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Investigating the Hybrid Effect of Micro-steel Fibres and Polypropylene Fibre-Reinforced Magnesium Phosphate Cement Mortar



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Abstract

To overcome the drawbacks caused by the intrinsic brittleness of cementitious materials, various types of fibres were incorporated as reinforcements. Extensive research on Ordinary Portland cement indicated that compared with the use of a single type of fibres, the mixed-use of multiple fibres can significantly improve both strength and toughness of the cementitious composites, which is referred to as the hybrid effect. However, such hybrid effect in multiple fibre-reinforced magnesium phosphate cement-based composite (HFRMC) still lack quantitative understanding. Therefore, this study conducted a series of experiments, including slump flow tests, compression tests, four-point bending tests and microstructure analysis, to investigate the hybrid effect of micro-steel fibres (MSF) and polypropylene (PP) fibres in HFRMC. Two types of mixed designs of HFRMC were conducted: 1. total fibres fraction (including both PP fibres and MSF) was fixed to be 1.6%; 2. PP fibres fraction was fixed to be 1.6% with different addition of MSF. Our results indicated that the slump flow of magnesium phosphate cement mortar varied around 7.6–8.8% with the hybrid use of MSF and PP fibres, while the flexural strength and toughness increased around 13.7–23.1% and 1.6–45.9%, respectively.

Keywords: magnesium phosphate cement, hybrid reinforcing effect, micro-steel fibres, polypropylene fibres

1 Introduction

Cementitious materials, as the most consumed manufactured materials in the world, were widely applied in many infrastructures, such as dams, buildings, bridges, etc. However, their intrinsic brittleness may result in many deterioration problems and structural failures. To overcome these drawbacks caused by the brittleness of cementitious materials, various types of fibres, such as steel fibres (Feng et al., 2018a), synthetic fibres (Hu et al., 2020a, 2020b), basalt fibers (Ghadikolaee and Korayem, 2020) and carbon fibres (Chen et al., 2018), were added

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as reinforcements, making fibre-reinforced cementitious composites (FRCCs).

Extensive research efforts have been made to improve the mechanical properties of FRCCs, such as manipulation of the interfaces between fibres and cement (Yang et al., 2018), modification of the geometry of fibres (Banthia & Sappakittipakorn, 2007; Dong et al., 2011) and incorporation of multiple types of fibres into the cement systems (Banthia et al., 2014). Among all these approaches, due to the high feasibility of application and low economic cost, the mix-use of multiple fibres have attracted great research interests. Previous studies have shown that mixed-use of multiple fibres can simultaneously promote the strength and toughness of FRCCs significantly (Chen & Qiao, 2011), which is referred to as the hybrid effects. For example, Li et al. (2017a, 2017b) developed a mixed design by incorporating steel fibres with a diameter of 0.7 mm and PP fibres with a diameter



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of 0.9 mm into concrete. Their experiments showed that compared with the concrete reinforced by singlesteel fibres or PP fibres, the incorporation of mixed 2.0% steel fibres and 1.1% PP fibres remarkably enhanced the mechanical performance of the FRCCs with 30.2%, and 64.3% increase of the flexural strength and ductility, respectively. Both experiments and theoretical analysis indicate that the hybrid fibres improving mechanical performance is mainly attributed to the fact that a combination of fibres with different geometry can resist the crack propagation at different structural levels, which, therefore, leverage the fibres' reinforcing capacity (Banthia & Gupta, 2004; Kang & Bolander, 2016; Wang et al., 2017).

