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Laboratory evaluation of magnesium phosphate cement paste and mortar for rapid repair of cement concrete pavement

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HIGHLIGHTS

- Pretreatment of borax and magnesium phosphate cement.
- Combination of borax, fly ash and aluminate cement as retarders.
- Replacement of monohydrogen phosphate cement to balance between setting time and strength.
- Enhancement of water resistance and toughness by crumb rubber.
- Enhancement of strength and toughness by silica sol.

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ABSTRACT

This study investigated the various aspects of magnesium phosphate cement (MPC) paste and mortar, both of which were made after pulverization of potassium dihydrogen phosphate and borax. Borax and fly ash could remarkably delay MPC paste setting time but not long enough to accommodate the operational needs in some occasions. On the other hand, high dosage of aluminate cement could result in significant increase in setting time, but it reduced strength as well. The result showed that the substitution of monohydrogen phosphate for potassium dihydrogen phosphate in MPC paste could strike a balance between strength and extended setting time. Blending MPC paste with 5% crumb rubber not only significantly improved water resistance but also reduced brittleness as indicated by a decreased compressive–flexural strength ratio. Laboratory testing results of MPC mortars were presented regarding fluidity, dry shrinkage, bonding strength and abrasion resistance. The results demonstrated that the MPC mortar exhibited a much lower dry shrinkage of 25.6 millionths than that of 200–1000 millionths in common concrete pavement, a desirable bonding strength (of 4.1 MPa) with the old pavement substrate, and a favorable abrasion resistance (with a mass loss of 2.45 kg per square meter). The field application case of the MPC patching material indicated desirable both for construction and quick opening to the traffic.

1. Introduction

Cement concrete is the preferred choice for building durable, energy efficient and eco-friendly pavements. The failure and subsequent repair of cement concrete pavements often causes traffic jams, giving rise to the need for rapid repair materials. In the past three decades, magnesium phosphate cement (MPC) attracted intensified attention due to its rapid strength growth, long durability and close color resemblance (for more detailed reviews, see [1–4]). Following its initial patent authorization in 1976 [5], a great deal of MPC research has been directed to understanding its strength, delay of setting time, and hydration mechanism (e.g., [6–8]). The compressive and flexural strength of MPC aging at 24 h usually ranges 5–30 MPa and 2–6 MPa, respectively, which may meet the requirement for speedy repair distresses of cement concrete pavements. However, the delay in setting time of MPC sometimes results in early strength reduction. Consequently, it is important to balance between rapid strength gain and short setting time for construction. Additionally, limited studies have been carried out on dry shrinkage [9], water resistance [10] and abrasion resistance of MPC, all of which are key indicators dominating the potential service life span of the repair.

The current investigation aims to broaden our understanding of MPC with regard to the issues discussed above. The laboratory test

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results and analysis are divided into two separate parts. Part I examines the properties of MPC paste, focusing on the setting time, strength and moisture resistance while part II details the characteristics of MPC mortar related to fluidity, effect of MPC–sand ratio on strength, dry shrinkage, bonding strength and abrasion resistance. After that, discussion regarding the construction and performance of MPC paste as patching material was presented.

2. Experimental program

2.1. Raw materials

All the raw materials used in this investigation are listed in Table 1. KH_2PO_4 (P) and MgO (M) were chosen as the basic ingredients for making MPC. KH_2PO_4 was replaced partially or completely by monohydrogen phosphate-that is, $K_2HPO_4{\cdot}3H_2O$, $Na_2HPO_4{\cdot}12H_2O$ or $(NH_4)_2{\cdot}HPO_4$ in order to curb the reaction speed. Borax (B), fly ash (FA) and aluminum cement were taken as retarders. Crumb rubber was blended to enhance both the water resistance and toughness of MPC paste. Silica sol was blended to enhance the strength as well as the toughness. To simulate the old concrete substrate for bonding strength test, ordinary cement (compressive strength $F_c \geqslant 52.5$ MPa and flexural strength $F_b \geqslant 7$ MPa at the curing age of 28 days) was used. To prepare MPC mortar, three types of river sand were employed except for the abrasion resistance test where International Standard Organization(ISO) sand was used.

2.2. Pretreatment of borax and potassium dihydrogen phosphate

It has been demonstrated that the fineness of MgO significantly affects the strength of MPC [11,12]. Little attention, however, has been paid to the influence of both borax and potassium dihydrogen phosphate on MPC. The microstructure of the hydration products of MPC made with original and pretreated KH_2PO_4 and $Na_2B_4O_7{\cdot}10H_2O$ was compared in this investigation. Borax and potassium dihydrogen phosphate for making MPC were categorized into two groups. In group I, KH_2PO_4 and $Na_2B_4O_7{\cdot}10H_2O$ were mixed according to the optimized molar ratio (B:M and P:M is 0.05 and 0.25, respectively)without grinding. In group II, KH_2PO_4 and $Na_2B_4O_7{\cdot}10H_2O$ were mixed and subjected to a grinding process of 4 h with steel ball mills prior to use. The microstructure of the MPC paste hydrates (at the age of 24 h) with or without grinding was measured by SEM, as shown in Fig. 1a and b, respectively. The layered structure of the hydration products in group I (Fig. 1a) might result in lower strength. Additionally, few micro-cracks with average width of 2 μm also suggested possible strength reduction. Because the hydration products in group II were made of uniform granular particles ranging 1–3 μm (Fig. 1b), more densified structure could be observed and higher strength than that of group I could be expected. Therefore, for the subsequent preparation of both MPC paste and mortar, borax and potassium dihydrogen phosphate were subjected to the same grinding process prior to use.

