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Integrated utilization of recycled crumb rubber and polyethylene for enhancing the performance of modified bitumen

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HIGHLIGHTS

- Integrated modification by using CR and PE improved the bitumen properties at both high and low temperatures.
- Integrated modified bitumen obtained comparable rheological properties with the SBS modified bitumen.
- The integrated modified bitumen has much more economic benefit than SBS modified bitumen.

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ABSTRACT

With the development of urbanization, a huge amount of wasted vehicle tyre and wasted green house plastic film are generated everyday and they have a potential risk for human health and environment. In this article, an integrated modification method was developed by proportionally using recycled crumb rubber (CR) from vehicle tyre and polyethylene (PE) from wasted green house plastic film in the bitumen in order to modify its functioning in pavements. Experimental tests such as Softening point, Penetration, Dynamic Shear Rheometer (DSR), Multiple Stress Creep Recovery (MSCR) and Bending-Beam Rheometer (BBR) were carried out in comparison with the bitumen properties. Analysis on physical and rheological performance of modified bitumen binders indicated the addition of CR decreased the bitumen creep stiffness at low temperature which in turn reduced the brittleness and cracking risk. Meanwhile, the addition of PE increased the bitumen stiffness at high temperature. According to the morphology analysis, two continuous twisted phases were formed in the modified bitumen, which indicated enhanced rheological property and high-temperature performance. The addition of CR and PE cooperatively improved the bitumen properties at both high and low temperatures. Consequently, the utilization of these two waste materials not only improved the pavement performance with the modified bitumen, but also minimized their disposal at landfills.

1. Introduction

Since 2016, total expressway length in China is over 130 thousand km. In the field of pavements, the asphalt mixture is the dominant material for surface paving course. Asphalt mixture is produced at high temperatures by mixing predetermined ratio of aggregates (coarse and fine), bitumen and filler, after paving and compaction process to form a flexible pavement [1]. The physical and rheological properties of bituminous binders play an important role in the performance of asphalt mixtures [2,3]. Sybilski et al. reported that bitumen properties have approximately a 40% contribution to the rutting resistance of asphalt pavement [4]. In high-temperature regions, rutting (permanent deformation) is a major distress of asphalt pavements, where mixtures placed in the wheel paths compact to form a groove or rut due to a heavy vehicle. It is important to improve the bitumen properties so as to accommodate increasing traffic loading and environmental attack.

Traditionally, the incorporation of polymer based materials in bitumen by mechanical mixing or chemical reaction can significantly improve the properties of the conventional bitumen [5,6]. There are numerous polymer agents applied for bitumen modification which can generally be classified into two categories: thermoplastic elastomers and plastomers [7]. Thermoplastic elastomers are a type of copolymers exhibiting both thermoplastic and elastomeric properties which can resist permanent deformation under loading and elastically recovering once unloading [8]. There are several thermoplastic elastomers, such as styrene-butadiene

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styrene (SBS), styrene-isoprene-styrene (SIS) and styrene-ethylene/butylene-styrene (SEBS), were successfully used for bitumen modification [9,10]. Although these agents are capable of increase the bitumen complex modulus and viscosity to some extent, but the price is extremely higher than the conventional bitumen. Plastomers combined qualities of elastomers and plasticsus ually result in improved permanent deformation at elevated temperatures. The commonly used plastomers for bitumen modification include polyethylene (PE), polypropylene (PP), ethylene-vinyl acetate (EVA) and ethylene-butyl acrylate (EBA) [11,12]. However, use of these plastomer agents cannot improve the elastic recovery of bitumen which in turn failed to improve the low-temperature properties of asphalt mixtures [8].

Nowadays, in modern cities, a huge amount of wasted vehicle tyre and wasted green house plastic film are generated everyday. Commonly, these wastes management is to dispose at landfills, which certainly have a potential risk for human health and environment due to hazardous components in these wastes. It has been estimated that over 10 billion tires are discarded worldwide every year and the inadequate disposal of tyre pose a potential to fire risk, rodents, soil pollution and water pollution which eventually threat to human health and environment [13,14]. Besides, the improper disposal of wasted plastic film pollutes the soils through atmospheric precipitation, water irrigation, and fertilizer application, which threats to human health through contamination of the food chain [15,16]. Therefore, their recycling and reuse is becoming great significance and has been focused by many researchers [17,18].

In this article, the use of recycled crumb rubber (CR) and Recycled PE to modify the performance of bitumen has been researched. Previous researchers recognized that the CR is able to improve the resistance of bitumen to permanent deformation, fatigue cracking and crack reflection at both high and low in-service temperatures [19–21]. Additionally, researchers found that the PE can bring a high rigidity to the bitumen and improve its deformation resistant under traffic load at high in-service temperatures [22,23]. Since these two materials have high decomposition temperature, high resistance to ultraviolet radiation and are mostly not biodegradable, they can remain for years causing environmental pollution [24]. From an environmental and economic standpoint, the application of these recycled materials cannot only improve the performance of road pavement, but also solve a waste disposal problem [21]. Besides, the price of these two additives is significantly lower than the commonly used commercial modifying agents.