As a substitutes for OPC, magnesia phosphate cement (MPC) has drawn significant interest in recent decades due to its fast setting speed (Jin, et al., 2020), high early strength (Ma et al., 2021), excellent bonding performance Li et al., (2017a, 2017b), small drying shrinkage (Ma & Chen, 2016; Wu et al., 2021), good volume stability (Wu et al., 2021) and excellent durability (Chang et al., 2014). Therefore, the application of MPC can satisfy the demands of many engineering projects, such as hub road (Arora et al., 2019), airport runway (Yang, 2014), important bridge deck that needed be repaired quickly and open to traffic as soon as possible (Haque & Chen, 2019). Similarly to OPC-based FRCCs, various fibres, such as steel fibres and PP fibres, were also introduced into MPC as reinforcements to strengthen their mechanical properties. Feng et al., (2020) indicated that the addition of 1% micro steel fibres (MSF) led to the highest increase (15.0%) of the strength of MPC composites in comparison with other fibres, such as the cutting hook steel fibres, milling hook steel fibres and macropolypropylene fibres. Jean and Jean, (1998) found that the incorporation of PP fibres formed a randomly distributed network of the reinforcements in MPC composites. This network of PP fibres can effectively inhibit the development of micro-cracks, leading to the highest enhancement in toughness (400.1%) in comparison with other fibres. Given that the low elastic modulus of PP fibres can reduce the strength of MPC composites (Hu et al., 2020a, 2020b; Sarangi & Sinha, 2006), while the density and cost of MSF is relatively high (Khamees et al., 2020; Qian & Stroeven, 2000), the hybrid effect of PP fibres and MSF in MPC is, therefore, essential to be investigated for designing the high-performance MPC composites.

Therefore, in the present study, MSF and PP fibres with different fractions were incorporated into MPC to make hybrid fibre-reinforced magnesium phosphate cementbased composites (HFRMC). To comprehensively understand the hybrid effects of these two fibres, a series of experiments on HFRMC were conducted, including slump flow tests, compression tests and four-point bending tests. Besides, microstructure analysis was also performed to release the mechanism of hybrid effects of MSF and PP fibres in HFRMC. To the best of our knowledge, this is the first time that the hybrid effect of PP fibres and MSF was studied in MPC composites, which help guide the design of fibre-reinforced MPC with integrated high strength and high toughness.

2 Experiments

2.1 Materials

Fig. 1 illustrates the appearance of the raw materials used in this study. MgO (>97% purity) with a specific surface area of 315.7 m²/kg was obtained from Casting Material Company, Xinmi, Henan, China. Two types of industrialgrade KH₂PO₄ with particle sizes of 40 mesh and 80 mesh, respectively, were provided by Ronghong Chemical Co., Ltd. of Mianzhu, Sichuan, China. 95.0% purified Borax (Na₂B₄O₇·10H₂O) with a particle size of 80–220 mesh was applied as retarded in this study. Besides, quartz sands of 80–120 mesh were used to prepare MPC mortar, and fly ash with a surface area of 200 m²/kg was also incorporated as partial replacement of MPC.

Characterization of the raw materials that used in the study was conducted by analysing the particle size distribution. Besides, X-ray diffraction analysis (XRD) were also conducted to analyse the chemical components in the raw material, as shown in Fig. 2. The major chemical compositions of the MgO and fly ash are shown in Table 1. The hybrid effects of two types of fibres, namely, polypropylene fibres (PP) and micro-steel fibres (MSF), were investigated in this study. The geometry and mechanical properties of these fibres are indicated in Table 2.

2.2 Preparation of Fibre-Reinforced MPC Mortar

MgO, $\rm KH_2PO_4$, quartz sand, fly ash and borax were first dry-mixed by a concrete mixer for 120 s. Then water was added into the dry content and mixed for another 20 s. Following by addition of fibres, finally, the MPC mortar was mixed for an additional 120 s, making fibre-reinforced MPC mortar (Jian-ming et al., 2009). The mixed designs of the fibre-reinforced MPC mortar are indicated in Table 3.

After mixing was completed, the fibre-reinforced MPC mortars were poured into $50.9 \times 50.9 \times 50.9$ mm cubic moulds (for compression test) and $400 \times 100 \times 15$ mm beam moulds (for four-point bending test). Then shaking table vibration was applied to remove air bubbles in the slurry. After 2 h of initial hardening, the prepared specimens were demoulded and cured at 25 ± 2 °C temperature, $45\pm5\%$ RH humidity for 1, 7, 28 days.



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2.3 Measurement of the Consistency of MPC Mortar

The slump flow tests consistency of each mixture. First, the bottom plate was placed on solid level ground, and the slump cylinder was located at the centre of the bottom plate. The geometry of the slump cylinder is illustrated in Fig. 3. Both the slump cylinder and the bottom plate were prewetted to provide enough lubrication. Then the slump cylinder was filled with the slurry of HFRMC three times. After each filling, 25 times of pounds were applied from inside to the outside of the slump cylinder, removing the large voids inside the slurry. When the slump cylinder is full, the excess slurry was scraped off to keep the top surface levelled. Finally, the slump cylinder was vertical lifted, ensuring minimum lateral disturbance.

