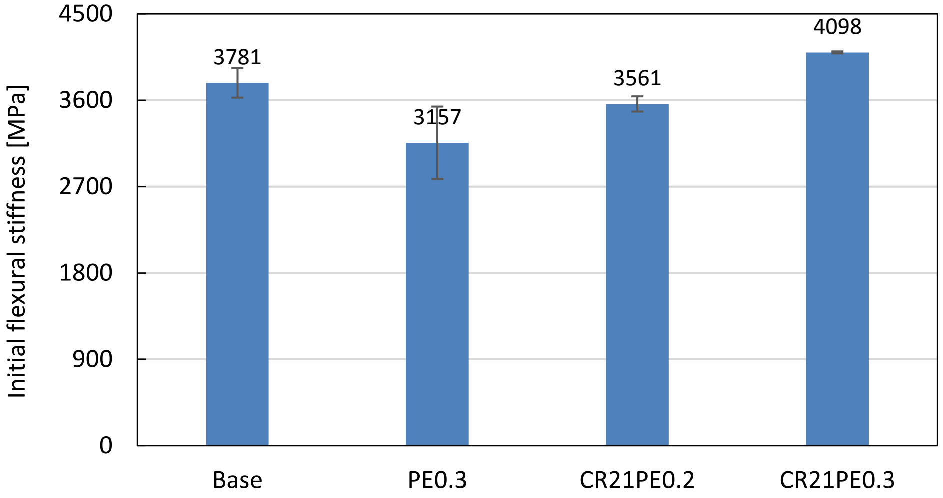

Figure 11. Initial flexural stiffness of asphalt mixtures before and after modification

Phase angle is defined as the time difference between the applied loading and the created deformation, with a lower value indicating more elasticity and rigidity of asphalt mixtures. The phase angle values of asphalt mixtures before and after modification are shown in Figure 12. It can be revealed that the normal asphalt mixture and the PE modified asphalt mixture (PE0.3) obtained the highest and lowest phase angle results, with the value being 38.71° and 28.91°, respectively. This result indicated that the addition of PE resulted in an increased elastic component of bituminous binder, which improved the rigidity of modified asphalt mixtures. With respect to the integrated modified asphalt mixtures by using CR and PE, their phase angle values were higher than that of the PE modified asphalt mixture. This can be attributed to the lower stiffness of CR than that of the PE, by which the high rigidity of the PE modified binder was softened resulting in the increased phase angle. This phenomenon was in agreement with the author's previous research on modified bitumen [0]. As the stiffness of CR was higher in comparison with the base bitumen, the phase angle value of the integrated modified asphalt mixture cannot surpass that of the normal asphalt mixture.

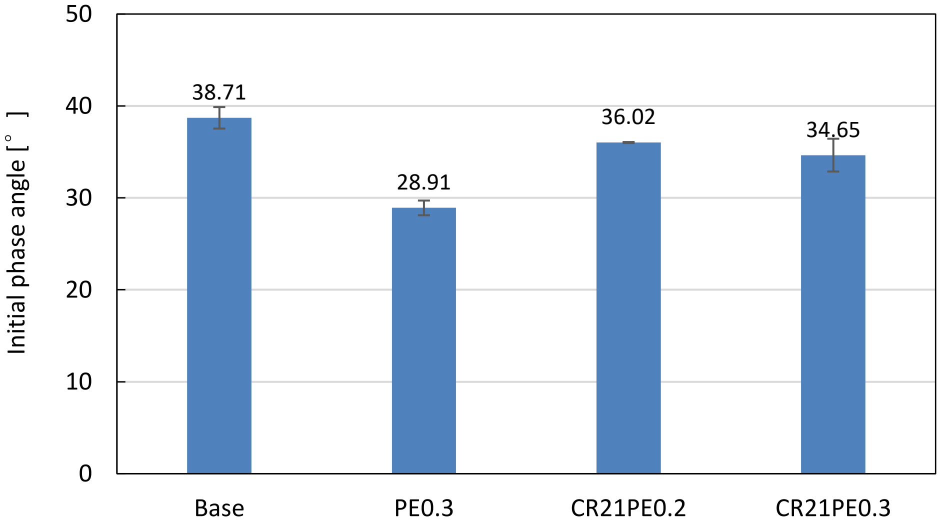

Figure 12. Phase angle of asphalt mixtures before and after modification

In this research, the fatigue life of the asphalt beams was defined as the loading cycles that cause 50% reduction of the specimen's initial flexural stiffness. The cumulative dissipated energy was calculated by summing the dissipated energy from each cycle up to the defined failure. Figure 13 and 14 show the fatigue life and the cumulative dissipated energy of asphalt mixtures before and after modification, respectively. The normal asphalt mixture had the highest fatigue life with a value of 187075, indicating its superior resistance to fatigue damage. However, the fatigue life declined to 30160 after adding PE, which showed significantly reduced fatigue resistance. As a type of thermoplastic material, although PE can increase the bitumen stiffness, its incorporation absorbed many light components from the base bitumen and resulted in the reduced adhesive properties of the bituminous binders. Moreover, PE increased the rigidity of the asphalt mixture and the stress inside the specimen was not easy to dissipate, as shown in Figure 14. When the repeated loading was applied, the asphalt mixture with the addition of PE was prone to form micro-cracks and to accelerate the fatigue damage. In terms of the integrated modified asphalt mixtures, their fatigue life experienced an obvious increase with the values increasing to 110005 and 104140 for CR21PE0.2 and CR21PE0.3, respectively. Moreover, the cumulative dissipated energy also increased due to the addition of CR. It was thus suggested that the addition of CR was able to improve the fatigue properties of the PE modified asphalt mixture. After modification by adding CR, the most volatile components of bitumen were transferred to the rubber, which resulted in more viscous binders (López-Moro et al., 2013). The improved bitumen viscous response had a positive effect on the integrity of the asphalt structure and finally contributed to the fatigue resistance. Due to the detrimental effect of PE, the fatigue properties of the integrated modified asphalt mixtures cannot be higher than that of the normal asphalt mixture.

