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Influence of thermoplastic polyurethane and synthesized polyurethane additive in performance of asphalt pavements

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HIGHLIGHTS

- Performance of TPU and PU was investigated.
- Five tests were conducted to evaluate the performance of modified asphalt.
- Synthesized polyurethane leads to higher asphalt viscosity and stiffness.
- Modifiers cause better asphalt performance and thermal cracking resistance.

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ABSTRACT

One of the main concerns in road and transportation engineering is asphalt distress and the immense amount of money spent on repair and maintenance of asphalt pavements. There have been a lot of efforts on improving the bitumen properties to increase the pavement service life span. The modified bitumen with polymers have been used extensively during last decade. In this research, the thermoplastic polyurethane and synthesized polyurethane were employed as the modifier additives in bitumen specimens. The penetration grade, softening point, rolling thin film oven, pressure age vessel, dynamic shear rheometer, bending beam rheometer and fourier transformation infrared spectroscopy tests have been conducted on the modified specimens. The test results indicate that polyurethane causes a lower penetration grade, greater softening point. In addition, polyurethane improved the base bitumen performance in high temperature condition including the higher rutting resistance and the performance grade. Polyurethane has no notable effects on the bitumen performance in low temperature conditions to increase the performance grade. FTIR test results specified the urethane bonds in the modified bitumen which confirms the bond formation in the chemical structure of the binder.

1. Introduction

Traffic loading and weather conditions are the most important factors in degradation of asphalt pavements. The maintenance and repair cost of asphalt pavements should be considered by engineers to save time and money for fixing defects in the pavement during the service life. The pavement cracks cause the service life reduction and eventually the crucial failure mode of asphalt pavements. The initial increase in cost of modified pavement construction can be compensated by increasing the service life. Traffic loading on the pavements causes rutting and fatigue cracks. The small cracks join and develop larger cracks, leading to the pavement failure. The combination of humidity, light, traffic load, and temperature during the service life of the pavement, gradually damages the pavement materials [1–3]. Thermal cracking is one of the four most common distresses in the asphalt or concrete pavements due to a sharp temperature drop or several temperature cycles greater than fracture temperature of aggregates in the asphalt mixture [4–7].

It is proposed that thermal cracking is likely to happen in cold climates and thermal fatigue cracking to happen in moderate climates [8,9]. Thermal cracks can be recognized as transverse cracks at regular intervals [10]. The first thermal crack modification related to asphalt pavement started in 1843. During the 1930's, the trial thermal cracking projects in Europe have been executed and Neoprene Latex has been employed as the first asphalt modifier in North America [11]. The beginning of asphalt modification

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with polymers dates back to the year 1843 [11]. The first trial roads with the application of the modified asphalt were made in France in 1963 to investigate the modified asphalt behaviors [12]. An ideal modified asphalt should have enhanced cohesion and low-temperature susceptibility in the range of expected temperatures during its service life. In addition, it should contain appropriate viscosity during the construction, low load susceptibility, high permanent deformation resistance, high breaking strength, and high fatigue resistance [12].

The modification has not always been without defects; since there is not a certainty of compatibility between an asphalt and a modifier, and even because of separation during the storage or application. If these issues have not been addressed, poorly performing pavement will be resulted [4]. Now a days, polymers are being used as additives in asphalts and bitumens to ameliorate their properties by modifying the hot rheological properties, or to improve their physicochemical properties (cold brittleness, toughness, flexibility, stability, thermal susceptibility, mechanical strength with respect to shocks, vibrations, abrasions, etc.) [13]. The polymers may help to improve the bituminous pavements to prevail the road distress under severe conditions including rutting at high temperature, permanent deformation, fatigue and thermal cracking [14,15].

Different modifiers have different effects on the mechanical and physical properties of the asphalt which can provide different functional properties. For this reason, the object of this study is defined to investigate the effects of adding polyurethane on the adhesive thermal cracking behavior of asphalt in medium temperature. Moreover, effects of this additive on asphalt performance in high and low temperatures and its temperature susceptibility is perused. As the thermal cracking mostly happens in the binder phase of asphalt pavement, the temperature dependent experiments are beneficial to study the thermal behavior of asphalt pavement in this study.