2.4 Measurement of the Mechanical Properties of Fibre-Reinforced MPC Mortar

The compressive strength of the prepared MPC mortar specimens was measured according to ASTM C109 (Cao et al., 2016). At least three cubic specimens were tested for each batch using a pressure testing machine (YAW-2000B) compression machine at a loading rate of 0.9 kN/s.

Flexural properties of HFRMC were also tested by conducting four-point bending tests according to CECS 13:2009 (Onuaguluchi et al., 2014). As shown in Fig. 4, a load cell and the linear variable differential transformer (LVDTs) were installed on the top surface and the middle of the beam specimen, respectively, which measured the relationship between deformation and applied force during testing. The four-point bending tests were performed by an electronic universal testing machine (WDW-100) load frame at 0.3 mm/s loading rate. To calculate the I_{10} and I_{20} , the load applied on the specimens was recorded until the mid-span deflection was over 10.5 times the first crack deflection. Similar to the compression tests, at least 3 beam specimens were tested for each batch to minimize the deviation. Toughness index (I_{10} and I_{20}) was calculated following the literature (Naaman et al., 1996; Shaikh & Design 2013). showing the post-crack capacity of energy absorption of the fibre-reinforced MPC. The expression of I_{10} and I_{20} are shown in Eqs. 1 and 2:

$$T_{10} = T_{5.5}/T_{\rm LOP} \tag{1}$$

$$I_{20} = T_{10.5}/T_{\rm LOP} \tag{2}$$

where $T_{5.5}$ and $T_{10.5}$ are the area under load-mid span deflection curve until 5.5 and 10.5 times the first crack deflection, and T_{LOP} is the area under load-mid span deflection curve up to the first crack occurs. Therefore, to calculate the I_{10} and I_{20} , the load applied on the specimens was recorded until the mid-span deflection was beyond 10.5 times the first crack deflection. Following the literature (Committee, 1997), the initial cracking point is the point at which the slope of the ascending segment of the load-deflection curve changes significantly (i.e., the transition point from the straight line to curve). The calculation results of I_{10} and I_{20} are shown in Tables 4 and 5.



Table 1 Major chemical composition of MgO and fly ash.

	Composition	MgO	Fe	e ₂ O ₃	SiO ₂	CaO	Al ₂ O ₃
MgO	Mass fraction (%)	97.0	0.2	2	0.4	1.4	0.1
	Composition	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	Na ₂ O
Fly ash	Mass fraction (%)	54.0	31.2	4.2	4.0	1.0	0.9

 Table 2
 Geometry and mechanical properties of MSF and PP fibres.

Fibre type	Fibre profile	Length (mm)	Diameter (µm)	Young's modulus (GPa)	Nominal strength (MPa)	Elongation (%)	Tensile strength (MPa)
PP		12.0	25.0	3.5	410.0	12.0	/
MSF		13.0	220.0	210.0	/	/	2580.0

Hybrid system	Specimens	M/P	w/c	s/c	Fa%	Fibre volume fraction		Curing age (days)
						PP (%)	MSF (%)	
PS0	1.6%PP+0.0%MSF	4/1	0.19	0.2	40	1.6	0.0	7
PS4	1.2%PP+0.4%MSF					1.2	0.4	
PS8	0.8%PP+0.8%MSF					0.8	0.8	
PS12	0.4%PP+1.2%MSF					0.4	1.2	
PS16	0.0%PP+1.6%MSF					0.0	1.6	
fPS0	1.6%PP+0.0%MSF					1.6	0.0	
fPS2	1.6%PP+0.2%MSF					1.6	0.2	
fPS4	1.6%PP+0.4%MSF					1.6	0.4	
fPS6	1.6%PP+0.6%MSF					1.6	0.6	

Table 3 Mix design of fibre-reinforced MPC mortar.

Cement is composed of MPC and fly ash. The content of M/P is MgO to KH₂PO₃ mole ratio; s/c is sand to cement ratio; Fa% is the proportion of fly to cement; w/c is water to cement ratio.



slump cylinder; **b** front view of the slump cylinder; **c** measured slump flow of HFRMPC slurry.



Fig. 4 Illustration of the four-point bending test for fibre-reinforced MPC mortar.