The main aim of this paper was to develop an integrated bitumen modification method by using these cheap recycled waste and their unique characteristics in order to overcome some drawbacks of commonly used modified bitumen. One type of additive was first added to bitumen with different dosages to characterize the influence of a single component on the bitumen property. Then, these two recycled waste additives were mixed with bitumen and finally determined the best formula for integrate modification. Fluorescence Microscopy (FM) technique was carried out to characterize the morphology of the integrated modified bitumen and evaluate the homogeneity and phase structure. Experimental tests such as Softening Point, Penetration, Dynamic Shear Rheometer (DSR), Multiple Stress Creep Recovery (MSCR) and Bending-Beam Rheometer (BBR) were applied to analyze the mechanical performance of bitumen at both low and high temperatures.

2. Materials and sample preparation

2.1. Materials

One type of 70# base bitumen was selected to prepare modified bitumen. This is widely used for expressway construction in China. Commercial SBS modified bitumen (with the SBS dosage of 5%) which was produced using the same 70# base bitumen was selected as a reference to compare the properties with the modified bitumen by using selected recycled agents. These two bitumen were all supplied by Huarui Road Material Company. The physical properties of these two bitumen are listed in Table 1.

The CR derived from reclaimed vehicle tyre was selected as one additive for bitumen modification. The tyre was first shredded and chipped using large machinery to obtain rubber shreds [13]. Furthermore, large rubber shreds were experienced ambient grinding process to reduce the particle size in the range of 0.4–0.8 mm, as showed in Fig. 1a. Another additive, reclaimed PE was produced from wasted plastic greenhouse film. The wasted plastic film experienced cleaning, drying, extrusion and pelleting process to obtain the reclaimed PE with the particle size of 2.0–3.0 mm, as showed in Fig. 1b. The CR and PE used in this research were supplied from Shandong Qilufa transportation technology co. Ltd.

2.2. Sample preparation of modified bitumen

Before preparing the modified bitumen, the contribution of a single additive to bitumen property should be evaluated. Therefore, the modified bitumen with single additive was first prepared. The bitumen was heated to 160 °C until it has melted. Then, the additive was added to the bitumen with different dosage (11% and 15% for CR, or 6% and 7% for PE) and followed by swelling process at 160 °C for 1 h [25]. During swelling process, the polymer agents can adequately contact with the hot bitumen to make the agents expand and soft. Furthermore, the hot bitumen with additive experienced high-speed shear process at the speed of 5000 r/min for 1 h to obtain essentially homogeneous modified bitumen. The same procedure was applicable to prepare integrated modified bitumen by adding both CR and PE agents with different dosages. Well mixed modified binders were stored at room temperature and ready for further evaluation.

Herein, three groups of bitumen including ten samples were investigated in the next section as listed in Table 2.

3. Methodology

3.1. Morphology evaluation

A Fluorescence Microscopy (FM) test was performed to evaluate the morphology of binders before and after modification. By attempting this test, factors such as the dispersion state of polymer additives as well as the nature of continuous and discontinuous phases in the modified bitumen can be characterized [26,27]. During testing, polymer components in the modified bitumen can be illuminated by fluorescent light so that the polymer rich phase appears light while the bitumen rich phase appears dark or black [26]. It has been reported that the FM test is the most advantageous method to study the morphology of polymer modified bitumen due to its ability to observe the homogeneity and the structure in the raw state [26,28].

By preparing specimens for FM test, the liquid bitumen was first dropped in the center of a clean glass slide and followed by covering a piece of glass slide on the top. Then, covered samples were placed in an oven at 135 °C for 5 min with the view of obtaining a smooth and flat surface. After cooling down to room temperature, these samples were examined under a microscope with the images were taken with a digital camera.

3.2. Conventional bitumen tests

The ring and ball test was performed based on the ASTM D36 standard to evaluate the softening point of bitumen before and after modification. According to ASTM D5, the penetration test

Table 1
Physical properties of bitumen.

Property	Sample	
	Base bitumen	SBS modified bitumen
Softening point (°C)	46.2	61.3
Penetration (25 °C, 0.1 mm)	68.2	53.9
Ductility (15 °C, cm)	>100	>100

Fig. 1. Morphology of the additives before and after reclaim (a) crumb rubber and (b) reclaimed PE.

Table 2
Bitumen samples and their sample ID used for further evaluation.

