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Fiber-reinforced Magnesia–phosphate Cement Composites for Rapid Repair

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Abstract

Magnesia–phosphate cements are fast setting materials which can be used for rapid repair. While they are typically brittle in nature, their ductility can be significantly improved by addition of fibers. This paper presents some results obtained with five different types of fibers, namely E-glass, polyester, polypropylene, polyamide, and metallic. E-glass and polyester fibers are usually destroyed by chemical reaction with ordinary Portland cement but are compatible with magnesia–phosphate cement. The fiber volume fraction ranged from 0.69% (metallic) to 1.32% (polyamide). The composites were prepared according to the premix method, the matrix being composed of 50% magnesia–phosphate cement and 50% sand. The behavior of such composites was compared to that of a control composite made with ordinary Portland cement based composite reinforced by 0.97% A.R. glass fibers. Besides the type of fiber and cement matrix, the test parameters included the age at loading (from 3 h to 90 days) and the exposure conditions by prior immersion in hot water or by cycles of wetting and drying. Test results include the load–deflection response, the modulus of rupture, the toughness indices, the residual strength factor and a comparison of the various modes of failure. It is pointed out that the performance of magnesia–phosphate cement composites, at 3 h of age, was about the same as that obtained at 28 days by the control composite. Moreover, when subjected to accelerated aging, these composites maintained their performance, and elastic–plastic behavior in bending was observed as polypropylene and metallic fibers were used.

Keywords: Rapid set cement, fibers, durability, flexure, toughness, repair.

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INTRODUCTION

Among various rapid-hardening cements available for concrete repair, magnesia–phosphate based systems are of considerable interest.[1] Frequently the disruption in time caused by the repair and the consequent inconvenience to the traveling public, added to the financial costs resulting from traffic control and diversion or delay in delivery, can be much more expensive than the repair itself.[2] It follows, therefore, that there is an increasing demand for new materials and methods for rapid but durable repairs of concrete pavements, where the closure time is measured in hours instead of days.

Magnesia–phosphate cements (MPC) provide the essential requirements for such applications, namely quick setting and the development of high early strength. These cements fall under the broad category of acid–base cements and the most common cementing ingredients are deadburned magnesia (MgO) and an acid ammonium phosphate. The products of the reactions are hydrated magnesium-containing phosphates, which are insoluble in water and frequently incorporate a second cation such as Al^{3+} or NH_4^+. The hydration reactions can be

Table 1. Mixture proportions of composites

	Fiber					
	A.R. glass	*E-glass*	*Polyester*	*Polypropylene*	*Polyamide*	*Metallic*
Water/dry matter	0.20	0.22	0.25	0.20	0.20	0.20
Fiber weight fraction (%)	2.50	2.50	1.00	1.00	1.50	5.00
Fiber volume fraction (%)	0.97	0.97	0.72	1.09	1.32	0.69

controlled and modified by the use of retarders.[3]

Fast setting cementitious composites are typically brittle in nature. Moreover, their brittleness could be worse than Portland cement based matrices because of the high volume of cementitious compounds.[4] Addition of fibers to these composites is a method for improving their ductility. A very limited number of investigations have been carried out in this area. This paper describes the behavior of MPC based composites reinforced by different types of fibers. The variables discussed include type of cementitious matrix, fiber type, fiber volume fraction, and the load–deflection behavior in flexure. Strength and toughness characteristics at early ages and long-term are also discussed.

EXPERIMENTAL

Component materials

The magnesia–phosphate cement (MPC) used in this study was a mixture, by weight, of 50% deadburned magnesia (MgO) and 50% mono-

Table 2. Characteristics of the fibers used

Fiber type	*Cross-section*	*Length (mm)*	*Tensile strength (MPa)*	*Young's modulus (GPa)*	*Ultimate strain (%)*
A.R. glass	Ø[a] = 20 μm	25	3700	76.0	4.9
E-glass	Ø = 15 μm	25	3600	75.0	2.5
Polyester	Ø = 65 μm	20	875	13.0	15.5
Polypropylene	Fibrillated 20 × 300 μm²	25	730	6.4	14.0
Polyamide	Ø = 19 μm	18	900	4.0	25.0
Metallic	Rectangular 29 × 600 μm²	20	2000	140.0	7.0

[a]Ø = diameter.