 Table 4
 Effects of curing age on ductile index and toughness index of fibre-reinforced MPC.

Specimens	I ₁₀	I ₂₀
PS8-1d	8.8±0.3	18.9±1.7
PS8-7d	11.2 ± 0.6	23.6 ± 0.8
PS8-28d	11.4 ± 1.0	25.8 ± 0.3
fPS4-1d	5.9 ± 0.2	11.9 ± 1.1
fPS4-7d	7.0 ± 0.2	18.8 ± 1.6
fPS4-28d	6.7 ± 0.4	15.1 ± 0.3

Table 5 Hybrid effects of PP fibres and MSF on ductile index and toughness index of fibre-reinforced MPC mortar.

Specimens	I ₁₀	I ₂₀
PSO	6.5 ± 0.1	14.3 ± 1.5
PS4	6.3 ± 0.1	13.6 ± 0.3
PS8	8.6 ± 0.4	17.0 ± 0.7
PS12	8.0 ± 1.0	14.9±0.9
PS16	9.4 ± 0.6	17.0 ± 1.4
fPS0	6.5 ± 0.5	14.3 ± 1.2
fPS2	5.7 ± 0.1	11.4 ± 0.7
fPS4	7.8 ± 0.6	15.6 ± 0.3
fPS6	8.3 ± 0.2	17.1 ± 1.9

3 Results and Discussion

3.1 Influence of Hybrid Fibres on the Consistency of MPC Mortar

Fig. 5 shows the slump flow of fresh HFRMC with different mix designs. As shown in Fig. 5a, the increase of MSF proportion from 0 (PS0) to 1.6% (PS16) improve 7.7% of the slump flow, which is mainly attributed to the corresponding reduction of the fraction of PP fibres. Due to



their hydrophobic surface and low elastic modulus, PP fibres tend to entangle with each other during mixing. This entanglement consequently raise the viscosity of HFRMC (Zebarjad et al., 2003).

To further investigate the influence of hybrid PP fibres and MSF on the consistency of MPC, Fig. 5b shows the slump flow of MPC mortar with a fixed fraction (1.6% in volume) of PP fibres. Different from HFRMC with a total fibres fraction of 1.6%, the increase of MSF from 0 (fPS0) to 0.6% (fPS6) results in a reduction of slump flow from 261 to 240 mm. This reduction is caused by the increasing steel fibres' amount generally leads to lower consistency of the composites (Figueiredo and Ceccato, 2015) and interweave between PP fibres and MSF during cement mixing, which exacerbates the fibres' entanglement and decreases the consistency. Similar phenomena of OPC based cementitious composites have also been reported by Eaha et al., (2020), where they found consistency of steel-polypropylene hybrid fibre-reinforced cement was also relatively poor in comparison with the single type fibre-reinforced composites, which is consistent with our results.

3.2 Effects of Hybrid Fibres on Compressive Strength

Fig. 6a shows the development of the compressive strength of MPC mortar after different curing ages. The compressive strength of HFRMC increases dramatically by about 35.1% after the initial 7 days' curing, which shows a rapid hydration process of MPC mortar. Since the hydration reaction of MPC mortar is an exothermic reaction of acid-base neutralization, the temperature inside MPC mortar increases rapidly at an early stage. This temperature increase would intensify the hydration reaction of MPC mortar by dissolving phosphate quickly, leading to a further rise of the temperature (Liu et al., 2014). Consequently, the growth rate of early strength of MPC mortar is significantly greater than that of late strength (Soudée and Péra, 2000), which explained why the increase of compressive strength of HFRMC slowed down with further curing after 7 days.

The hybrid effects of PP fibres and MSF on the compressive strength of MPC mortar were investigated by mixing MSF and PP fibres with different fractions into MPC mortar. As indicated in Fig. 6b that after curing for 7 days, the compressive strength of hybrid