Group	Sample composition	Sample ID
Reference bitumen	Base bitumen	Base
	SBS modified bitumen	SBS
Modified bitumen with single additive	Bitumen + 11% CR	CR11
	Bitumen + 15% CR	CR15
	Bitumen + 6% PE	PE6
	Bitumen + 7% PE	PE7
Composite modified bitumen	Bitumen + 11% CR + 6% PE	CR11PE6
	Bitumen + 11% CR + 7% PE	CR11PE7
	Bitumen + 15% CR + 6% PE	CR15PE6
	Bitumen + 15% CR + 7% PE	CR15PE7

Note: CR is the crumb rubber; PE is the polyethylene.

was carried out with the view of measuring the influence of modification on bitumen hardening.

3.3. Temperature sweep tests

The influence of modifying waste agents on the viscoelastic properties of bitumen was evaluated using DSR (AR2000ex) by applying a sinusoidal displacement within the linear visco-elastic range. The temperature sweeps were performed in the temperature range of 46–82 °C with a 6 °C increment at fixed frequency of 10 rad/s, with the values of the complex modulus ($G*$) and phase angle (δ) being recorded. In this temperature range, parallel plates with 25 mm diameter and 1 mm gap were applied.

3.4. MSCR tests

The MSCR test (AASHTO TP 70 2009) was performed to evaluate the resistance of bitumen to permanent deformation at 60 °C. This test was modified from the fixed-stress repeated creep-recovery method with the view of assessing the delayed elastic response of bituminous binders and their plastic deformation at high temperatures [29]. In this research, the MSCR test was carried out by using parallel plates with 25 mm diameter and 1 mm gap. The test first applied 10 creep-recovery cycles of low stress (0.1 kPa) and followed by 10 creep-recovery cycles of extreme stress (3.2 kPa) for a total of 20 cycles. One creep-recovery cycle including one second of shear loading and nine seconds of recovery phase (ASTM D 7405-08a). Percent Recovery (R) obtained in this test reflects how much of the sample returned to its previous shape after being repeatedly stretched and then relaxed with higher value demonstrating better fatigue resistance [30]. Another parameter, the Non-Recoverable Creep Compliance (J_{nr}), is the amount of residual strain left in the specimen after repeated creep and recovery which reflects the resistance of bitumen to permanent deformation [31].

3.5. Bending-Beam Rheometer tests

BBR (ASTM-D6648) is a well-known method which is widely applied for evaluating the resistance of bituminous binders to thermal cracking at low temperatures [32]. This test is used to evaluate the creep response of bitumen at low temperature with creep stiffness (S) and m-value (m) were obtained. The S measures the resistance of bitumen to constant loading and m measures the changes of bitumen stiffness under loading. During testing, a constant load of 980 ± 50 mN is applied on the bitumen beam with the deflection being recorded. The creep stiffness of the specimen is then calculated by:

$$S = \frac{PL^3}{4bh^3\delta_t} \qquad (1)$$

where S is the creep stiffness (MPa); P is the applied load (N); L is the span length of the specimen (102 mm); b is the width of the specimen (12.7 mm); h is the thickness of the specimen (6.35 mm) and δ_t is the deflection at time t.

The m-value is the absolute value of the slope of the log[S(t)]-log(t) curve obtained by:

$$m = \left| \frac{d \log S(t)}{d \log(t)} \right| \qquad (2)$$

where S is the creep stiffness (MPa) and t is the time (s).

Based on the ASTM D6648 standard, with the view of resisting thermal cracking at low temperatures, the creep stiffness should be less than 300 MPa to avoid high tensile stress in bitumen, while the m-value should be >0.300 to ensure stress relaxation [33].

4. Results and discussion

4.1. Morphology evaluations

The morphology changes of bitumen before and after modification were captured using fluorescence microscopy in Fig. 2. Due to the fluorescent effect of the polymer, the polymer phase is illuminated by the blue light and appears yellow while the bitumen phase absorbs the blue light and appears dark. So, the base bitumen without adding any polymer additive appears absolutely dark as illustrated in Fig. 2.

After modified with the addition of CR, it can be seen that the CR was well dispersed in the bitumen phase with irregular morphology. It demonstrated that the CR is well interpreted in the bitumen under the shear process at high temperatures. The PE particle seems relatively larger in comparison with the CR with the particle size over 10 µm. Furthermore, the interface between bitumen and PE is very clear and the morphology is approximately regular, it is indicated that the PE is very difficult to absorb enough oily fraction. By only adding one additive (CR or PE), it does not disperse in the bitumen phase without forming continuous polymer phase.

In terms of the integrated modified bitumen, the images show a clear change in morphology. At a lower polymer content (CR11PE6), the polymer particles are swollen by the oily phase of base bitumen and dispersed homogeneously in the bitumen. When the PE dosage is increased to 7%, as shown in Fig. 2 (CR11PE7), a nearly continuous polymer phase which is distributed in the bitumen. In this situation, the bitumen tends to have high stiffness which makes them perform well at high temperatures. At higher polymer content (CR15PE6 and CR15PE7), the images showed two continuous twisted phases. Two interlocked phases which form a network structure is recognized as an ideal microstructure for polymer modified bitumen and which could significantly enhance the properties of bitumen [34].