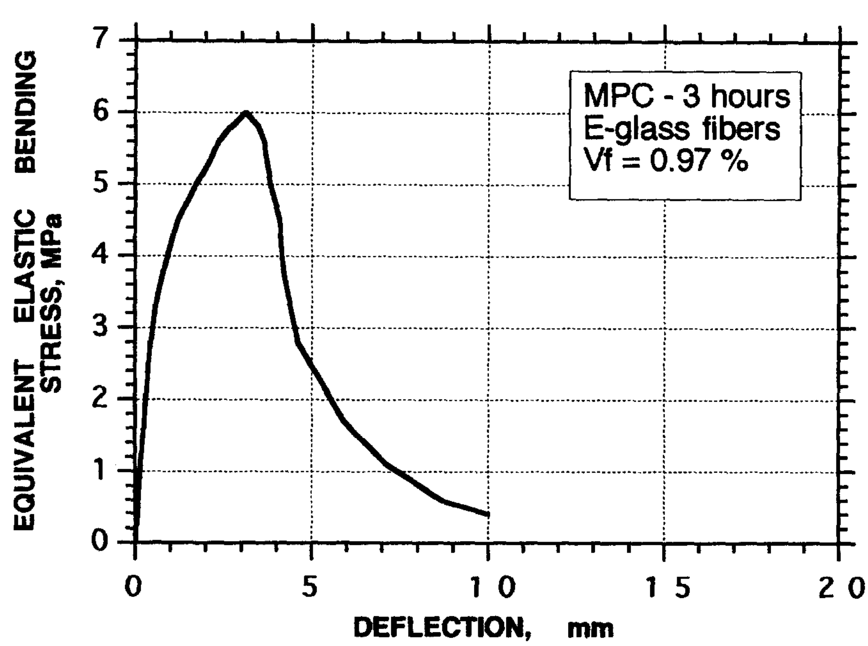

Fig. 1. Typical equivalent elastic bending stress versus deflection curve of MPC reinforced by E-glass fibers, after 3 h of age.

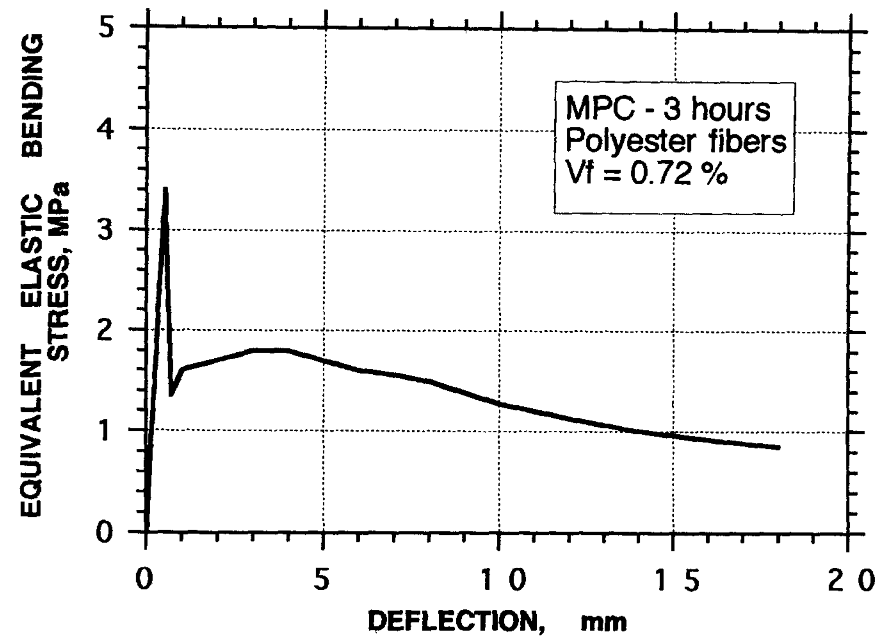

Fig. 2. Typical equivalent elastic bending stress versus deflection curve of MPC reinforced by polyester fibers, after 3 h of age.

ammonium dihydrogen orthophosphate (MAP). Boric acid was used as a set retarder in proportion of 2% by weight of MPC. Fine siliceous sand, of particle size ranging from 0 to 1 mm, was added to MPC in the weight ratio 1:1. To compare the behavior of the various MPC composites, a control composite, made with ordinary Portland cement and sand in proportion of 1:1 by weight was also prepared. The mixture proportions for the various systems are given in Table 1.