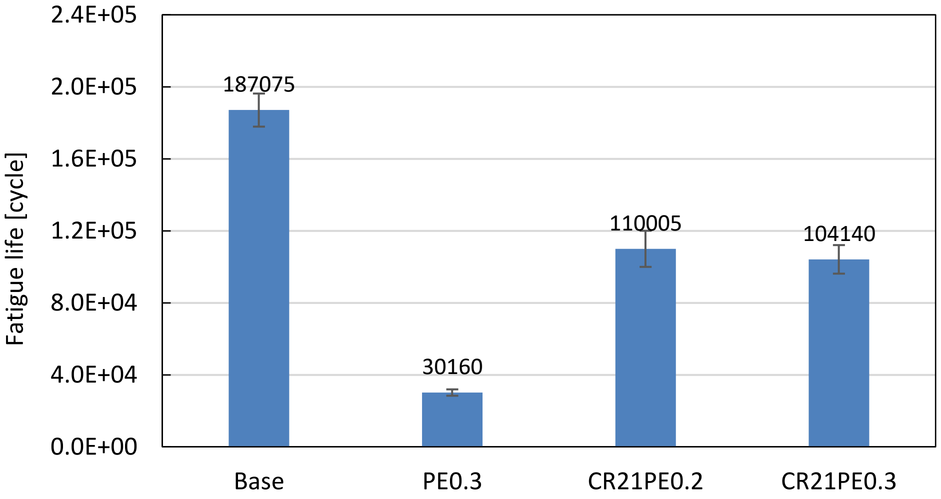

Figure 13. Fatigue life of asphalt mixtures before and after modification

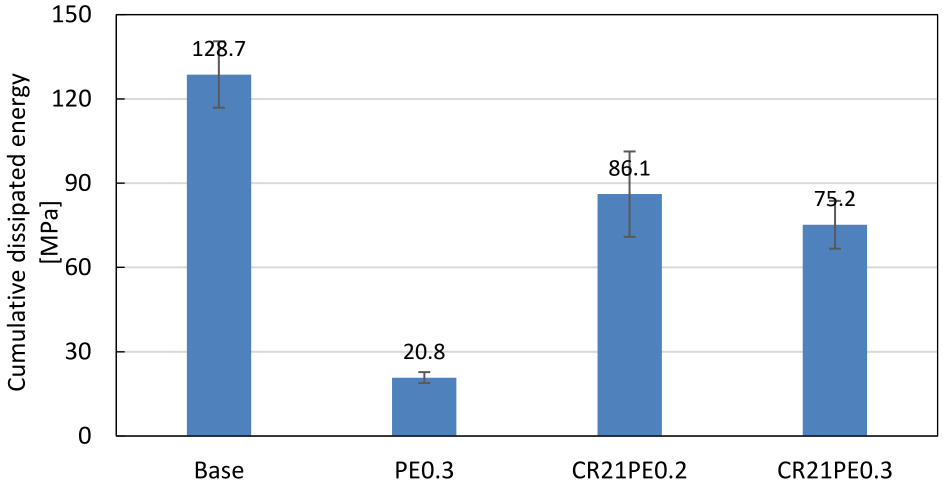

Figure 14. Cumulative dissipated energy of asphalt mixtures before and after modification

5. Conclusions

In this study the contribution of PE and CR on the pavement performance of asphalt mixture was evaluated by using wheel tracking, uniaxial penetration as well as four-point bending fatigue tests. The following findings can be given:

- The integrated modified asphalt mixture prepared with PE and CR obtained significantly higher dynamic stability than that of the normal asphalt mixture, indicating better rutting resistance. The PE dosage was a key variable for enhancing the rutting resistance of the modified asphalt mixtures.
- The integrated modification method by adding both PE and CR enhanced the shear strength of asphalt mixtures at high in-service temperatures, which in turn had the potential to reduce the flow rutting of asphalt pavements.
- The addition of both CR and PE can increase the cohesion of asphalt mixtures. Once the two interlocked phases were formed, increasing the PE dosage had less contribution to the improvement of the mixture cohesion, while increasing the CR content can further enhance the cohesion. In addition, the friction angle of asphalt mixtures was mainly determined by the addition of PE.
- With respect to the results from the four-point bending test, the addition of PE significantly reduced the fatigue life of asphalt mixtures while the CR was able to improve the fatigue properties of the PE modified asphalt mixture. This indicated that the improved bitumen viscous response after adding CR had a positive effect on the fatigue resistance.
- Based on the experimental results, it was found that the integrated modified mixture CR21PE0.2 obtained, relatively speaking, the best pavement properties compared to that of other asphalt mixtures. Therefore, the asphalt mixture prepared with the CR dosage of 21% by weight of the base bitumen and the PE content of 0.2% by weight of the asphalt mixture was considered as the optimum mixture design.

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