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Experimental study on mechanical properties and fracture toughness of magnesium phosphate cement

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HIGHLIGHTS

- Different types of strength of MPC with or without fly ash were studied.
- The effects of fly ash on various types of strength were compared and analyzed.
- Relationship among axial tensile, splitting and compressive strength was analyzed.
- The fracture characteristics of different MPC were studied.

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ABSTRACT

The mechanical properties and fracture toughness of magnesium phosphate cement (MPC) were studied in this paper. The results show that the strengths (compressive, flexural, axial tensile and splitting strengths) of MPC increased rapidly over curing ages and then increasing rates slowed down. The compressive strength increased with the addition of fly ash, while the tensile strength decreased. For both the specimens with and without the addition of fly ash, the axial tensile strength was lower than the splitting strength. The axial tensile strength of MPC without fly ash was 1/13–1/10 of compressive strength and the axial tensile strength of MPC with fly ash is 1/17–1/14 of compressive strength. The ratio decreased over time. The load–deflection curve showed the failure mode of MPC is brittle failure. The fracture energy increased over time, while the value was relatively small. The failure load and the corresponding mid-span deflection of MPC decreased in presence of fly ash, which results in the further decrease of fracture energy of MPC.

1. Introduction

Compared with ordinary Portland cement, magnesium phosphate cement (MPC) possesses many advantages, such as very rapid setting and hardening, high early strength, high bonding strength, small drying shrinkage, hardening at low temperature, high wear resistance, and excellent frost resistance [1–7]. Therefore, MPC is widely used in the reinforcement and fast-repairing of airport runways, roads, bridges and military engineering [1,8].

Hitherto, the studies of MPC mostly have focused on the mix proportions, setting time, hydration mechanism, and microstructures [9–16]. For example, Soudee investigated the effects of magnesia surface on the setting time of magnesium phosphate cement. Hall et al. studied the effects of retarders on the microstructure and mechanical properties of magnesium phosphate cement mortar; Sarker et al. researched the hydration/dehydration characteristics of struvite and dittmarite pertaining to magnesium ammonium phosphate cement systems. For the mechanical performance of MPC, previous studies mostly concentrated on the compressive strength and flexural strength [9–12]. Qiao et al. studied the setting and compressive strength characteristics of magnesium phosphate cement paste. However, the research findings of axial tensile strength and splitting strength of were relatively rare and the investigations of relationship between mechanical properties and fracture toughness were rare either. This paper researched the mechanical performances, and the relationship between mechanical performances and the fracture toughness of MPC.

2. Experimental materials and methods

2.1. Materials

The 1600 °C burned magnesia powder with a specific surface of 806 m^2/kg and with an averaged particle size of about 20 μm, was obtained from Taishan Refractory Plant, Shanghai, China. The density of the powder was approximately

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3460 kg/m^3. In addition, industrial grade potassium dihydrogen phosphate (KH_2PO_4 or PDP), fly ash and borax ($Na_2B_4O_7 \cdot 10H_2O$) were used in this study. The Physical and chemical characteristics of MgO and fly ash are given in Table 1. The potassium dihydrogen phosphate (KH_2PO_4) used was industrial-grade white crystalline powder with purity of 98%. Borax ($Na_2B_4O_7 \cdot 10H_2O$) in the form of white crystalline powder with purity of 99.5% was used as a retarder.

2.2. Preparation

Potassium dihydrogen phosphate, fly ash, borax and water were mixed in certain proportions and stirred for 60 s. Magnesia was then added to the mix to obtain MPC paste, and was stirred slowly for 30 s. Finally, after 60–90 s of rapid stir, MPC was prepared. The mixing proportions of the MPC samples are given in Table 2. The content of borax is expressed as the mass percentage of borax to the sum of magnesia and PDP, and the ratio of potassium dihydrogen phosphate to magnesia (P/M) is a molar ratio. The ratio of water to the binders is represented as W/B.

MPC pastes were cast in the cubic molds with dimensions of 100 × 100 × 100 mm for measuring splitting strength and molds with size of 40 × 40 × 160 mm for testing flexural strength, compressive strength, axial tensile strength and fracture toughness. The specimens for axis tensile strength tests were embedded by bolt anchorage at both ends, and two notches (length 40 mm × width 2 mm × depth 10 mm) were cut on the both sides in the middle point of length of the specimens (Fig. 1). One notch was cut on bottom side in the middle of each specimen of fracture toughness experiment. The specimens were demolded and then cured under the conditions of 20 ± 1 °C and relative humidity (RH) 50 ± 5%.

2.3. Methods

All of the specimens were tested under the same environmental conditions (20 ± 2 °C, RH 60 ± 5%).

2.3.1. The compressive strength and flexural strength were tested according to GB/T17671-1999 "Cement mortar strength testing method (ISO)".

