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Multiple scaling investigation of magnesium phosphate cement modified by emulsified asphalt for rapid repair of asphalt mixture pavement

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HIGHLIGHTS

- Performance of MPC–EA was evaluated on the scale of paste, mortar and concrete.
- Emulsified asphalt was efficient in extending setting time and improving fluidity.
- Toughness, bonding strength and permeability could be improved.
- Compressive/flexural strength and abrasion resistance could be adversely affected.

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ABSTRACT

This study aims to evaluate the performance of magnesium phosphate cement and emulsified asphalt combination (MPC–EA) on the scale of paste, mortar and concrete, respectively. Experimental results indicated that the emulsified asphalt was more efficient in extending the setting time (from 10 to 90 min) than traditional retarders (borax and fly ash). Meanwhile, fluidity, toughness, bonding strength and permeability of the MPC–EA composite were enhanced. A reduction of compressive strength, flexural strength and abrasion resistance could be observed due to the released water from emulsified asphalt, indicating the need of seeking additives for offsetting its adverse effect.

1. Introduction

Hot-mix asphalt (HMA) pavement is the preferred choice today in the majority of the world. For example, it accounts for more than 90% of pavement in the United States, Europe, China and many other countries. However, various distresses of HMA pavement such as rutting, pothole and cracking may occur during the service life. Consequently, its maintenance which is generally costly, laborious and time consuming, has been recognized as one of the most important challenges for road engineers and researchers for decades. A considerable number of Refs. [1–6] regarding its maintenance can be found in the literature, primarily focused on mix design, materials selection, quality control in construction and field performance evaluation. Hot-mix asphalt and emulsified asphalt (EA) mixtures have been typically used as patching or crack-sealing materials [7,8]. In contrast, most cementitious materials (e.g., Portland cement concrete), which are featured with inferior permeability resistance, higher brittleness and shrinkage, have seldom been utilized as alternatives for maintenance of HMA pavements. Magnesium phosphate cement (MPC), a particular type of cementitious binder, has been used as a rapid concrete patching material since 1976 [9] due to its fast strength growth, strong bonding with the substrate, low shrinkage, slow aging and ease of construction [10–15]. However, very limited research has been conducted on applying MPC for rapid repair of HMA pavement. In this study, the properties of MPC combined with emulsified

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asphalt, i.e., MPC–EA composite, were investigated comprehensively. Three patching forms of MPC–EA were evaluated: paste (without aggregates), mortar (with sand) and concrete (with sand and stone). The objectives of this study are to:

- Evaluate the performance of MPC–EA paste, including the fluidity, setting time and strength.
- Evaluate the performance of MPC–EA mortar, focusing on the fluidity and strength.
- Evaluate the performance of MPC–EA concrete, including the setting time, fluidity, strength (compressive strength, flexural strength and bonding strength) and durability (permeability and abrasion resistance).

2. Experimental program

2.1. Raw materials

The raw materials used in this study are listed in Table 1. $(NH_4)_2HPO_4$, MgO and borax are the common ingredients for manufacturing MPC [10]. The molar ratio of borax to MgO and $(NH_4)_2HPO_4$ are kept at 0.05 and 0.25, respectively. Cationic and slow cure emulsified asphalt is used as a modifier to change the color, making the patch appearance resemble the HMA pavement and to improve the performance (e.g., reduce the brittleness). River sand and crushed aggregate are employed to prepare MPC–EA composite concrete and asphalt concrete (AC) specimens for the bonding strength test.

2.2. Testing methods

2.2.1. Setting time test

The setting time test of MPC paste is carried out using a Vicat needle apparatus as specified in ASTM C191-08. It refers to the time needed from the mixing of water with MPC powder until the moment that the needle fails to pierce the test block 5.0 ± 0.5 mm measured from the bottom of the Vicat mould.

2.2.2. Fluidity test

Favorable bonding between the rapid repairing materials and the HMA pavement substrate is critical to ensure an effective long term repair. Desirable fluidity of MPC can significantly contribute to strong bonding of the repairing material and the substrate. The maximum spreading diameter after lifting the modified slump cone (bottom diameter: 60 mm, top diameter: 30 mm, height: 90 mm) is measured as the slump flow. This testing method has been widely used since its incorporation into Japanese standards [16]. The measurement of the diameter is indicative of the fluidity of the paste, mortar or concrete, with a higher value being better.

