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Performance evaluation of bitumen modified with pyrolysis carbon black made from waste tyres

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HIGHLIGHTS

- Two types of PCBs were selected to modify road bitumens.
- The high-temperature properties of bitumen are obviously enhanced by the PCBs.
- The aging resistance of bitumen is improved significantly by the PCBs.
- The PCB-2 affects bitumen performance more obviously than the PCB-1.

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ABSTRACT

Two types of pyrolysis carbon blacks (PCBs) made from waste tyres were selected to modify road bitumens (SK70# and SK90#) via melt blending. The effects of the PCBs on physical properties, storage stability, rheological characteristics and performance grading (PG) of the bitumens were investigated. The thermal- and photo-oxidative aging of the PCB modified bitumens were evaluated by thin film oven test (TFOT), pressurized aging vessel (PAV) and natural aging (NA). Experimental results show that the high-temperature properties of the bitumen were obviously enhanced by both PCBs, leading to an improved resistance of bitumen to permanent deformation at high temperatures. The thermal- and photo-oxidative aging of bitumen were improved significantly by the PCBs. The pelleting pyrolysis carbon black (PCB-2) with bigger particle displayed more significant influence on bitumen performance than the normal pyrolysis carbon black (PCB-1) with relatively smaller grain size. The modified bitumen with appropriate dosage of PCBs can be used for road construction, which is of great significance for the improvement of pavement performance and recycling of waste tyres.

1. Introduction

Bitumen has been widely used in pavement construction due to its special viscoelastic characteristics and excellent performance [1]. Distresses such as permanent deformation (rutting), fatigue cracking, thermal cracking and water damage occur in the bitumen pavement due to the combination of traffic loading and natural environment [2–4]. Bitumen modification is one of the most widely used methodologies to improve the performance and reduce the distress in the bitumen pavement [5,6]. A large number of modifiers (e.g. styrene-butadiene-styrene, styrene-butadiene-rubber, ethylene vinyl acetate, etc.) have been used in the world wide to modify bitumen, generating various bituminous products with improved performance [7–9].

Nowadays, a very large amount of waste tyres are produced due to the rapid development of automobile industry all over the world. Most of these waste tyres are simply dumped in the open or in landfills, which not only pollute the environment seriously, but also cause huge waste of the resources [10]. Therefore, many feasible methods, including tyre pyrolysis (thermal breakdown in the absence of oxygen), have been applied to degrade or recycle the waste tyres to solve this environmental challenge [11]. Pyrolysis carbon black (PCB), a by-product of scrap tyre pyrolysis, is known as a very useful additive for rubber and other compounds [12,13].

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As reported previously, the pyrolytic carbon black was tried by researchers as a filler to improve the temperature susceptibility of bitumen. The addition of pyrolytic carbon black was found to have changed the rheological properties of bitumen positively [14,15]. However, it is not clear how the PCB affects other properties of bitumen (e.g. storage stability and aging) and whether various kinds of PCBs have same or similar effects on bitumen properties. Moreover, it was reported that some commercial carbon black was used in bitumen to improve the photo-oxidative aging resistance by means of shielding action to UV rays [16,17]. Nevertheless, whether the PCB has the same effect on bitumen aging as the commercial carbon black is still lack of research. Therefore, investigating the influence of different kinds of PCBs on comprehensive properties of bitumens will be very helpful in preparing PCB modified bitumens with excellent performance. This is also of great significance for the recycling of waste tyres.

With this objective, this research selected two types of PCBs to modify two road bitumens (SK70# and SK90#) via melt blending. Effects of the PCBs on physical properties, storage stability and rheological characteristics of the bitumens were investigated. The performance grading (PG) of PCB modified bitumens was determined according to the American Association of State Highway and Transportation Officials (AASHTO) specification. The thermal- and photo-oxidative aging of the PCB modified bitumens were evaluated by thin film oven test (TFOT), pressurized aging vessel (PAV) and natural aging (NA).

2. Materials and methods

2.1. Materials

Two bitumens (SK70# and SK90#) were selected in this study. The physical properties of the bitumens are listed in Table 1.

Two types of pyrolysis carbon blacks (PCB-1 and PCB-2) were used in this study. Both of the PCBs were made from waste tyres via pyrolysis, ultrafine grinding and surface activation. The PCB-1 was a normal type and its grain size was about 25 μm while the PCB-2 was a pelleting processed product with the grain size of about 150 μm.

