Construction and Building Materials 188 (2018) 946–955

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Mechanical properties of basalt fiber reinforced magnesium phosphate cement composites

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HIGHLIGHTS

- Effect of basalt fiber dosage and length in BFRMPC was studied.
- BFRMPC showed higher mechanical strengths and fracture toughness at higher fiber content.
- The reinforcing efficiency and mechanism of basalt fiber in MPC matrix were evaluated.
- Basalt fiber has advantages over glass fiber in MPC reinforcing applications.

ARTICLE INFO

Article history:
Received 3 May 2018
Received in revised form 8 August 2018
Accepted 9 August 2018

Keywords:
Magnesium phosphate cement (MPC)
Basalt fiber
Mechanical strength
Load-deflection behavior
Fracture toughness

ABSTRACT

Magnesium phosphate cements (MPCs) have found a wide range of applications due to their superior properties. However, as a chemically bonded ceramic material, MPCs show highly brittle behavior. Fiber inclusion is a simple and effective way to improve their ductility and toughness. In this study, short discrete basalt fibers with different fiber contents by mixture volume (i.e. 0–1.5%) and lengths (i.e. 6 mm–30 mm) were added into MPC matrix. Properties of basalt fiber reinforced MPC composites (BFRMPCs) including workability, compressive, splitting tensile, flexural and post-peak residual strengths, and toughness were assessed. The fracture surfaces of BFRMPC samples were also investigated by using scanning electron microscopy (SEM). The results revealed that the addition of basalt fibers into MPC mixture led to a significant decrease in workability and a slight decrease in bulk density. The beneficial effect of basalt fibers on compressive strength began to weaken after 1% of fiber volume, while splitting tensile strength, flexural strength, and fracture toughness significantly increased with the increase of fiber volume. Moreover, the load-deflection behavior was highly related to the fiber content and testing age. In addition, the effect of basalt fiber lengths on the properties of MPC mixtures was insignificant. The results also suggested that basalt fiber reinforced MPCs showed better mechanical properties than glass fiber reinforced MPCs.

1. Introduction

Magnesium phosphate cements (MPCs) typically involve the rapid aqueous reaction of calcined magnesia with $NH_4H_2PO_4$ or KH_2PO_4, forming crystalline magnesium phosphates with cementitious properties, and sometimes they are also called chemically bonded magnesium phosphate ceramics [1]. The main crystalline phase identified in MPC is normally struvite or k-struvite which is preferred in producing MPC because of its excellent mechanical properties [2]. As a binder, MPCs exhibit ultra-high early and long-term strength [3,4], low dry shrinkage [5], good adhesive properties [6,7], and high wearing resistance [7] compared to traditional Portland cements (PCs). Due to their unique properties, MPCs become very attractive in various applications, such as fast repairing and reinforcement of concrete structure [8–10] and encapsulating nuclear waste [11,12]. However, similar to other rapid hardening cementitious materials, MPCs are also highly brittle and of low strain capacity in nature [13]. Moreover, their brittleness could be even worse than PC-based matrices, due to the intrinsic difference in the microstructure and volume fraction of crystalline phases [14]. Thus, it is concerned that MPCs with insufficient material ductility are liable to failure when applied to some environments with high impact or flexural load, such as runway and bridge decks.

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https://doi.org/10.1016/j.conbuildmat.2018.08.044
0950-0618/© 2018 Published by Elsevier Ltd.

Fortunately, the ductility and toughness of cementitious composites can be effectively improved through incorporating short fiber [15,16]. Because of the relatively low pH (8.6 at 24 h and 10.2 at 28 days) in MPC binder [8], a wide range of fibers, including natural and artificial fibers may be added to the matrix. The earlier attempts in this aspect for MPCs were reported by Péra and Ambroise [17], who provided a preliminary study on the feasibility of MPC composites reinforced with different types of fibers for rapid repair. Péra and Ambroise [17] mentioned that MPC matrices with 1.09% polypropylene fibers and 0.69% metallic fibers showed an elastic-plastic or strain-hardening behavior under bending. However, steel fiber reinforced MPC composite still faces some challenges, including increased dead-load, reduced workability due to balling effect in mixing, and susceptibility to corrosion. Recently, Wang et al. [18] demonstrated that the enhanced flexural and tensile strengths along with significant improved fracture energy were observed in MPCs with the inclusion of 2–3% polyvinyl alcohol fibers. But due to a low stiffness and poor interfacial bonding with cementitious material, the synthetic fibers rarely improve the first-crack control or the ultimate load of composites. For these reasons, E-glass fiber is also a popular alternative in MPC composites due to its relatively high tensile strength, low cost and light weight [17,19–21]. The addition of more than 1% glass fibers to MPC matrix leads to considerably higher flexural and direct shear strength, post-cracking capacity and toughness [19–21]. However, glass fiber may be susceptible to corrosion in the alkaline environment of hardened MPC matrix in the long term.