4.2. Conventional physical properties

Conventional physical properties including softening point and penetration were measured and shown in Figs. 3 and 4, respectively. In Fig. 3, the softening point increases with the addition of CR or PE, indicating the improvement of high-temperature performance. The penetration results experience contrast trend with the values declined with the addition of CR or PE, as shown in Fig. 4. By adding CR, particles absorb the oily phase which increases the asphaltene component of bitumen and finally results in the increased stiffness. Then, PE particles are swollen by the oily component to form two twisted continuous phases so as to improve the stiffness and rutting resistance. It is clear that the PE modified bitumen showed significantly higher softening point and lower penetration in comparison with the CR modified bitumen.

The integrated modified binders with both CR and PE additives were evaluated with properties compared with one-component modified bitumen. In terms of the same CR dosage, the modified bitumen shows higher softening point and lower penetration in comparison with the CR modified bitumen, as shown in Figs. 3 and 4. However, in the integrated modified bitumen, the addition of CR slightly decreases the softening point and increases the penetration values. This could be attributed to the much lower stiffness of CR than the PE, by which the PE modified bitumen was softened and results in the reduced softening point values.

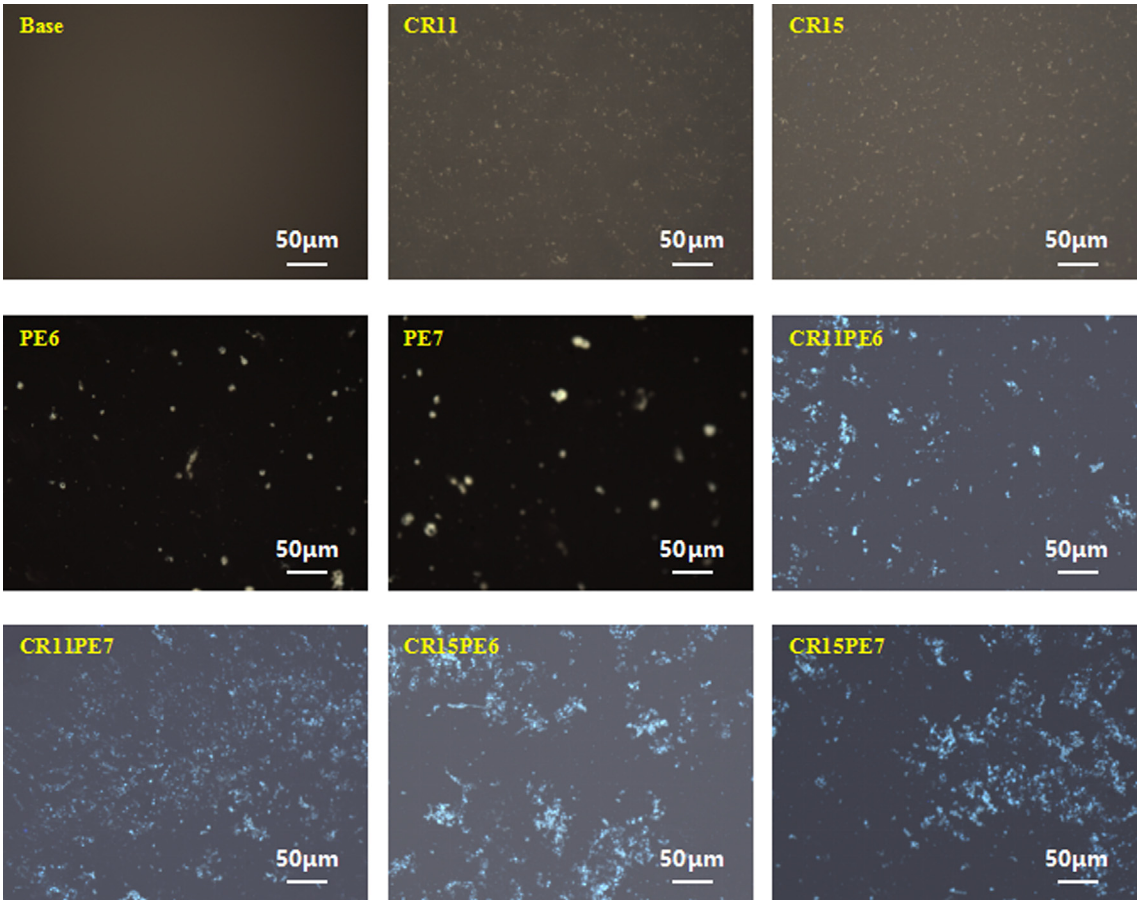

Fig. 2. Fluorescence microscopy image of base bitumen and modified bitumen with 40 magnifications.