It is noted that the fiber content and the water–cementitious ratio are not constant. They were arrived at from various trials to achieve about the same workability. The workability was assessed by means of the flow-table test. A truncated cone of the mixture to be cast was filled. The height of the mold was 50 mm and the upper and lower diameters were 70 mm and 100 mm, respectively. The static spread of each mixture was 120 mm and, after 10 strikes, reached 190 mm. The water–cementitious ratio

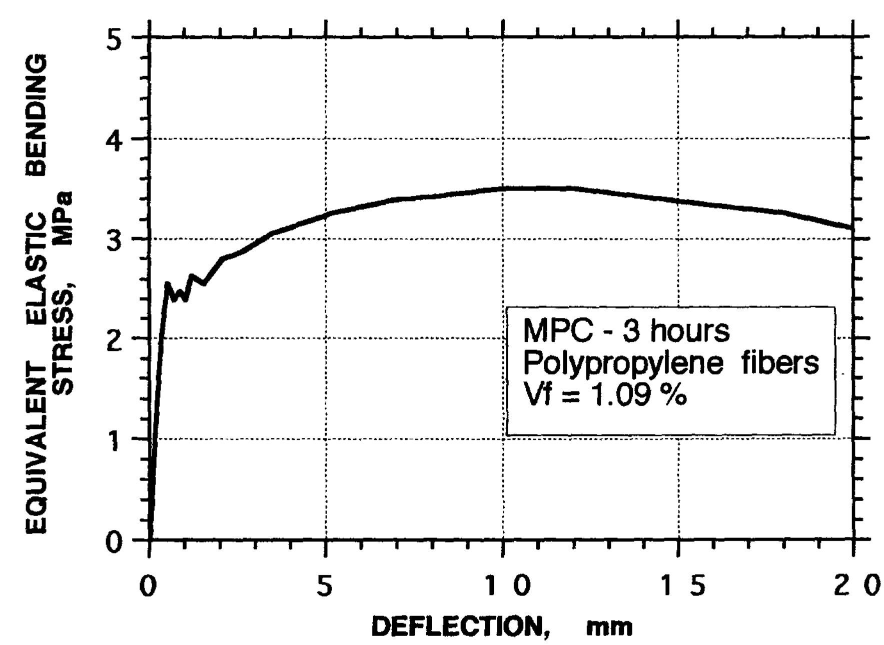

Fig. 3. Typical equivalent elastic bending stress versus deflection curve of MPC reinforced by polypropylene fibers, after 3 h of age.

