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Mechanical properties of micro-steel fibre reinforced magnesium potassium phosphate cement composite

Hu Feng [a], M. Neaz Sheikh [b], Muhammad N.S. Hadi [b,*], Danying Gao [a], Jun Zhao [a]

[a] School of Civil Engineering, Zhengzhou University, Henan 450001, China
[b] School of Civil, Mining and Environmental Engineering, University of Wollongong, NSW 2522, Australia

HIGHLIGHTS

- Mechanical properties of MSF reinforced MPPC composites have been presented.
- Compressive strength and flexural strength of MSFRMC have been investigated.
- Flexural toughness and flexural ductility of MSFRMC have been investigated.
- Compressive and flexural strengths of MSFRMC were high at early stage of curing.
- Reinforcing effect of MSF was higher in MPPC composites than in SAC and OPC composites.

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ABSTRACT

This paper presents the mechanical properties of micro-steel fibre (MSF) reinforced magnesium potassium phosphate cement (MPPC) composites with multi-composite retarder. The compressive strength, flexural strength, flexural toughness and flexural ductility of the MSF reinforced MPPC composite (MSFRMC) were experimentally explored. The variables of the experiment included sand-cement mass ratio, water-cement mass ratio, curing time and fibre volume fraction. In addition, the effect of different types of cement on the mechanical properties of MSF reinforced composites was investigated. It was found that with the increase of water content in the MPPC paste, the average compressive strength, flexural strength and flexural toughness of MSFRMC decreased significantly and the ductility of MSFRMC increased slightly. With the increase of MPPC content in the paste, the flexural toughness of MSFRMC increased significantly and the flexural ductility of MSFRMC increased moderately. With the increase of the addition of MSF, the compressive strength, flexural strength, flexural toughness and flexural ductility of MSFRMC improved significantly. The compressive strength, flexural strength, flexural toughness and flexural ductility of MSFRMC were high at the early stage of curing, especially during the first 3 days. The addition of MSF in MPPC composite improved the compressive strength, flexural toughness and flexural ductility significantly more than the addition of MSF in sulphoaluminate cement and ordinary Portland cement composites.

1. Introduction

Magnesium Phosphate Cement (MPC) is a new type of binder which forms the chemical bond through an acid-base reaction between magnesia and phosphate. The MPC was first discovered and developed as dental cement in the late 19th century [1–3]. Since 1970, MPC has been used to prepare light magnesium cement foamed material [4] and building materials [5]. It has also been used to stabilize and solidify wastes [6,7]. Compared to the Portland cement, the MPC possesses excellent engineering properties including very rapid setting time, high early strength, low shrinkage, high bond strength, high abrasion resistance, high durability and ability to set and harden at temperatures as low as −20 °C. Therefore, it has the potential to be used in the rapid repair of airfield runways, bridges and highways. The research on MPC as a repair and quick construction material has received increased attention [8–10].

The ammonium dihydrogen phosphate ($NH_4H_2PO_4$), as the bisalt of the acid-base reaction, was used to prepare MPC [11–15]. However, the limitation of using $NH_4H_2PO_4$ is that some ammonia was released as a gas during the reaction of magnesia

* Corresponding author.
E-mail address: mhadi@uow.edu.au (M.N.S. Hadi).

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and $NH_4H_2PO_4$ [8]. The released ammonia created an unpleasant environment. Potassium dihydrogen phosphate (KH_2PO_4) has recently been identified as a good candidate for replacing ammonium phosphate [16]. Previous research on MPC prepared with KH_2PO_4 indicated that the performance of composite was mainly influenced by the reactivity of magnesia, the molar ratio of magnesia-phosphate (M/P), and the retarder and water content [17–22]. Usually, borax ($Na_2B_4O_7 \cdot 10H_2O$) is used as a retarder to control the fast reaction. However, the excessive use of the borax resulted in a decrease of the compressive strength [23]. Addition of a small amount of sodium tripolyphosphate ($Na_5P_3O_{10}$) or sodium dihydrogen phosphate dodecahydrate ($NaH_2PO_4 \cdot 12H_2O$) improved the mechanical properties and controlled the setting time as well [24,25]. Due to this positive effect of $NaH_2PO_4 \cdot 12H_2O$, the setting time and compressive strength of MPC cured for more than 28 days improved significantly by the addition of a certain amount of multi-composite retarder (CR), which consisted of borax, sodium dihydrogen phosphate dodecahydrate and calcium chloride [26].

Although a significant number of studies were carried out on the development of MPC, the MPC-based composites are typically brittle. Because of the high volume of cementitious compounds, the MPC-based matrix is more brittle than the Portland cement and sulphoaluminate cement (SAC) based matrices [27]. One of the most effective ways of reducing the brittleness and improving the toughness is the addition of steel fibres in the matrix [28]. The MPC can be used as a binder in fibre reinforced composites. The tensile chemical bond tests revealed better bonding of steel fibre with magnesia phosphate matrix compared to accelerated calcium aluminate [29,30]. The steel fibre may improve significantly the strength of the MPC mortar and reduce the shrinkage of the MPC [31]. Also, the addition of the proper type and amount of steel fibres into MPC-based matrix lead to composites with elastic-plastic or deflection hardening behaviour under bending. Not only the quick setting and high early strength are essential requirements but also a high ductility is needed to guarantee the long life of the repair. Hence the steel fibre reinforced MPC-based composites are considered suitable as quick repair materials [32]. While some studies provided preliminary results on the feasibility of steel fibre reinforced MPC-based composites, a large number of research investigations are still warranted, which include optimization of the matrix, determination of the type and the volume fraction of fibre, and improvement of the durability. Compared to the ordinary steel fibre, the micro-steel fibre (MSF) has the advantages of larger number fibres per kilogram, higher strength and easier dispersion. It was found that the addition of MSF improved the tensile strength, flexural strength and toughness of the Reactive Powder Concrete with an ultra-high compressive strength of more than 100 MPa [33–35]. Hence, MSF has the potential to improve the toughness and ductility of MPC composites.

