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Properties of magnesium phosphate cement containing redispersible polymer powder

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HIGHLIGHTS

- The effects of a redispersible polymer powder (RPP) on MPC mortar are evaluated.
- The addition of RPP can improve the bonding strength and water resistance of MPC mortar.
- The possible mechanism is that RPP may modify the pore structure in set MPC mortar.

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ABSTRACT

Magnesium phosphate cement (MPC) prepared with dead burned magnesia oxide (MgO), potassium dihydrogen phosphate (KH_2PO_4, KDP) and some retarders at a given proportion was applied as repairing material. In this research, the mechanical properties and durability of MPC modified by a silane-based redispersible polymer powder (RPP) were investigated. The experimental results demonstrate that the compressive and flexural strength at different curing ages increased as increasing RPP content initial, and decreased as the content going beyond 0.35%. The addition of RPP significantly improved the bonding strength between MPC mortar and substrate OPC concrete, and the flexural and tensile bonding strength of MPC with 0.233% RPP at 1 day of curing were 4.6 MPa and 1.65 MPa, respectively. The addition of RPP can improve the pore structure and transfer the hydrophilic surface of some minerals to hydrophobic one, hence improving the water resistance of MPC. For MPC mortar with RPP after freeze-thaw cycles, the mass loss and the freeze-thaw influence coefficient were both smaller due to less water permeating into hardened MPC mortar. Due to more harmless pores in MPC mortar with RPP, the volume stability was improved. The XRD analysis illustrates that small amount of RPP has little impact on the hydration reaction of MPC. The SEM micrographs confirms that the pore structure of set MPC could be improved by adding an appropriate content of RPP.

1. Introduction

The degradation of the concrete constructions which are exposed to severe environmental conditions, such as expressways, airport runways, etc. gives rise to many problems and the damaged structures require strengthening or rehabilitation [1]. Generally, the appropriate repairing materials should meet the projected physical-mechanical properties and a relatively economic benefit. It's notable that the repairing processes of traditional repairing materials delay the reuse of structures for a long time. Therefore, different types of rapid-hardening cements have been employed as repairing materials [2–4].

Among these repairing materials, magnesium phosphate cement (MPC) have been of increasing interest to researchers in the past decade [5–7]. It is a new type of cementitious material, and the strength development of MPC benefits from the through-solution acid-base reaction between burned magnesia and phosphate [8]. Due to the vigorous acid-base reaction immediately after the addition of water, the initial setting time is very short and the high-early-strength can be achieved. Therefore, the repairing operations on the dilapidated concrete structures can be completed within a quarter of an hour and the structures may return to service within few hours [9,10]. Besides, MPC is able to set and harden at the temperatures as low as −20 °C on account of the strong heat release generated by the hydration reaction [7].

MPC systems include magnesium ammonium dihydrogen phosphate cement system (MAPC) and magnesium potassium dihydrogen phosphate cement system (MKPC) [9,11–15]. MAPC has been

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studied by many researchers and applied in many emergency constructions. However, the popularization of MAPC is limited to the ammonia emission from the acid-base reaction and the storage of set cement. In comparison to MAPC, MKPC with potassium dihydrogen phosphate (KH_2PO_4, KDP) does not produce an unfriendly odor during processing and storage and the hydration reaction rate can be reduced due to the smaller dissociation constant of KDP [16]. Based upon the above two advantages, many researchers have studied the properties of MKPC and concluded that MKPC also has the characteristics of rapid-hardening and healthy strength development [14,17–19]. Even so, the bonding strength between MKPC and substrate concrete and the durability of MKPC should be investigated to evaluate the availability of MKPC in repairing and rehabilitation of concrete structures.

Water permeation in concrete can lead to the degradation in mechanical properties, which can significantly affect the service life of concrete structures [20]. Hence, different redispersible polymer powder (RPP) admixtures are used in Portland cement-based system to modify the pore structure and reduce the water permeation into hardened mortar. Apparently, it is believed that the RPP admixtures can remarkably improve the water resistance and durability of OPC mortar [21,22]. Moreover, it is generally agreed that other properties such as bonding strength, modulus of elasticity, corrosion resistance and freeze-thaw resistance are also influenced by the addition of the RPP admixtures. Among the common RPP admixtures, powder silane-based polymer powders (silane-based RPPs) are favored silanes used in dry-mix mortars [24].

As reported in previous studies, the properties of MPC can be affected by many factors, such as water content, magnesia-to-phosphate molar ratio and age, etc. [7,9,23,24]. In general, the degradation in mechanical properties of MPC occurs after water immersion, freeze-thaw cycles and salts crystallizations [25–27]. Owing to the improvement of RPP admixtures on the pore structure of OPC mortar, a selected RPP is proposed to improve the water resistance, freeze-thaw resistance and salt resistance of MPC mortar. But in fact, there are only few studies on the influence of the RPP admixtures on the properties of MPC mortar [27–29].

This current study reports on MPC repairing mortar which was prepared in the laboratory and the influence of a silane-based RPP on mechanical properties and durability of MPC mortar was investigated. The compressive and flexural strengths of MPC mortar with different RPP contents were evaluated. And then, the four-points bending and pull-off tests were employed to study the flexural and tensile bonding strength. The durability of RPP modified MPC mortar, including its water resistance, freeze-thaw resistance and drying shrinkage were also estimated. Finally, the phase analyzes were performed by XRD and SEM.