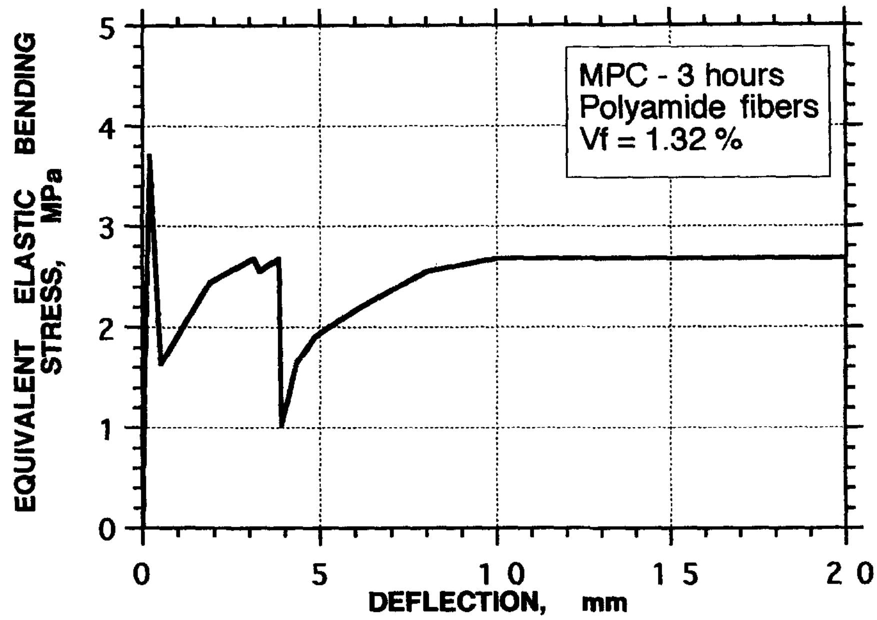

Fig. 4. Typical equivalent elastic bending stress versus deflection curve of MPC reinforced by polyamide fibers, after 3 h of age.

varied from 0.2 to 0.25 and the fiber volume fraction varied from 0.69% to 1.32%.

Five types of fibers were used to reinforce the MPC system: E-glass, polyester, polypropylene, polyamide, and metallic. The metallic fiber was amorphous cast iron. The OPC matrix was reinforced by A.R. glass fibers (Alkali Resistant). It should be noted that E-glass and polyester fibers are usually destroyed by chemical reaction with ordinary Portland cement but not in magnesia–phosphate cement, where the pH of the pore solution is 7 to 8. The characteristics of the fibers used are given in Table 2.

Sample preparation

The various composites were prepared by the premix method. The amount of added fibers was limited by the workability of the composite.

Composites were cast in plastic molds ($15 \times 70 \times 270$ mm^3) and vibrated for 1 min at 50 Hz. Then, they were kept at 20 ± 2°C and

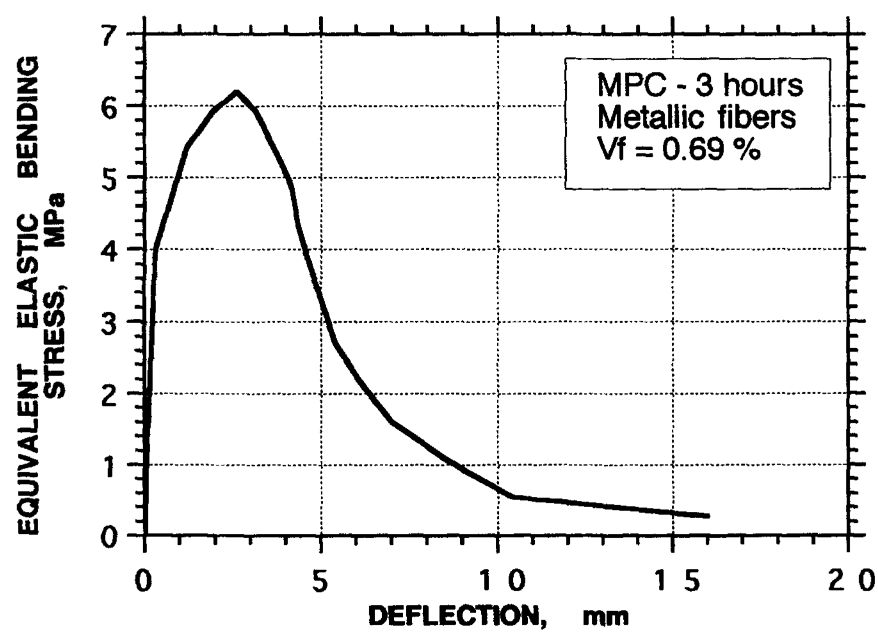

Fig. 5. Typical equivalent elastic bending stress versus deflection curve of MPC reinforced by metallic fibers, after 3 h of age.