2.3.2. The axial tensile strength and splitting strength were tested by universal material testing machine, as shown in Fig. 1 and Fig. 2.

The axis tensile strength calculation formula:

$$f_{at}^{0} = \frac{F}{A} \tag{1}$$

F – failure load; A – weak plane area.

The splitting strength calculation formula:

$$f_{st}^{0} = \frac{2F}{\pi A} \tag{2}$$

F – failure load; A – splitting plane area.

2.3.3. The fracture toughness of MPC was tested by RILEM 1985 TC50 - FMC three point bending method [18].

The schematic diagram and photograph of three-point bending test of notched specimen are shown in Fig. 3 and Fig. 4, L = 160 mm, l = 120 mm, h = 40 mm, and t = 40 mm. The notch depth, a, was 20 mm. Three-point bending test was carried out by the universal testing machine. The displacement-loading rate was 0.05 mm/min. Fracture energy calculation method is shown in Fig. 5 and Eq. (3) [17]:

$$G_F = \left[\int_0^{\delta_0} p(\delta)d\delta + mg\delta_0\right] \Big/ A_{lig} = (W_0 + mg\delta_0)/A_{lig} \tag{3}$$

W_0 – fracture work; m – the mass of specimen between two supports; g – acceleration of gravity, 9.8 m/s^2; δ_0 – span-deflection of the beam at failure; A_{lig} – ligament area.

2.3.4. *Measurement method of pore distribution:* The internal pore microstructure of MPC at 28 d was tested by AutoPore IV9510 automatic mercury porosimeter. The specimens were broken into particles with the size of 5.0 mm. The crushed particles were dried in a vacuum drier before the test. Finally, the micro-pore diameter distribution test was carried out.

Table 2
Mix design of MPC.

No.	P/M	Borax/%	Fly ash/%	W/B
1	1/4	5	0	0.14
2	1/4	5	20	0.14

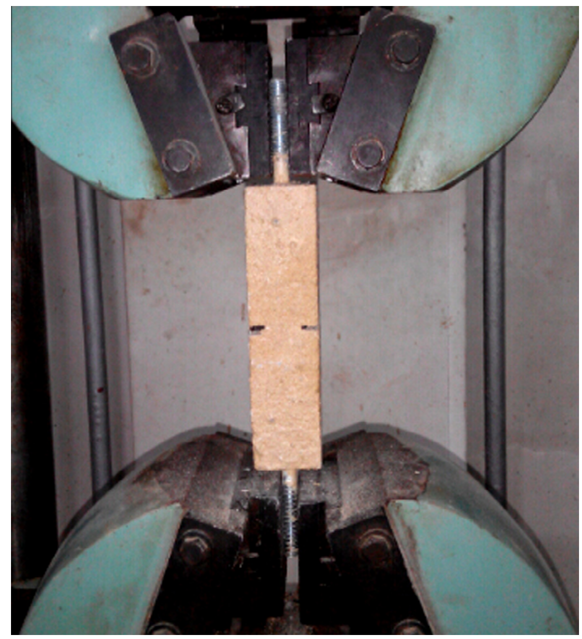

Fig. 1. Axial tensile strength test.

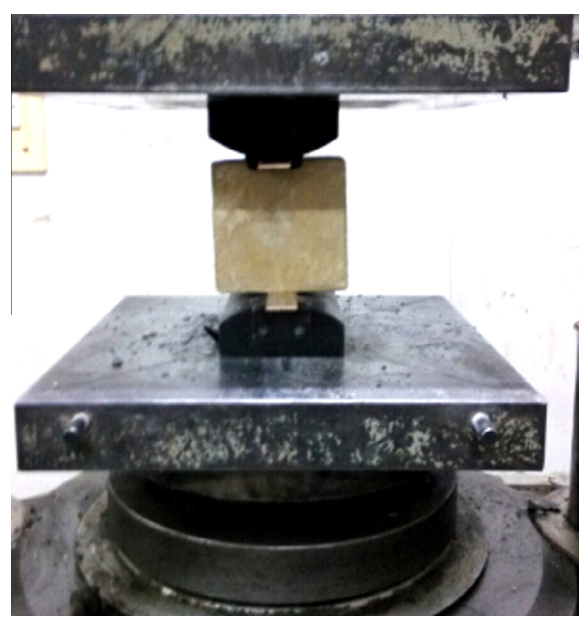

Fig. 2. Splitting tensile strength test.

Table 1
Physical and chemical properties of MgO and fly ash.

Samples	MgO	CaO	SiO_2	Al_2O_3	Fe_2O_3	Loss	Specific gravity (kg/m^3)	Specific surface area (m^2/kg)
Magnesia	91.7%	1.6%	4%	1.4%	1.3%	–	3460	806
Fly ash	1.7%	6.2%	45.3%	25.4%	11.4	7.5%	2310	401