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Experimental study on materials composition design and mixture performance of water-retentive asphalt concrete

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HIGHLIGHTS

- Workability, water absorbing capacity were tested for water-retentive materials.
- Performance and cooling effect were tested for water retentive asphalt concrete.
- Materials composition of water retentive slurry is recommended.
- Mechanisms of water absorbing capacity and mechanical properties are analyzed.

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ABSTRACT

Water-retentive asphalt concrete (WRAC), produced by incorporating water-retentive slurry (WRS) into porous asphalt concrete (PAC), could significantly reduce the surface temperature of pavements and is currently considered a promising tool for alleviating urban heat island effect. Based on laboratory test and microstructural analysis, the present study investigated the effects of varying the proportions of ground granulated blast furnace fly ash, calcium hydroxide and mixing water amount on workability of fresh WRS. In addition, the water absorbing capacity, compressive strength and flexural strength of the cured (hardened) WRS were determined. The microstructures of hardened WRS were examined using scanning electron microscopy in order to better understand the effect of hydration level and pore structure on the water absorbing capacity and mechanical properties of hardened WRS. The results showed that materials composition have significant effects on the water absorbing capacity, compressive strength and flexural strength of hardened water-retentive slurry, as well as the workability of fresh WRS. WRAC showed good moisture resistance, rutting resistance and low deformation resistance comparable to the control PAC. However, the use of WRAC resulted in a temperature drop of about 10 °C compared to the control PAC.

1. Introduction

Most of the world's major metropolises face the urban heat island effect which means the temperature in a city is significantly higher than surrounding suburban or rural areas. And this phenomenon is becoming serious with the expanding number of the megacities [1–3]. Under the circumstances, water-retentive asphalt concrete (WRAC) has received significant attention by pavement engineering and urban environment researchers over the recent years. WRAC is able to mitigate the urban heat island effect by exploiting the water absorbing and water preserving properties of specially designed water-retentive slurry (WRS) into the comparatively large air voids of porous asphalt concrete (PAC). As a result of their unique properties, WRAC is able to absorb water (rainwater or artificially sprayed water) rapidly and hold it for a significant period of time. As a result of the retained water in WRAC, the temperature of a pavement will be reduced by evaporation when the ambient temperature is high resulting in a comfortable pavement environment (lower ambient temperature) for pedestrian and others city inhabitants.

In recent years, studies conducted to investigate the performance of WRAC were mainly concentrated on the cooling effect. Santamouris et al. [4] summarized the cool materials used in the urban built environment, including highly reflective and emissive light colored materials, cool colored materials, phase change materials and

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dynamic cool materials. Their study indicated that cool materials could significantly contribute to the mitigation of the heat island effect and the improvement of urban environmental quality. Karasawa et al. [5] conducted experiments on water-retentive concrete block pavement at 33.8 °C and a day after rainfall. The relation between the block surface lightness and the road temperature was studied. Results showed that the higher the block surface lightness, the lower the road surface temperature of concrete-block pavements. Light-colored water-retentive concrete block pavement caused a drop in ambient temperature ranging from 7.2 °C to 16.6 °C compared to dense asphalt pavement. Ishimaru et al. [6] studied the cooling effect of WRAC. Their results showed that, compared with dense asphalt pavement, the temperature of WRAC pavement was significantly reduced by 15 °C. Yamagate et al. [7] assessed the heat island mitigation effects of sprinkling reclaimed wastewater on water retentive pavement. Their study showed that sprinkling reclaimed wastewater decreased the road surface temperature by 8 °C during the daytime and by 3° at night. They also found that sprinkling reclaimed wastewater reduced the amount of sensible heat flux and increased that of latent heat flux. Takahashi et al. [8] studied the water absorbing capacity, compressive strength and long-term cooling effect of a water-retentive material (Road Cool) using blast furnace slag. Their study indicated that 10 cm thick Road Cool pavements kept their surface temperature relatively low for almost a week after a single rainfall. Nakayamaa et al. [9,10] expanded a model to simulate the water and heat budgets for the various materials and to reproduce the cooling of water-retentive pavement by evaporation. Based on the results of the estimates by the model, they found that the air temperature above the water-retentive pavement was 1–2 °C lower than that above the nearby lawn and 3–5 °C lower than that above nearby building rooftops. The results also showed that the surface temperature decrease in water-retentive pavement was closely related to evaporation from the surface, the water volume of the pavement and the surface reflectance.

Previously, studies have been conducted to evaluate the cooling effect of water-retentive pavement based on simulation and laboratory test. However, the design and composition of WRAC have not been comprehensively investigated yet. For this purpose, the present paper aims to study the raw material composition effect on the fresh water-retentive slurry's workability, as well as the hardened water-retentive slurry's water absorbing capacity, compressive strength and flexural strength. Further, reasonable raw material composition was recommended; rutting resistance, moisture susceptibility, low temperature fracture resistance and cooling effect about WRAC were evaluated. The findings from this study can be used to optimize the materials composition design method and the performance of WRAC.