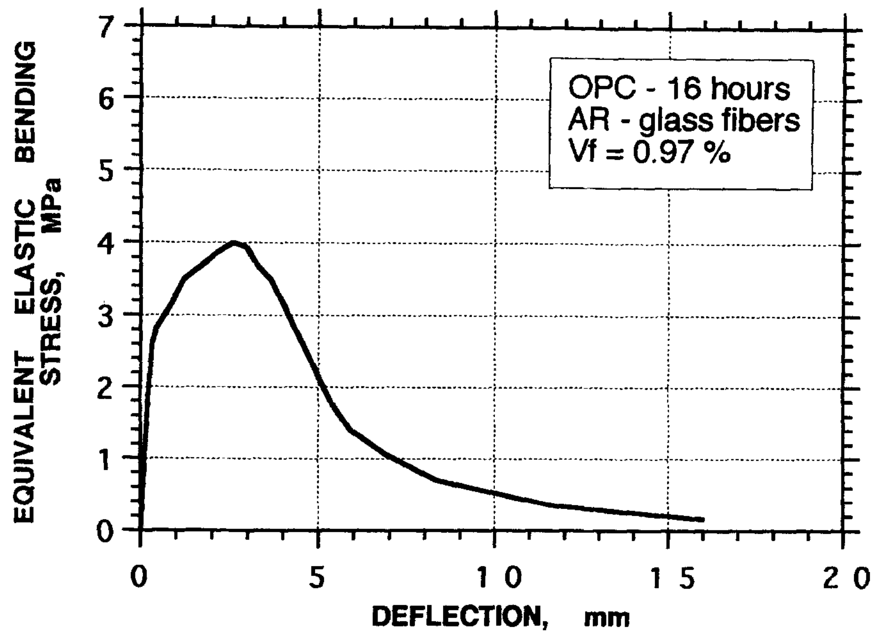

Fig. 6. Typical equivalent elastic bending stress versus deflection curve of OPC reinforced by A.R. glass fibers, after 16 h of age.

Table 3. Modulus of rupture of composites cured at 20°C (MPa)

Time of hydration	*Composite*					
	OPC	*MPC*				
	A.R. glass	*E-glass*	*Polyester*	*Polypropylene*	*Polyamide*	*Metallic*
3 h		6.0	3.4	3.5	3.7	6.2
16 h	4.0					
24 h		6.2	3.7	6.6	3.5	6.6
7 days	8.5					
28 days	9.0	6.5	8.5	8.6	5.0	8.5
90 days	9.1	6.0	8.5	8.7	5.4	9.7

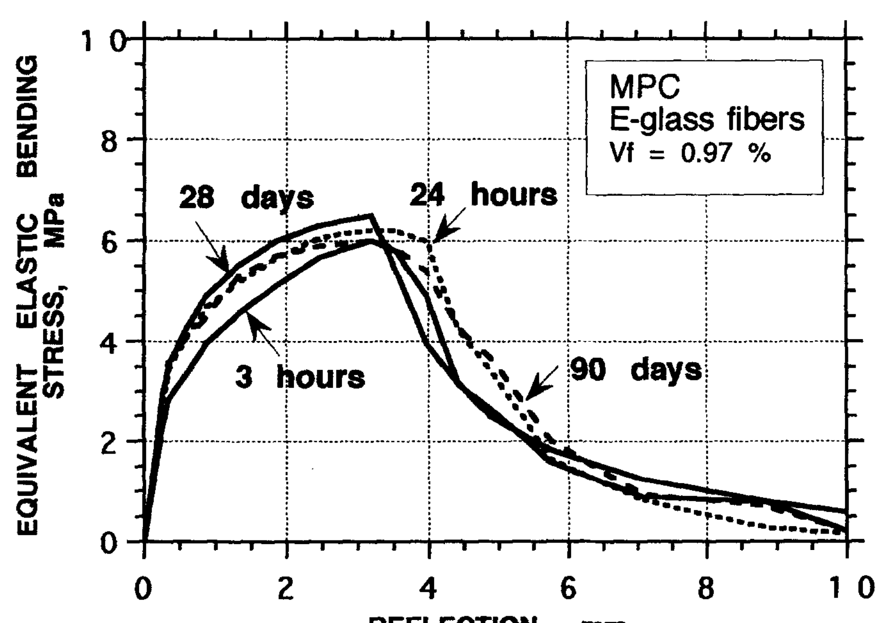

Fig. 7. Influence of aging on the flexural behavior of MPC reinforced by E-glass fibers.