2. Experimental details

2.1. Raw materials

Dead burnt magnesium, potassium dihydrogen phosphate (KH_2PO_4, KDP) and retarder were used to prepare the magnesium phosphate cement (MPC). The magnesia powder calcined at about 1500 °C for about 6 h and with a purity of 89.5%, was achieved from the Taishan Refractory Plant of Shanghai. The industrial-grade KDP with a purity of 94.5% was selected to perform acid-base reaction with the magnesia powder. The retarder is a composite of sodium tripolyphosphate ($Na_5P_3O_{10}$) and borax ($Na_2B_4O_7{\cdot}10H_2O$), and both components are chemically pure. Natural river sand with the maximum size of 5.0 mm was used in experiments to prepare MPC mortar. The selected redispersible polymer powder is a type of siloxane-based polymer powder which have amounts of hydrophilic and hydrophobic groups [as shown in Fig. 7(a)]. And it is covered with protective colloid and anti-caking agent which are both soluble in water.

2.2. Specimen preparation

For each specimen, the mass ratio of water and binder which consists of magnesia and KDP (w/c) was fixed at 0.11, and that of magnesia and KDP (M/P) was always 3.5 in this study. The MPC mortar was prepared using a fixed content of retarder (about 5.06% of the weight of magnesia and KDP, $R/(M+P)$) with a sand/binder mass ratio (S/B) of 0.6. Besides, the addition of the siloxane-based RPP is calculated by the weight of magnesia and KDP [$RPP/(M+P)$], and different contents of RPP listed in Table 1 were employed in order to study the effects of RPP on the properties of MPC. Table 1 summarizes the mixing proportions. To prepare three specimens per batch, the needed weight of the mixture for one batch is about 2.2 kg. The mixing procedure can be divided into two steps; solids were first weighted and dry-mixed, and then mixed with a specific mass of water as calculated from w/c.

2.3. Property measurements

2.3.1. Compressive and flexural strength

The prepared mixtures were subsequently transferred to cuboid molds (40 mm × 40 mm × 160 mm) for the measurement of compressive strength and flexural strength. The set mortar specimens were demolded after an hour of curing and cured in a lab at a temperature of 20 ± 2 °C and a relative humidity of 50 ± 5%. After 1 h, 1 day, 7 days and 28 days of curing, an MTS servo hydraulic testing machine with a loading rate of 3 kN per second was used to obtain the strength according to ASTM standard C348-02. To assure the reproducibility of experimental results, at least three replicates of each specimens were prepared and tested under the same conditions.

2.3.2. Bonding strength

To investigate the bonding strength between MPC repairing materials and the substrate OPC mortar or concrete, two test methods were applied in experiments. One was flexural bonding strength test, and the used specimens were called "prismatic mortar" (PM). The PM were also prepared by using cuboid molds (40 mm × 40 mm × 160 mm), and half of OPC mortar and half of MPC mortar were employed. Firstly, the OPC mortar with a size of 40 mm × 40 mm × 80 mm was prepared. Secondly, the set OPC mortar after 28 days of curing was put into the cuboid mold, and then the MPC slurry was poured into the mold [as shown in Fig. 1(a)]. To prepare OPC mortar, ASTM Type I ordinary Portland cement is used, and the mass ratio of water to OPC (w/OPC) and sand to OPC (S/OPC) are 0.45 and 2.0, respectively. The 28-day compressive strength of OPC mortar was 47.3 MPa, and the 28-day flexural strength was 6.7 MPa. Flexural bonding test was performed in an MTS servo hydraulic testing machine at a loading rate of 3 kN per second, with a four-points bending device as it is shown in Fig. 1(a). The specimens PM were cured in a lab at a temperature of 20 ± 2 °C and a relative humidity of 50 ± 5%.

The tensile bonding strength was calculated on the basis of the maximum pull-off force at the rupture of interface between MPC and OPC concrete substrate. To prepare the two-layer specimens illustrated in Fig. 1(b), OPC concrete substrate with a roughness surface was prepared. The 28-day compressive strength of the OPC concrete substrate after sand blasting surface treatment was about 42.5 MPa. To improve the surface wettability of concrete substrate, water-spray procedure was employed. And then, according to Chinese standard JGJ110-2008, PVC molds with 40 mm of width and length and 6 mm of height were put onto the concrete substrate. Soon after, the MPC slurry was poured into the PVC molds. About an hour later, the set MPC mortar were demolded and the two-layer specimens cured in a lab at a temperature of 20 ± 2 °C and a relative humidity of 50 ± 5%. Before tensile bonding strength test, an epoxy resin used as adhesion agent was smeared on the upper surface of the rectangle MPC to bond the metal disk with a pull pin, and the diagram is shown in Fig. 1(b). The values of bonding strength are sensitive to the experimental operations, and big eccentricities may be generated by a very small misoperation. Therefore, at least five specimens for each formulation were prepared to ensure the reproducibility of bonding strength tests.

2.3.3. Porosity

The porosity of MPC mortar was characterized through mercury intrusion porosimetry (MIP) test. As is well known, the MIP technique can give representative values of around 375–0.003 μm [31]. Although the total porosity intruded by

Table 1
Mixing proportions of MPC mortars.

Formulation	M/P	w/c	$[R/(M+P)]\cdot 100\%$	S/B	$[RPP/(M+P)]\cdot 100\%$
S-0	3.5	0.11	5.06	0.6	0
S-1	3.5	0.11	5.06	0.6	0.117
S-2	3.5	0.11	5.06	0.6	0.233
S-3	3.5	0.11	5.06	0.6	0.350
S-4	3.5	0.11	5.06	0.6	0.467
S-5	3.5	0.11	5.06	0.6	0.583
S-6	3.5	0.11	5.06	0.6	0.700