More recently, basalt fiber has shown superiority as a candidate in reinforced cementitious composites because of its environmentally friendly nature and excellent properties [22–24]. The fiber typically has higher tensile strength than E-glass and steel fiber, greater failure strain than carbon fiber as well as good resistance to chemical attack [22–24]. These features, combined with its lower cost than E-glass or carbon fiber, could make basalt fiber a competitive reinforcing material [22]. For these reasons, it seems that basalt fiber can be considered as a potential material to enhance the mechanical strength and toughness of MPC matrix. However, the efficiency of basalt fiber inclusion in MPC composite remains unclear in view of distinctive properties of MPC matrix. Therefore, a comprehensive experimental investigation on mechanical behavior of basalt fiber reinforced MPC composites (BFRMPCs) was carried out.

The main aim of this work is to evaluate the effects of basalt fiber parameters (contents and lengths) on the mechanical properties of MPC composite, compared with glass fiber reinforced MPC composite. The fundamental properties of BFRMPCs, including fresh state properties, physical properties, compressive strength, splitting tensile strength, flexural strength, and fracture toughness, were tested and analyzed in this study. Through scanning electron microscopy (SEM), the microstructure and fractured surface of BFRMPC samples was also studied.

2. Experimental program

2.1. Raw materials

Dead-burnt magnesia was obtained from Chongqing Guolian Refractory Plant, China. Technical grade $NH_4H_2PO_4$ and $Na_2B_4O_7 \cdot 5H_2O$ (borax) of 99% purity were supplied by Chengdu Xincheng Phosphate Plant and Wuhan Huanuo Chemicals Co., Ltd., China, respectively. Low calcium fly ash (FA) obtained from local coal-fired thermal power station was incorporated to reduce the overall cost of the binder and modify the properties of MPC matrix. The physical and chemical properties of magnesia and FA are listed in Table 1. In addition, tap water and locally available river sand (maximum size of 2.36 mm) were used in all mixes.

Discrete basalt and E-glass fibers made as filament bundles were purchased from Haining Anjie Composite Material Co., Ltd., China. Detailed properties of the fibers provided by manufacturers are outlined in Table 1, while Fig. 1 presents the appearance and geometry of the fibers.

2.2. Mix design and sample preparation

MPC binder consisted of MgO powders, $NH_4H_2PO_4$, borax, and FA. A MgO to $NH_4H_2PO_4$ molar ratio of 6 was used, with additions of 10% borax, by weight of the magnesia, and 20% of FA, by weight of the sum of MPC binder (where the mass ratio of MgO:$NH_4H_2PO_4$:borax:FA is 1:0.48:0.10:0.39). The inclusion of 10% borax allowed practitioners more than 25 min to mix and apply MPC mixtures. Mortar specimens used in this study were cast with proportions of 1:0.18:0.5 by mass of MPC binder, water, and sand, as shown in Table 2. At first, all the dry ingredients, including sand, FA, magnesia, $NH_4H_2PO_4$, and borax were combined together and mixed for 3 min using a 20 L capacity horizontal mortar mixer at a low speed. The water was then gradually added and the mixture was allowed to homogenize for another 4–6 min. After that, fibers were slowly added and further mixing for 2 min was performed. The basalt fiber bundles were observed to disperse uniformly throughout the fresh mix, and no balling of fibers occurred during mixing. All the mix types used in this work are summarized in Table 2. Mix code is labelled according to fiber types, lengths, and dosages. For example, the codes of BF12-0.5 and GF20-0.5 indicate chopped basalts fibers of 12 mm and glass fibers of 20 mm length were used at a volume fraction of 0.5% in composite, respectively.

Table 1
Chemical composition and physical properties of magnesia, fly ash, basalt fiber and glass fiber.

		Magnesia	Fly ash	Basalt fiber	Glass fiber
Constituent (%)	MgO	95.25	1.82	10.23	3.51
	SiO_2	1.53	76.98	51.32	54.02
	Al_2O_3	0.25	10.86	15.80	13.35
	CaO	2.14	2.91	7.43	20.31
	Fe_2O_3	0.60	2.96	9.55	0.41
	Na_2O	–	2.18	3.07	0.52
	K_2O	–	1.83	1.03	0.37
	TiO_2	–	0.46	1.57	0.28
Density (g/cm^3)		3.45	2.30	2.64	2.60
Specific area (m^2/kg)		228	413	–	–
Filament diameter (μm)		–	–	13	12
Modulus of elasticity (GPa)		–	–	98	76
Elongation (%)		–	–	3.05	2.65
Tensile strength (MPa)		–	–	4200	3300