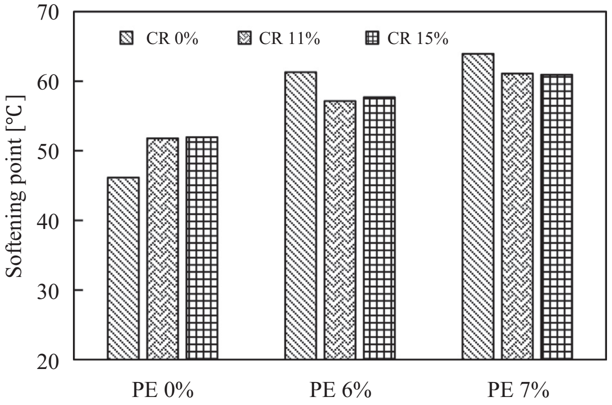

Fig. 3. Softening point of bitumen before and after modification.

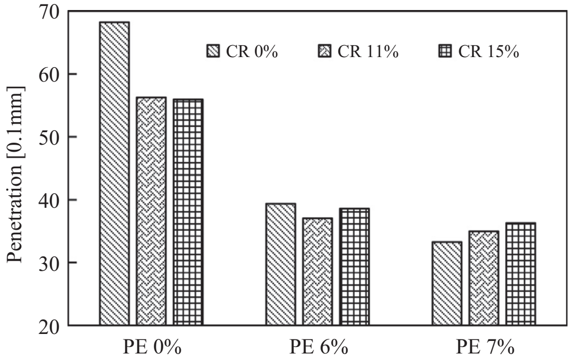

Fig. 4. Penetration of bitumen before and after modification.

As the purpose of this research is to develop modified bitumen with rutting resistance, the softening point results were compared with commercial SBS modified bitumen showing in Table 1. It can be seen that bitumen containing 6% and 7% of PE can obtain comparable stiffness with SBS modified bitumen.

4.3. Temperature sweep results at high temperatures

Temperature sweep tests were performed at a frequency of 10 rad/s with the complex modulus (G∗) and phase angle (δ) curves are shown in Fig. 5. In order to obtain a clear comparison, the modified sample CR15PE7 and its related reference samples were selected and plotted in the figure. It can be seen that when temperatures are lower than 70 °C, the based bitumen shows the lowest complex modulus while the PE7 shows the highest value. Because of the addition of CR, the complex modulus of CR15PE7 experiences a slight decline in comparison with the PE7, but the value is higher than that of the SBS modified bitumen. With the temperature increasing, the complex modulus values decrease continuously. When temperatures exceed 70 °C, CR15PE7 shows the highest complex modulus in comparison with other binders. It is demonstrated that the addition of both CR and PE increases the complex modulus of bitumen which in turn improves the resistance to permanent deformation at high temperatures.

In terms of the phase angle curves, the base bitumen shows the highest value and the SBS modified bitumen shows the lowest value. It is generally considered that the phase angle is more sensitive to the chemical structure variation in comparison with the complex modulus. With the addition of PE and CR, the phase angle of bitumen experiences a significant decrease demonstrating the increase of the elastic behaviour of bitumen. This phenomenon indicates that the integrate modification leading to the increase of the elastic component of bitumen and it is contributing to the flexibility of asphalt pavement.

The development of complex modulus and phase angle can be attributed to two major factors. First, the addition of PE (plastomers) creates two interlocked continuous phases in the bitumen, which results in the increase in stiffness. Secondly, owing to the contribution of CR, a rubbery supporting network is formed in the bitumen and results in the improved elastic response [7].

The rutting parameter G * /sinδ at 10 rad/s angular frequency was considered as an important indicator in characterizing the rutting resistance of bitumen [21]. The bitumen is considered to be rutting resistant if the value of rutting parameter is above 1 kPa at a frequency of 10 rad/s [35]. As observed in Fig. 6, the addition of CR and PE causes an increase in the G * /sinδ with the PE7 and CR15PE7 obtained the highest values, which is expected to be more resistant to permanent deformation. In addition, the rutting parameters for all specimens decrease with the increase of temperature, indicating the reduction in the rutting resistance.