2. Material testing

The bitumen is selected based on the surrounding climate, the traffic intensity, the pavement type, the aggregate gradation, and the pavement construction. The lower viscosity bitumen is desired regarding the lower annual average temperature and less vehicle loads. The basic properties of the binder (performance grade PG 58-22) are presented in Table 1.

Table 1
The properties of the binder.

Testing item	Standard	Testing Result
Penetration (25 °C, 100 g, 5 S) (0.1 mm)	ASTM D5 [16]	92
Softening point (B&R) (°C)	ASTM D36 [17]	46.4
Ductility (5 cm/min, 15C) (cm)	ASTM D113 [18]	>100
Flash point (COC) (°C)	ASTM D92 [19]	232
Density at 15 °C (g/cm^3)	ASTM D70 [20]	1.02

Table 2
The properties of thermoplastic polyurethane.

Testing Item	Standard	Testing Result
Specific Weight (g/cm^3)	DIN 53479 [21]	1.19
Hardness Shore A/D	DIN 53505 [22]	A66
Elongation Module (N/mm^2) 50%	DIN 53504 [23]	1.8
100%		2.7
300%		5
Tensile Strength (N/mm^2)	DIN 53504	30.7
Elongation at failure (%)	DIN 53504	880
Rupture strength (N/mm)	DIN 53515 [24]	45
Softening point (°C)	ISO 306 [25]	63

Table 3
Characteristics of synthesized polyurethane materials.

Item	K-FLEX 3673 polyol	KABONATE 401 Isocyanate	Standard
Physical property	White liquid	Brown liquid	ASTM D445 [26]
Dynamic Viscosity at 25 °C (MPa.s)	1400 ± 200	65 ± 15	ASTM D891 [27]
Specific Weight (g/cm^3)	1.02 ± 0.01	1.18 ± 0.03	ASTM D5155 [28]
NCO (%)	–	29 ± 1	–
OH (%)	36–41	–	–

In this study, two types of polyurethane were used. Thermoplastic polyurethane (TPU) is an elastomer with full thermoplastic characteristics. It is polyester based with excellent abrasion resistance, great mechanical properties, good water, light resistance, and high hardness of A65grade. The properties of thermoplastic polyurethane are shown in Table 2.

Another type of polyurethane used in this study is synthesized polyurethane (PU) with active hydrogen. KABONATE 401 Isocyanate and K-FLEX 3673 polyol were applied as the isocyanate material. The characteristics of these materials are shown in Table 3.

3. Experimental program

3.1. Specimen preparation

The TPU modified specimens were prepared by a high shear mixer machine in order to mix 3%, 5%, and 7% of TPU with asphalt specimens which were called BTPU3, BTPU5, BTPU7, respectively. The mixing process was conducted in the high shear mixer at 4000 rpm mixing speed and 175 ± 5 °C temperature for 1 h. The other modified samples were made by adding 3 wt%, 5%, and 7% of PU to the asphalt mixture and were called BPU3, BPU5, BPU7, respectively. To make polyurethane pavements (modified pavements), 2 wt% water was added to the modified PU asphalt for 45 min. The polyurethane temperature and dosage were chosen based on the previous research and studies [29,30]. The purpose of adding water is modifying the bitumen by producing foam resulted from the reaction of water and isocyanate bitumen. The recent reaction which is referred as blowing reaction forms a urea linkage and carbon dioxide gas and therefore the resulting polymer contains both urethane and urea linkages. Bitumen in contact with environmental conditions undergoes the massive difference in the rheological performance in comparison with the initial sample. The humidity develops the progressive intermolecular reactions and causes higher module and viscoelastic properties. Under this condition, water is easily dispensed in the bitumen and produces the thermal reactions which intensify the viscosity due to polymer-bitumen membrane. The polyurethane asphalt specimens containing 3%, 5%, and 7% of PU and 2 wt% water were named BF3, BF5, and BF7. HAAKE Pheomix 4500 apparatus was used for synthesizing the polyurethane including the isocyanate and polyol at 2000 rpm. Then, modified asphalt specimens and polyurethane pavements were made by a high shear mixer Polytron 6000 at 4000 rpm followed by 1 h of mixing at 2500 rpm and 90 °C.

3.2. Tests procedures

Five tests were conducted to evaluate the performance of modified and unmodified asphalt specimens in high, medium and low temperatures in accordance with ASTM and AASHTO standards (Table 4). These tests include: 1 – penetration grade 2 – softening