fibre-reinforced MPC mortar improved greatly from 32.2 to 46.1 MPa when the fraction of MSF increased from 0 to 1.6%. Similar results were also reported in previous studies that due to its high stiffness and excellent bonding with cement, MSF could significantly promote the elastic modulus of the cementitious composites before matrix cracking, leading to a high compressive strength (Feng et al., 2018b). However, it is noticed that this increase of MSF fraction does not lead to a continuous enhancement of the compressive strength. For example, an increase of MSF fraction from 0.4 (PS4) to 0.8% (PS8) resulted in a slight 0.6% reduction of the compressive strength. This slight reduction is likely to be caused by the interweaving between PP fibres and MSF inducing uneven fibre distribution (Atea, 2019), which was overcome by a continuing replacement of PP fibres with MSF. Similarly, for the HFRMC with a fixed fraction of PP fibres, as shown in Fig. 6c, a small addition of MSF from 0 to 0.4% has a limited influence on the compressive strength with a fluctuation of 1.2% during 7 days of curing. This can also be attributed to the fact that the increase caused by the addition of MSF was offset by the interweaving between MSF and PP fibres. Therefore, with the addition of MSF, the compressive strength of magnesium phosphate cement-based composites shows an overall upward trend, but the overall increase is relatively limited due to the interweave between PP fibres and MSF. It is also worth noting that in comparison between the hybrid systems with fixed total fibres fraction and with fixed PP fibres fraction, for example, PS8 and fPS4, despite a lower total fibres fraction in PS8, its compressive strength is about 8.6% higher than that of fPS4. This can be attributed to the higher amount of MSF in PS8, which can more effectively improve the mechanical properties of cementitious composites than PP fibres (Li et al., 2017a).

3.3 Effects of Hybrid Fibres on Flexural Properties

Apart from compressive strength, more importantly, the flexural behaviour of hybrid fibre-reinforced MPC mortar were investigated by conducting the four-points bending tests. Three specimens were tested for each batch of mixed design, the load-mid-span deflection curves of each test were shown in the Additional file 1. Similar to the compressive strength, the flexural strength of MPC mortar also grows with the curing age. As indicated in Fig. 7a, b, the increase of curing age from 1 to 7 days leads to a significant improvement of the ultimate flexural strength (from 5.4 to 7.9 MPa) of PS8. However, on



the other hand, 34.6% of the maximum mid-span deflection reduces as the curing age grows from 1 to 7 days. This is because with a low fibre fraction, the flexural behaviour of fibre-reinforced composites is mainly governed by the MPC matrix (Pacheco-Torgal & Jalali, 2011). As MPC mortar hydration proceeds, hydrated product crystal nuclei grow and are interconnected, gradually forming a crystalline structure network (Lai et al., 2014). This crystalline structure network increases the strength of the MPC matrix on the one hand while reducing its toughness (Yao et al., 2020). Consequently, an increase of strength and reduction of maximum mid-span of MPC composites were observed simultaneously as the curing age grows for 1–7 days.

However, with the incorporation of more PP fibres (fPS4: 1.6% PP + 0.4% MSF), the flexural properties, especially the post-crack behaviour of HFRMC, is mainly dominated by the interfaces between fibres and matrix (Uskokovic et al., 1999). As interfacial bonding between fibre and MPC mortar developed rapidly at early curing age (1–7 days) (Li et al., 2016), consequently, shown in Fig. 7c, d, the maximum mid-span deflection of fP-S4 extends remarkably for about 170.1%, and ultimate flexural strength increases about 64.3%. However, since the

interfacial bonding between fibres and MPC mortar has been well-developed after 7 days' curing, longer curing age from 7 to 28 days has little improvement in both the ultimate flexural strength and maximum mid-span deflection.

Fig. 8a, b shows the hybrid effect of PP fibres and MSF on the flexural properties of HFRMC. The ultimate flexural strength increases from 6.81 to 10.8 MPa with the increase of MSF fraction from 0 to 1.6%, while the maximum mid-span deflection decreases from 9.2 to 6.2 mm. This increase in ultimate flexural strength and decrease in maximum mid-span is also attributed to the conflicts between strength and toughness of the cementitious composites that contain a low fraction of fibres (Yao et al., 2020). Besides, it is also interesting to find that comparing PS0-PS4, a slight increase of MSF content leads to a slight decrease of ultimate flexural strength from 6.8 to 6.5 MPa. Previous studies (Fantilli et al., 2018) also reported that the incorporation of multiple types of fibres in cementitious composites can induce the interweaving among fibres, which is likely to lead to an uneven fibre distribution. Consequently, this uneven fibres distribution is believed to result in a reduction of flexural strength (Banthia & Gupta, 2004). However, with



the continuing increase of the fraction of MSF from PS4 to PS16, cracking strength and ultimate strength increase about 28.4 and 77.9%, respectively. This is because the MSF has strong mechanical properties (e.g., elastic modulus of 210 GPa) (Iqbal et al., 2015) and excellent interfacial bonding with cement matrix (Ranjbar et al., 2016), increasing the content of MSF can effectively enhance the flexural strength of MPC mortar. Similar effects of MSF was also reported in previous studies (Shin et al., 2014).