This paper describes the strength and toughness of MSF reinforced Magnesium Potassium Phosphate cement (MPPC) based composites which include a multi-composite retarder. This composite is termed as MSF reinforced MPPC composite (MSFRMC). The variables investigated include mixture design parameter (water-cement mass ratio and sand-cement mass ratio), fibre volume fraction and curing time. Also, the compressive strength and toughness characteristics of MSF reinforced MPPC, SAC and ordinary Portland cement (OPC) based composites were compared.

2. Experimental program

2.1. Materials

The Magnesium Potassium Phosphate Cement (MPPC) was prepared from a mixture of calcined magnesia (MgO), potassium dihydrogen phosphate (KH_2PO_4) and multi-composite retarder (CR). The multi-composite retarder consisted of borax ($Na_2B_4O_7 \cdot 10H_2O$), disodium hydrogen phosphate dodecahydrate ($Na_2HPO_4 \cdot 12H_2O$) and calcium chloride ($CaCl_2$). The calcined magnesia was sourced from Zhengyang Casting Material Company of Xinmi, Henan, China [36] in the form of Dead Burnt Magnesia powder with a specific surface area of 639 m^2/kg and calcined at 1200° C for 6 h. The detail oxide composition of calcined magnesia is provided in Table 1. The industrial grade potassium dihydrogen phosphate (KH_2PO_4) with a purity of 98%, particle size of 180–385 μm and relative density of 2.338 was supplied by Weitong Chemical Co., Ltd of Wujiang, Jiangsu, China [37]. The industrial grade borax ($Na_2B_4O_7 \cdot 10H_2O$) with a purity of 95% and particle size of 80–220 μm was provided by Banda Technology Co., Ltd. of Liaoning, China [38]. The analytical grade disodium hydrogen phosphate dodecahydrate ($Na_2HPO_4 \cdot 12H_2O$) with a purity of 99% and calcium chloride ($CaCl_2$) with a purity of 96% were provided by Kermel Chemical Reagent Co., Ltd. of Tianjin, China [39]. Tap water, natural river sand with fineness modulus of 2.06 and micro-steel fibre (MSF) with hooked ends were also used in this study. The properties of MSF provided by the manufacturer [40] are detailed in Table 2. As shown in Fig. 1, the length of the MSF is 13 mm.

Table 1
Oxide composition of MgO [36].

Composition	MgO	Fe_2O_3	SiO_2	CaO	Others
Mass fraction of the sample (%)	92.53	0.87	3.1	1.6	1.9

Table 2
Properties of micro steel fibres [40].

Type	Length, *L*(mm)	Diameter, *D* (mm)	Tensile strength (MPa)	Number per kilogram
RS60/13–2850	13	0.22	2850	224,862

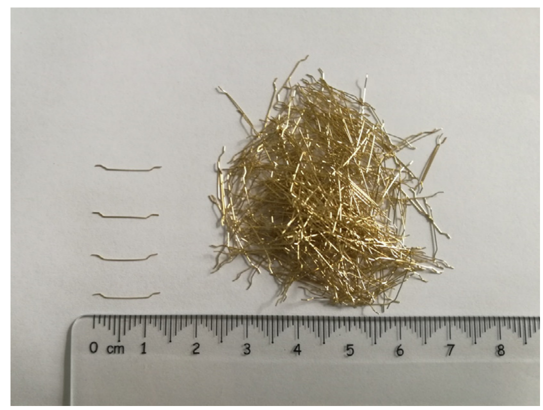

Fig. 1. Micro-steel fibres.

The SAC of Grade P.O 42.5R according to GB20472-2006 [41] and the OPC of Grade P.O 42.5 according to GB175-2007 [42] used in this study were obtained from Anda Special Cement Co., Ltd. Group of Yicheng, China [43] and Mengdian Group Cement Co., Ltd of Henan, China [44], respectively.

2.2. Mixture proportions

The mole ratio of MgO to KH_2PO_4 was fixed at 4 (M/P = 4) in all MPPC mixtures. The dosage of multi-composition retarder was 9.0% of MgO by mass for all MPPC composites. The mass ratio of borax, disodium hydrogen phosphate dodecahydrate and calcium chloride in the multi-composition retarder was 1:3:1. The MPPC consisted of MgO and KH_2PO_4. The addition of MSF was by volume. The SAC and OPC based composites were also prepared to compare the strength characteristics, flexural toughness and ductility. The mixture proportions of MPPC, SAC and OPC based composites are listed in Table 3.

As shown in Table 3, there are three components for the group names of the specimens. The first component of the group names is about the type of cement, where the "M", "S" and "P" represent MPPC, SAC and OPC, respectively. The second component of the group names is about the variables of tests, where the "S/C", "W/C" and "F" represent the sand-cement mass ratio, water-cement mass ratio and fibre volume fraction, respectively. For the third component of the group names, the numbers represent the values of the variables of the second components of the group names. The default values of the sand-cement mass ratio and fibre vol-