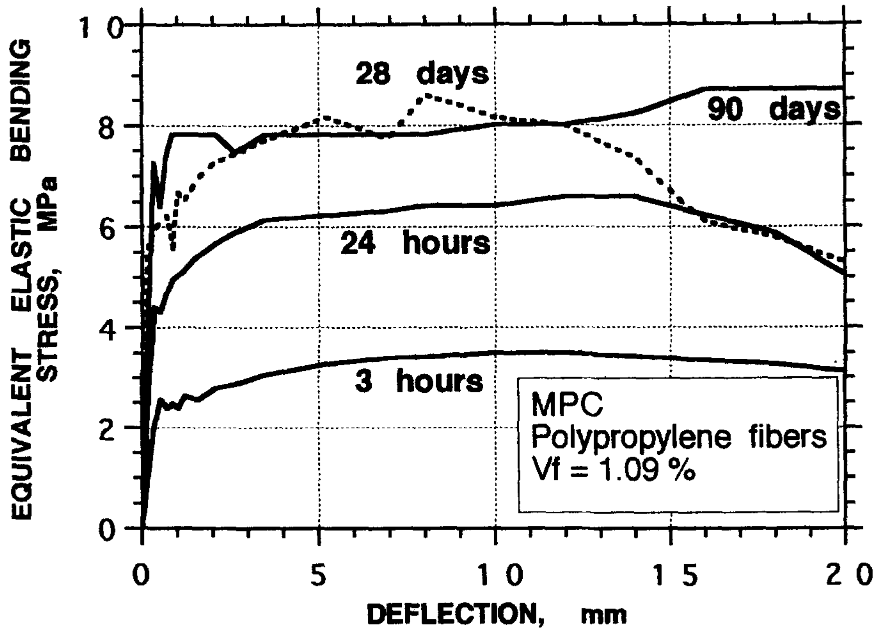

Fig. 8. Influence of aging on the flexural behavior of MPC reinforced by polypropylene fibers.

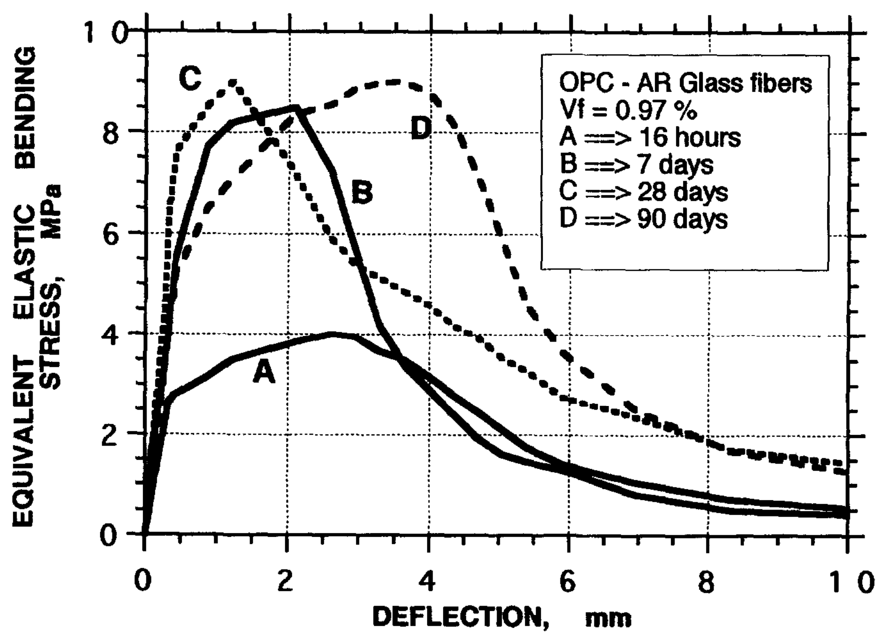

Fig. 9. Influence of aging on the flexural behavior of OPC reinforced by A.R. glass fibers.