The failed temperature of all specimens corresponding to G * / sinδ = 1 kPa were calculated and shown in Table 3. From this table it can be seen that the addition of CR increased the failed temperatures from 67.3 °C to slightly over 70 °C, while the values after

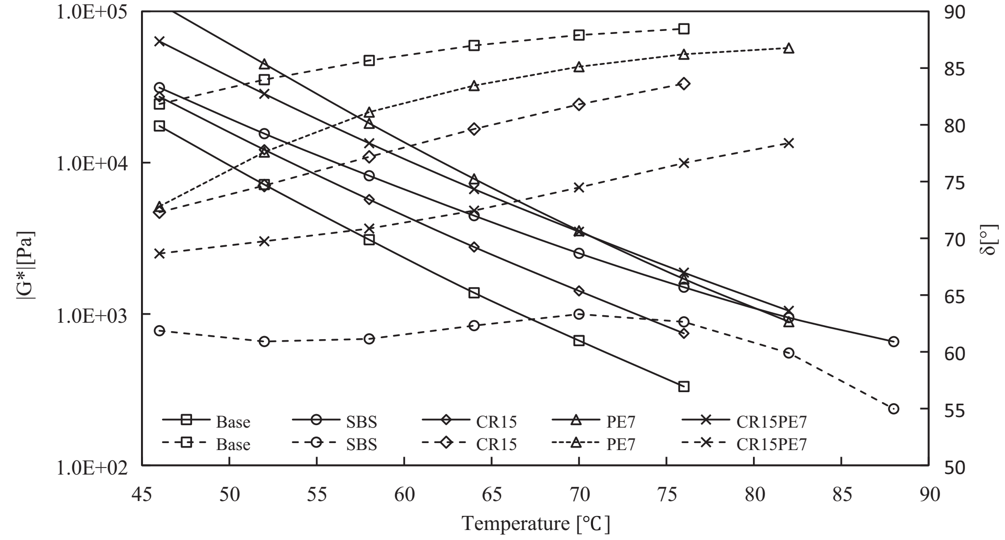

Fig. 5. Complex modulus and phase angle of all specimens.

adding PE reached at 80 °C. In terms of the integrated modified bitumen, the failed temperatures showed nearly the same values as the PE modified bitumen, indicating PE is the dominant factor for rutting resistance. Moreover, the CR15PE7 and SBS modified bitumen shows nearly the same failed temperature. Based on the temperature sweep test, it can be concluded that the integrated modified bitumen obtained comparable high-temperature properties with SBS modified bitumen.

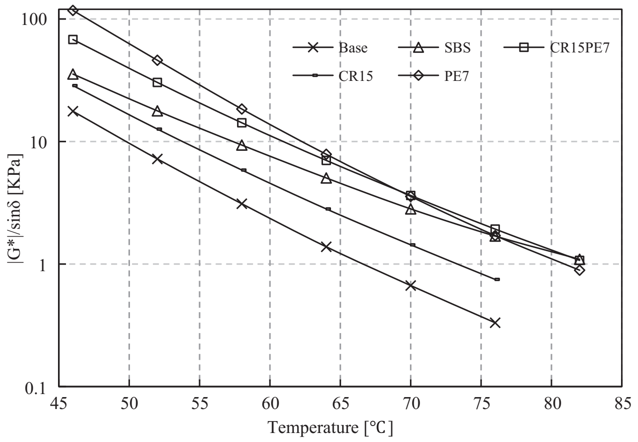

Fig. 6. Effect of temperature on rutting parameter for base bitumen and modified bitumen at a frequency of 10 rad/s.

4.4. MSCR test results

As the oscillatory sweep shear experiments employed small strain within the linear visco-elastic range, the rutting parameter does not always illustrate the real rutting resistance of bituminous binders. Moreover, sweep shear applied cyclic reversible loading, which cannot simulate the irreversible deformation of rutting [36]. So, the MSCR test was performed as a supplement to rutting parameter.

MSCR tests were performed at 60 °C under two stress levels of 0.1 kPa and 3.2 kPa, with the accumulated strain of selected specimens versus loading and unloading time were plotted and shown in Fig. 7. By comparing Fig. 7(a) and (b), it can be seen that higher creep stress results in higher accumulated creep strain. At the same stress level, the addition of CR or PE decreases the creep strain, while the PE causes the lowest value. It is demonstrated that PE significantly improves the resistance of bitumen to permanent deformation. In terms of the integrated modified bitumen (CR15PE7), the accumulated strain value is slightly higher in comparison with PE7 and SBS. This phenomenon correlates well with the Softening Point result.

The values of Percent Recovery (R) and Non-Recoverable Creep Compliance (J_{nr}) of all specimens were calculated according to ASTM D7405-10a and shown in Table 4. As it can be observed, the modifying agents, especially the PE, play an important role in increasing R values and reducing J_{nr} values. The integrated modified bitumen binders also show the same trend with the increased R values and the decreased J_{nr} values. In this case, binders show more elastic behaviour indicating the resistance to plastic deformation and fatigue deterioration under repeated loading. It should

Table 3
The failed temperature of all specimens corresponding to G * /sinδ = 1 kPa.