2.2.3. Strength test

To evaluate the strength of MPC paste or mortar, prism specimens (40 mm × 40 mm × 160 mm) are prepared for flexural strength and compressive strength testing as specified in ASTM C109/109M. To evaluate the strength of MPC concrete, cubic specimens (150 mm × 150 mm × 150 mm) and prism specimens (150 mm × 150 mm × 550 mm) are prepared for compressive strength and flexural strength testing, respectively. In addition, to test bonding strength, cubic specimens are also prepared with half MPC concrete and half AC mixture (as shown in Fig. 1).

2.2.4. Permeability resistance test

Inferior permeability resistance of cementitious material usually leads to a failure of the HMA pavement repair. The addition of impermeable EA after emulsification can theoretically improve the permeability resistance of MPC. Fig. 2 shows the cone specimens (top diameter: 185 mm, bottom diameter: 175 mm, height: 150 mm) for permeability testing by a HS-40 concrete penetrometer. After curing for 7 days (relative humidity: 50%; temperature: 20 °C), the permeability resistance test is carried out. The water pressure starts at 0.5 MPa with an increase of 0.5 MPa every 6 h. When the water pressure reaches 4.0 MPa, it is held at that pressure for 12 h and then the water penetration depth of the specimen is immediately measured and recorded.

Table 1
Raw materials involved in the experimental program.

Raw materials	Chemical formula or description
Diammonium phosphate	$(NH_4)_2HPO_4$
Magnesium oxide	MgO
Borax	$Na_2B_4O_7{\cdot}10H_2O$
Emulsified asphalt	Cationic/slow cure
River sand	Fineness modulus: 2.0
Crushed aggregate	Nominal maximum size: 25 mm

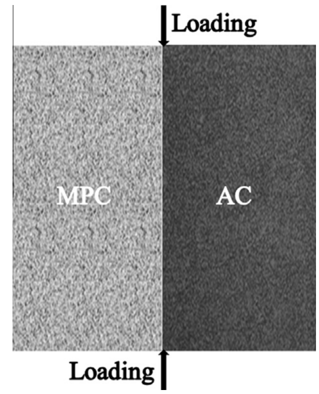

Fig. 1. Bonding strength test.

Fig. 2. Specimens for permeability test.

2.2.5. Abrasion resistance test

To measure abrasion resistance, the MPC concrete specimens (150 mm × 150 mm × 30 mm) are cured for 7 days, as specified in China [17]. Next, the mass loss per unit area is calculated during a 2-step wearing procedure. First, the concrete surface is subjected to 30 cycles of wearing with a loading of 200 Newton. Second, it is subjected to an additional 60 cycles of wearing. The initial mass after the first wearing is recorded as G_1 and the remaining mass at the end of the second wearing is recorded as G_2. The difference between G_1 and G_2 is recorded as the mass loss, from which the abrasion resistance is calculated as mass loss per unit area.

3. Results and discussions

3.1. MPC–EA composite paste

The fast setting of MPC often inconveniences construction operations [18]. Efficient retarders, including borax and fly ash, can extend the setting time of MPC paste to approximately 10 or 15 min [19,20]. However, the setting time remains too short, especially in case of long term transportation and during construction in hot summers. Additionally, fresh MPC paste's fluidity helps the binder to soak deeply into HMA pavement. Furthermore, high strength and low brittleness of MPC–EA paste enables a strong and durable repair.

The mixing procedure of MPC and emulsified asphalt is discussed below. First, MgO and borax are mixed with water for two minutes. Then, $(NH_4)_2HPO_4$ is mixed with the slurry for another two minutes. After that, emulsified asphalt is added and mixed for 1 min prior to testing.

3.1.1. Setting time

The molar ratio of borax to MgO and $(NH_4)_2HPO_4$ to MgO was kept at 0.05 and 0.2, respectively. Emulsified asphalt was mixed with MPC paste in several dosages (i.e., 0, 20%, 40%, 60%, 80% and