To further explore the hybrid effects of these two fibres on MPC composites, flexural tests on other mix designs were conducted by fixing the fraction of PP fibres to be 1.6% and gradually changing the fraction of MSF. Although the addition of MSF is expected to improve the mechanical performance of MPC mortar due to its high mechanical properties and excellent bonding with cement, this improvement caused by a small addition of MSF (less than 0.6%) can be comprised by the lower reinforcing efficiency and air voids induced by the uneven fibre distribution (Iqbal et al., 2015). Consequently, as demonstrated in Fig. 8d, the small addition of MSF from 0 to 0.6% has limited effects on both ultimate flexural strength and cracking strength with fluctuations of 5.6 and 5.7%, respectively, which shows a similar trend with the compressive strength of fPS samples as mentioned before.

As shown in Table 4, in terms of PS8, I_{10} and I_{20} increased significantly about 26.6 and 25.0%, respectively, after 7 days of curing. However, further curing from 7 to 28 days only slightly improved 1.8% of I_{10} and 9.2% of I_{20} . This is mainly attributed to the rapid hydration of MPC mortar leading to well-developed interfacial bonding between fibre and matrix at an early stage (Nuaklong et al., 2020).

Investigation of the hybrid effect of PP fibres and MSF on the toughness of MPC mortar were conducted by calculating I_{10} and I_{20} for different mixed designs of MPC, as listed in Table 5. With little addition of MSF (PS4), the value of I_{10} and I_{20} reduced slightly about 3.2 and 4.6%. However, a further increase of the proportion of MSF (PS16) remarkably improved the toughness of MPC mortar with 44.9% of I_{10} and 19.1% of I_{20} , suggesting that MSF showed better reinforcing effects than PP fibres (Feng et al., 2020). This enhancement can be attributed to the reduced PP fibres agglomeration due to the decrease in the fraction of PP fibres. Besides, previous studies (Wongprachum et al., 2018) also demonstrated that in comparison with steel fibres, PP fibres has a low elastic modulus and relatively weak interfacial bonding with cementitious matrix, which also explained the reason why replacing PP fibres with MSF can enhance the mechanical performance of HFRMC. On the other hand, as for the batch of MPC mortar with a fixed fraction of PP

fibres, a slight increase of MSF with 0.2% (fPS2) resulted in a 12.3% and 20.3% reduction of I_{10} and I_{20} , respectively. This slight reduction is likely to be attributed to the uneven distribution of fibres when incorporating multiple fibres in the cementitious composites (Yang et al., 2020), which could harm the toughness. However, this slight reduction in toughness was overcome by the addition of more MSF. In comparison with fPS0, the addition of 0.6% of MSF (fPS6) significantly improved 27.4% of I_{10} and I_{20} .

3.4 Microstructure Analysis

Fig. 9a shows the microstructure at the interface between PP fibres and MPC mortar. Large voids are noticed at this interface, indicating a weak adhesion between PP fibres and the MPC matrix (Lawler et al., 2003). This is because the surface of PP fibres is smooth and hydrophobic, MPC hydration products can hardly grow on fibre surface to form strong chemical bonds (Li et al., 2010). Consequently, shown in Fig. 9c, PP fibres are pulled out easily when subjected to external force, leaving a smooth hole on the MPC matrix. Furthermore, several large voids and cracks on MPC mortar were noticed near the interface between PP fibres and the matrix, which further confirmed the relatively weak interactions of PP fibres with MPC mortar (Feng et al., 2022). On the contrary, as shown in Fig. 9b, MSF and MPC matrix were densely bonded with MPC hydration particles growing on the fibre surface, suggesting a strong interface between MSF and MPC matrix. As result, a large external force is required to break this strong interface between MSF and MPC mortar, which lead to a rough hole on the MPC matrix after MSF pull-out, as shown in Fig. 9d. Therefore, in comparison with PP fibres, MSF shows a much higher reinforcing efficiency due to its strong interface with MPC mortar (Chanh 2004). This also explained the reason why the addition of MSF can significantly improve the post-cracking behaviour of hybrid fibre-reinforced MPC mortar as observed in our four-point bending tests.