Results Binder	Reference		Single modified				Composite modified			
	Base	SBS	CR11	CR15	PE6	PE7	CR11PE6	CR11PE7	CR15PE6	CR15PE7
Failed temperature (°C)	67.3	82.8	71.7	73.2	80.1	80.4	79.0	80.2	81.7	82.7

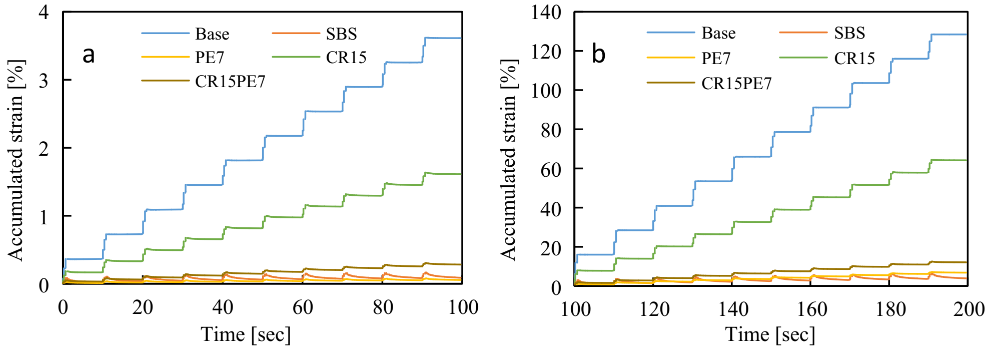

Fig. 7. Accumulated strain results of CR15PE7 and related specimens obtained from MSCR tests at 60 °C under different stress levels: (a) 0.1 kPa and (b) 3.2 kPa.

Table 4
Percent Recovery (R) and Non-Recoverable Creep Compliance (J_{nr}) values of all specimens under two creep stress.

Results Binder		Reference		Single modified				Composite modified			
		Base	SBS	CR11	CR15	PE6	PE7	CR11PE6	CR11PE7	CR15PE6	CR15PE7
0.1 kPa	R (%)	0.72	57.05	3.18	4.27	18.25	40.32	12.44	12.69	11.79	15.95
	J_{nr} (1/kPa)	0.36	0.01	0.19	0.16	0.02	0.01	0.04	0.04	0.04	0.03
3.2 kPa	R (%)	0.15	45.01	0.94	1.76	4.91	11.02	6.05	5.96	5.08	7.99
	J_{nr} (1/kPa)	0.39	0.01	0.23	0.20	0.04	0.02	0.05	0.05	0.04	0.04

be mentioned that the integrated modified bitumen shows less elastic recovery in comparison with the SBS modified bitumen.

4.5. BBR test results

The BBR test was performed at −18 °C to evaluate the low-temperature performance of bitumen, with the results of flexural creep stiffness (S) and m-values in Figs. 8 and 9, respectively. The bitumen with smaller creep stiffness and/or larger m-values is recognized to have a better low-temperature performance. By only adding PE, the creep stiffness is significantly increased, which indicates the decreased low-temperature property and is prone to crack at low temperatures, as shown in Fig. 8. However, after adding CR, the creep stiffness takes on steadily decline. It is noteworthy that when the CR dosage is increased to 15%, creep stiffness of composite modified bitumen can decrease by nearly the same level as that of the SBS modified bitumen. The m-values present an opposite trend as shown in Fig. 9. It is demonstrated that the CR could improve the flexibility of bitumen and result in a better low-temperature performance. In contrast, PE reduces the stress relaxation of bitumen which indicates a potential to thermal cracking at low temperatures.

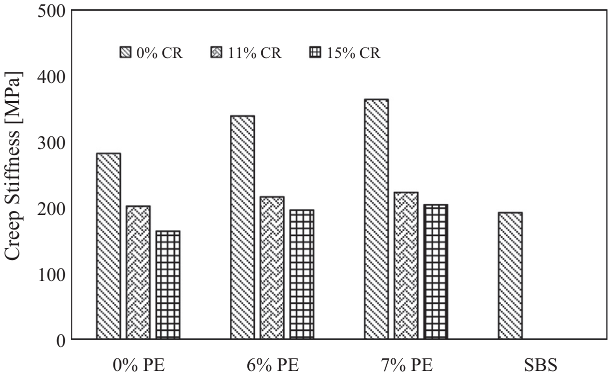

Fig. 8. Creep stiffness values of bitumen before and after modification at −18 °C.

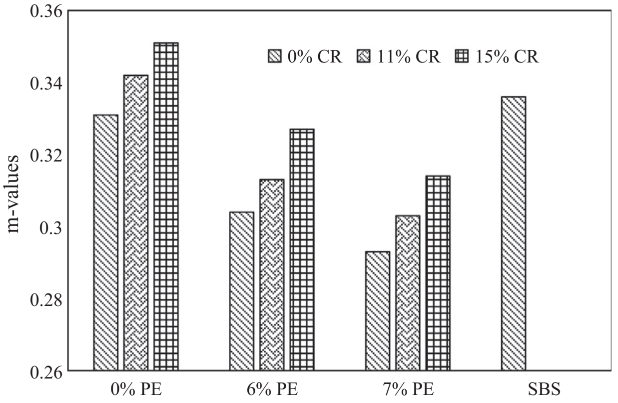

Fig. 9. m-values of bitumen before and after modification at −18 °C.