2.2. Preparation of PCB modified bitumen

The PCB modified bitumen was prepared via melt blending. The bitumen was firstly heated to 150 °C and then mixed with two different PCBs in various proportions (5%, 10% and 15%). The mix was then sheared at 150 °C for 1 h using a high speed shear mixer at a rate of 2500 r/min. It should be noted that the unmodified bitumen was also processed with this same procedure for a comparison purpose.

2.3. Physical properties test

The penetration, ductility, softening point and viscosity of the PCB modified bitumens were tested according to the standards ASTM D5, ASTM D113, ASTM D36 and ASTM D4402, respectively.

2.4. Storage stability test

The storage stability of the PCB modified bitumens was measured using the method similar to that of polymer modified bitumen. The PCB modified bitumens were sealed into an aluminum foil tube (32 mm in diameter and 160 mm in height). Then the tube was stored vertically in the oven at 163 °C for 48 h. After the tube was cooled to the ambient temperature, the top and bottom portion bitumen in the tube was tested for the softening point separately. The difference of the softening point for the top and bottom portion bitumen has been used as an indicator of the storage stability.

2.5. Performance grading (PG) and rheological test

Performance grading (PG) of the base and PCB modified bitumens was measured following the AASHTO R 29 method. The rheological properties of the PCB modified bitumens were measured by the DSR. Strain-controlled mode was applied in the temperature sweep test. The frequency of the DSR test was 10 rad/s. The temperature range was 30–70 °C with an increment of 4 °C/min. The plate used was 25 mm in diameter and the gap between parallel plates was 1 mm.

2.6. Aging procedures

The short-term thermal-oxidative aging of the PCB modified bitumens was simulated by the TFOT according to the ASTM D1754 procedure. The binders were aged for 5 h at 163 °C. The PAV was conducted to investigate the long-term thermal-oxidative aging of the PCB modified bitumens following the ASTM D6521 method. The aging was performed at 100 °C for 20 h under 2.1 MPa of air pressure.

A natural aging (NA) procedure was developed in this study to provide a relatively true condition of bitumen aging. Specifically, the TFOT residues were poured onto a glass pan to form a thin film with thickness of about 1 mm. Then the thin film was exposed to the sunlight for 24 h and immediately followed by 12 hours' water scouring. This 24 h sunlight plus 12 h water procedure is set as one cycle. The properties of the NA-aged binders were measured after three cycles of NA.

3. Results and discussion

3.1. Physical properties of PCB modified SK70# bitumens

Effects of the two PCBs on physical properties of the SK70# bitumen are shown in Table 2. It can be found that with the increase of PCB content, the penetration and ductility of bitumen gradually decrease, while the softening point and viscosity gradually increase. This indicates that the low-temperature properties of PCB modified bitumen are somewhat declined but the high-temperature properties are enhanced when compared with the base bitumen. It was also found that the PCB-2 changes the physical properties of bitumen more obviously than the PCB-1, as revealed by larger reduction of penetration and ductility but higher increment of softening point and viscosity for the PCB-2 modified bitumen. This manifests that the pelleting pyrolysis carbon black with bigger particle displays more significant influence on bitumen properties than the normal pyrolysis carbon black with relatively smaller grain size.

3.2. Storage stability of PCB modified SK70# bitumens

Segregation may occur when the PCB modified bitumens are blended and stored for a long period since the densities of bitumen and PCB are different. Similar to polymer modified bitumen, the storage stability is also a critical parameter for the PCB modified

Table 1
Physical properties of the bitumens.

Properties	Value		Methods
	SK70#	SK90#	
Penetration (25 °C, 0.1 mm)	68	81	ASTM D5
Ductility (10 °C, cm)	26.3	47.7	ASTM D113
Ductility (15 °C, cm)	>100	>100	ASTM D113
Softening point (°C)	50.3	48.3	ASTM D36
Viscosity (60 °C, Pa·s)	114.7	165.0	ASTM D4402
Viscosity (135 °C, Pa·s)	0.49	0.70	ASTM D4402

Table 2
Physical properties of PCB modified SK70# bitumens.

Properties	SK70# bitumen	PCB-1 modified SK70# bitumen			PCB-2 modified SK70# bitumen		
Content of PCB (%)	0	5	10	15	5	10	15
Penetration (25 °C, 0.1 mm)	62	60	59	53	56	52	46
Ductility (15 °C, cm)	88.9	67.6	52.2	42.1	59.9	44.8	32.3
Softening point (°C)	50.5	51.2	52.7	53.9	51.5	53.5	54.3
Viscosity (60 °C, Pa·s)	114.9	115.5	117.5	118.9	116.9	119.1	121.0