To further investigate the hybrid effect of PP fibres and MSF on MPC mortar, the microstructure of the hybrid fibre-reinforced MPC mortar (0.8% PP and 0.8% of MSF) was investigated. As shown in Fig. 10a, PP fibres were densely distributed around MSF, suggesting the entanglement of these two types of fibres. Since the distribution of MSF in MPC mortar is relatively uniform (Maha et al., 2019), the entanglement of PP fibres with MSF can impede concentrated fibre agglomeration at the local area (Li et al., 2018). Furthermore, this entanglement will also enhance the snubbing effect of PP fibres during fibre pull out (Zhong & Zhang, 2020), increasing the bridging stress at the crack surface and consequently improving the mechanical properties of HFRMC.



Fig. 9 Microstructure of the interface of a PP fibre and b MSF with MPC matrix; pull-out hole of c PP fibre and d MSF.

4 Conclusions

To understand the hybrid effect of PP fibres and MSF in magnesium phosphate cementitious composites, experiments were conducted to investigate the consistency, mechanical properties and the microstructure of HFRMC with the various proportion of PP fibres and MSF. Our slump flow tests indicated that the increase of the proportion of 1.2% PP fibres lead to an 8.1% decrease in the slump flow of HFRMC. Such decrease is mainly attributed to the hydrophobic surface of PP fibres resulting in a fibres agglomeration. Besides, results from the slump flow tests of the samples with a fixed fraction of PP fibres demonstrated that the interweave between MSF and PP fibres had a negative impact on the consistency, leading to a 5.4% reduction of the slump flow with a slight addition of 0.6% MSF. To further understand the hybrid effects of MSF and PP fibres on the performance of HFRMC, compressive strength and flexural strength were also tested. Results showed replacing 1.6% of PP fibres with MSF in HFRMC can significantly improve compressive strength and flexural strength for about 43.2 and 67.7%, respectively, indicating the reinforcing effects of MSF is better than that of PP fibres in MPC mortar. Furthermore, mechanical tests of the HFRMC with fixed content of PP fibres showed that a slight addition of MSF (less than 0.4%) can barely enhance the mechanical properties of HFRMC. This can be attributed to the fact that the enhancement caused by the MSF was offset by the interweave between MSF and PP fibres.

To provide an insight into the mechanism of the hybrid effects of MSF and PP fibres in MPC mortar, microstructure analysis of HFRMC was conducted using SEM. The SEM images confirmed that the hybrid effect of PP fibres and MSF is caused by interweaving between MSF and PP fibres, leading to a dense distribution of PP fibres around MSF. It is believed that although the fibre entanglement has a negative effect on mechanical properties with a small addition of MSF, a further increase of MSF fraction can prevent the large-scale agglomeration of PP fibres in local areas. Furthermore, this fibre entanglement can also enhance the snubbing effects of PP fibres, which consequently enhances the post-crack performance of HFRMC with an up to 27.7 and 19.6% increase of I_{10} and I_{20} . With a



Fig. 10 a Mixed distribution of PP fibres and MSF, surface morphology. b PP fibres pull-c MSF after pulled out from MPC matrix.

deep understanding of the hybrid effect in HFRMC, the findings in this study can help guide the design of highperformance fibre-reinforced MPC mortar.

Supplementary Information

The online version contains supplementary material available at https://doi. org/10.1186/s40069-022-00528-6.

Additional file 1: Figure S1. Load-mid-span deflection curves of PS8 with the curing age of a 1 day, b 7 days and c 28 days. Figure S2. Loadmid-span deflection curves of fPS4 with the curing age of a 1 day, b 7 days and c 28 days. Figure S3. Load-mid span deflection curve for MPC mortar with 1.6% hybrid fibres in total (PS). Figure S4. Load-mid span deflection curve for MPC mortar with fixed 1.6% PP fibres, respectively.

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Author contributions

QS and LL were responsible for data collection, analysis and interpretation. HF, XY and CY helped perform the analysis with constructive discussions. All authors read and approved the final manuscript.

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Availability of data and materials

The data sets used and analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests

The authors declare that they have no competing interests.

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