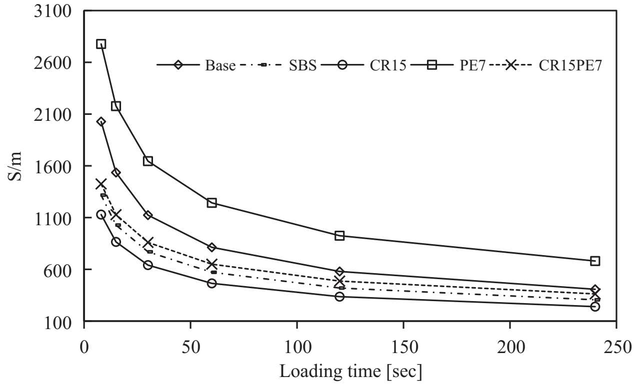

Fig. 10. Variation of S/m-values with loading time of samples related to CR15PE7.

Because bitumen with lower creep stiffness and higher m-value is considered to have good ability to crack resistance at low temperatures, the ratio of creep stiffness divided by m-value (S/m) is calculated and plotted versus the loading time, as shown in Fig. 10. It can be seen that the PE7 has the highest S/m value while the CR15 has the lowest value. It is indicated that the CR is the main factor to improve the low-temperature performance of bitumen. In addition, the S/m value of CR15PE7 integrated modified bitumen is lower than the base bitumen and nearly overlapped with the SBS modified bitumen. The results verifies that by changing the dosage of these two additives, the low-temperature performance of integrated modified bitumen is able to reach the same level compared to the commercial SBS modified bitumen.

5. Economic benefit analysis

Based on the experimental results presented in Section 4, the optimum ratio of CR and PE to base bitumen are 15% and 7%, respectively. In this part, the economic benefit of the integrated modified bitumen was analyzed and compared with the benchmark – SBS modified bitumen. As the PE was added into the hot aggregate directly during the on-site production, only CR modified bitumen need to be prepared.

According to the consultation in China, the price of the SBS modified bitumen used in this research is $ 650 per ton. The prices of related materials as well as operating cost used for integrated modification were presented in Table 5. As presented in this table, the total cost to produce one ton of integrated modified bitumen by using CR and PE was calculated as $ 551.2 which is about $ 100 cheaper than the SBS modified bitumen. So, the economic benefit of this integrated modified bitumen is very obvious in comparison with the commercial SBS modified bitumen.

6. Conclusions

Utilization of recycled CR and PE as modifying agents to prepare the modified bitumen has been investigated in this study. Properties of modified bitumen at both high and low temperatures were evaluated by using conventional physical tests and rheological measurements. Some major findings can be given below:

Table 5
Economic analysis of integrated modified bitumen.

Economic analysis	Base bitumen	CR	PE	Operating cost
Price ($/ton)	410	393	1060	106
Total Price ($/ton)	$\frac{410+393\times0.15+1060\times0.07}{1+0.15+0.07}+106=551.2$			

1) Based on the FM images, the phase morphology shows a continuous bitumen phase with dispersed polymer particles by adding a single agent. With the addition of CR and PE under integrate modification, a nearly continuous polymer phase was appeared and finally formed two continuous twisted phases. The formation of these two interlocked phases verify the improved high-temperature performance.
2) The conventional physical tests of the modified bitumen show that PE is the dominant factor to improve the bitumen stiffness. The integrated modified bitumen is able to obtain similar softening point compared to the SBS modified bitumen.
3) With the addition of CR and PE, the complex modulus experiences an obvious increase, which correlates well with the softening point results. The phase angle takes on obvious decline, which demonstrates the increase of elastic behaviour. The significantly increased failed temperature reveals the improvement of high-temperature performance after integrate modification.
4) The integrated modified bitumen significantly decreases the accumulated creep strain and this modification is able to improve its rutting resistance by increasing stiffness.
5) Referring to the BBR test, the CR is the main factor to decrease the creep stiffness and increase the m-value of bitumen at low temperature. The integrated modified bitumen prepared in this research obtained similar low-temperature performance as that of the commercial SBS modified bitumen.
6) Finally, it is possible and acceptable to produce high-performance modified bitumen by using CR and PE with significantly lower price than that of the SBS. It should be mentioned that the results presented in this article are based on properties related to modified bitumen. In further steps, the asphalt mixture will be prepared and the influence of integrated modified bitumen on related properties will be evaluated.

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