Table 1
Raw materials involved in the experimental program.

Raw materials	Chemical formula	Description
Potassium dihydrogen phosphate	KH_2PO_4	Purity: 99.8%
Dipotassium hydrogen phosphate	$K_2HPO_4{\cdot}3H_2O$	Purity: 99.8%
Disodium hydrogen phosphate	$Na_2HPO_4{\cdot}12H_2O$	Purity: 99.8%
Diammonium phosphate	$(NH_4)_2HPO_4$	Purity: 99.8%
Magnesium oxide	MgO	Purity: 85.0%
Borax	$Na_2B_4O_7{\cdot}10H_2O$	Purity: 95.0%
Fly ash	–	Class C
Aluminate cement	–	Grade 60
Ordinary Portland cement	–	Grade 52.5
Crumb rubber	–	40–100 mesh
Silica sol	$m SiO_2{\cdot}n H_2O$	–
River sand	–	–
ISO sand	–	–

2.3. Testing methods

The setting time of MPC paste was measured as specified in ASTM C403/C403M-08. Due to the small time gap between the initial setting and the final setting, only the initial setting time was reported in the current study. Prior to compressive strength and flexural strength tests of both MPC paste and mortar, the specimens (40 mm × 40 mm × 160 mm in size for flexural strength test and the fractured pieces for compressive strength test) experienced standard curing (i.e., relative humidity of 50 ± 5% and temperature of 20 ± 2 °C) after demolishing. Because the strength of MPC paste or mortar develops very well in the air, it is unnecessary to undergo moisture exposure curing. Thus, all MPC curing from this investigation was conducted by simulating the air curing condition.

The slump flow of the MPC mortar was measured by using a modified slump cone (bottom diameter: 60 mm, top diameter: 30 mm, height: 90 mm); the result was expressed as the maximum spread diameter that the fresh MPC mortar reached after the cone is lifted.

The MPC mortar prism specimens (360 mm × 100 mm × 100 mm) were prepared for dry shrinkage test, with linear dry shrinkage measurements taken 28 days after standard curing (Fig. 2). The formula for calculating the dry shrinkage rate is given below:

$$\varepsilon = \frac{\Delta L}{L_0},$$

where ε is the liner dry shrinkage rate, $\triangle L$ is the change in length, and L_0 is the original length of the mortar specimen.

The cement mortar specimens (40 mm × 40 mm × 160 mm) made with high strength Portland cement were prepared to imitate the old cement concrete pavements. After 28 days of curing (with relative humidity of 95% and temperature of

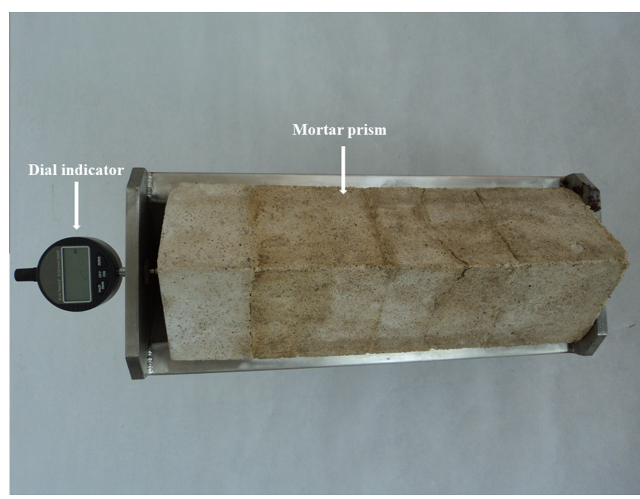

Fig. 2. Shrinkage test device for MPC mortar.

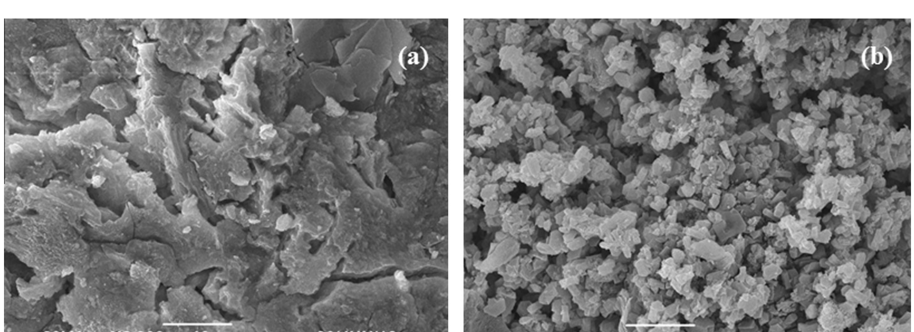

Fig. 1. SEM of MPC paste made with original (a) and pulverized (b) borax and KH_2PO_4.