2. Materials and sample preparation

The raw materials for preparing the water-retentive slurry (WRS) included ground granulated blast furnace slag (GGBFS), fly ash, alkali-activator and mixing water. GGBFS is a kind of uncrystallized ground glassy substance after the shock chilling process from molten slag of blast furnace ironmaking. Fly ash is the solid waste collected from coal power plants and has porous cellular organization. The hydraulic property of fly ash under the action of alkali activation is important for the long-term strength increase and reduction in drying shrinkage of hardened WRS [11]. GGBFS and fly ash could be activated under the affect of alkali, and finally form strength based on the hydration products. Sodium hydroxide (NaOH), potassium hydroxide (KOH) and calcium hydroxide ($Ca(OH)_2$) are the most common materials used as alkali-activator. However, results from some studies suggest that even though the use of NaOH and KOH could result in mixtures with high early strength, the long-term strength of the hardened materials will be compromised due to anti-alkali and high shrinkage [11]. For these reasons, $Ca(OH)_2$ was chosen as the alkali-activator in this study.

2.1. Ground granulated blast furnace slag (GGBFS)

The GGBFS used in this study was obtained from Long Cheng Steel Plant in Shaanxi Province of China. The appearance of GGBFS is tan-white and the fineness is 380–420 m^2/kg. Table 1 presents the seven main chemical components of the GGBFS. The data was supplied by the material suppliers. Among the chemical component of GGBFS, CaO, MgO and Al_2O_3 are classified as active ingredients while SiO_2, TiO_2 and MnO are classified as inactive ingredients. Also shown in Table 1 is the chemical modulus (CM) defined as the ratio of active ingredients and inactive ingredients (Eq. (1)). The higher the value of CM, the greater activity of GGBFS is. The CM of GGBFS in this study was 1.87, exceeding requirements of greater than 1.2 in the Chinese standard specifications [12].

$$CM = \frac{CaO + MgO + Al_2O_3}{SiO_2 + MnO + TiO_2} \quad (1)$$

2.2. Fly ash

The fly ash used in this test was obtained from Hancheng Coal power plant in Shaanxi Province of China. The main properties of fly ash are listed in Table 2. Also listed in Table 2, are the specification criteria for fly ash in China. The data indicate the fly ash sample satisfied the relevant criteria.

2.3. Calcium hydroxide [$Ca(OH)_2$]

The main properties of the $Ca(OH)_2$ employed in this study are listed in Table 3. The chemical quality of $Ca(OH)_2$ is based mainly on the overall CaO + MgO. The value of overall CaO + MgO is 72%, meeting the requirement of specifications [15] for pavement materials.

2.4. Porous asphalt concrete (PAC)

In this study, crushed diabase aggregates and limestone powder were used for fabricating the mixtures. The neat asphalt binders with penetration grade of 80/60 and high viscosity asphalt modifiers, (TAFPACK-SUPER, TPS), were used. The binder content was 4.7% by weight of mix. TPS was added at the rate of 12% by the mass of asphalt binder. TPS is a kind of asphalt modifier with thermoplastic rubber as the main components, compounded with resin and thickener. Particle size of TPS is about 2–3 mm. After modification, the penetration decreased, softening point increased, and dynamic viscosity of 60 °C increased significantly. The gradation of PAC is presented in Table 4. Air voids content was 22.1% of the PAC's specimens according to D3203 [17].

2.5. Sample preparation

To prepare the water-retentive slurry, first, GGBFS, fly ash and $Ca(OH)_2$ were weighed according to the composition ratio. Next, all the ingredients were mixed together with water and the mixture was stirred until a slurry of uniform consistency was formed. Special experiments were conducted to evaluate the workability for mixing and filling into the voids of the PAC to make WRAC. To accomplish this, the slurry was poured into moulds to form prismatic specimens measuring 40 mm × 40 mm in cross section and 160 mm in length. The slurry was cured at a temperature of (20 ± 1)°C and a relative humidity of not less than 90% to produce the hardened WRS. Tests were conducted to evaluate the water absorbing capacity, compressive strength and flexural strength on the performance of the hardened slurry. Finally, the WRAC was prepared by pouring the freshly mixed slurry into the porous asphalt concrete followed by a period of curing. Vibrating table could be used to place the slurry in the sample. During the construction process, the most commonly used method is firstly to dump the water-retentive slurry onto the pavement surface. And then the plate vibrators or small vibrating road rollers were used to assist the spreading. Finally, rubber harrow was used to remove slurry remained on the pavement surface.

The workability of the water-retentive slurry, the water absorbing capacity, compressive strength and flexural strength of hardened water-retentive slurry, as well as the rutting resistance, moisture susceptibility, low temperature fracture resistance and cooling effect of WRAC were tested using three replicate specimens each, and the arithmetic mean was taken for the result.

Table 1
Chemical components of GGBFS and chemical modulus.

Chemical component	CaO	MgO	Al_2O_3	SiO_2	TiO_2	MnO	Na_2O	CM
Mass percent, %	38.7	6.89	16.1	30.7	1.32	0.96	0.462	1.87