Table 4. Toughness indices and residual strength factor after 28 days of hydration

Composite		I_{10}	I_{20}	$R_{10,20}$	*Behaviour*
OPC	A.R. glass	10	16	60	Brittle
	E-glass	13	27	140	Strain-hardening
MPC	Polyester	3	6	30	Brittle
	Polypropylene	8	18	100	Elastic–plastic
	Polyamide	4	8	40	Brittle
	Metallic	14	26	120	Strain-hardening

Table 5. Performances of composites immersed in hot water (60°C)

Composite		LOP (MPa)	MOR (MPa)	I_{10}	I_{20}	$R_{10,20}$	Behaviour
OPC	A.R. glass	6.2	6.8	5	6	10	Brittle
	E-glass	5.1	6.6	7	6	−10	Brittle
MPC	Polyester	8.1	8.1	5	9	40	Brittle
	Polypropylene	5.0	7.1	8	18	100	Elastic–plastic
	Polyamide	4.2	4.2	5	9	40	Brittle
	Metallic	7.0	14.5	14	34	200	Strain-hardening

more than 65% R.H. MPC specimens were demolded after 3 h of hydration, while OPC specimens remained in their molds for 16 h prior to removal. For the long-term behavior study, specimens were kept in air (laboratory environment) at 20°C and 65% R.H.

Testing procedures

Four-point-bending tests of the different composites were performed using an Adamel-Lhomargy DY25 machine. The span was 250 mm, leading to a span to depth ratio of 16.7 ($l = 250$ mm, $h = 15$ mm); the crosshead speed was 1 mm/min. The load versus mid-span deflection was continuously recorded and led directly to the LOP (Limit of Proportionality), the MOR (Modulus of Rupture) and several toughness indices. These indices were those described by the ASTM C 1018-85:[5] I_{10} and I_{20}. The residual strength factor $R_{10,20} = 10(I_{20} - I_{10})$ was also calculated. The specimen's ages at testing were 3 h, 24 h, 28 days and 90 days for MPC composites, and 16 h, 7 days and 28 days for OPC composites.

Two types of durability tests were also undertaken:

(a) samples previously cured in air at 20°C and 65% R.H. were immersed in hot water (60°C) for 28 days;

(b) samples previously cured at 20°C and 65% R.H. were subjected to 25 cycles of immersion in water at 20°C for 18 h then drying at 60°C for 6 h.

RESULTS AND DISCUSSION

Behavior of composites cured at 20°C

From the load–deflection curves recorded, equivalent elastic bending stress versus deflection curves were derived. Typical stress–deflection curves of MPC composites after 3 h of hydration are shown in Figs 1–5. Figure 6 gives a similar curve using OPC after 16 h of hydration. These are average values, each obtained from six samples.

Overall excellent results are observed. Differences in the curves are primarily due to the type of fibers when MPC is used (Figs 1–5). With glass or metallic fibers, higher resistances are obtained while with polypropylene fibers more ductility after cracking is observed. Also, in comparing Fig. 1 with Fig. 6, it is observed that MPC at 3 h is much superior to OPC at 16 h.

The average values of MOR for the different composites tested at different ages are given in Table 3.

The influence of aging on the flexural behavior of some composites is shown in Figs 7–9. For MPC reinforced by E-glass fibers (Fig. 7), the behavior is about the same after 3 h, 16 h, 28 days or 90 days of age, implying first that optimum performance can be achieved at 3 h

Table 6. Performances of composites after wetting–drying cycles

Composite		LOP (MPa)	MOR (MPa)	I_{10}	I_{20}	$R_{10,20}$	Behaviour
OPC	A.R. glass	5.6	6.7	5	6	10	Brittle
	Polyester	6.5	6.5	7	12	50	Brittle
MPC	Polypropylene	5.3	6.5	10	21	110	Elastic–plastic
	Polyamide	5.8	5.8	5	9	40	Brittle
	Metallic	7.0	12.0	13	28	150	Strain-hardening

and that glass fibers are chemically stable in MPC matrices.

The deflection at MOR (Fig. 7) is in the range of 3.5 to 4 mm which is a deflection to span ratio (*f/l*) of 1:70 to 1:60, while the ultimate deflection reaches 10 mm ($f/l = 1/25$).

For MPC reinforced by polypropylene fibers (Fig. 8), the composite is elastic–plastic after 3 h of hydration and the flexural strength increases with time. The elastic–plastic behavior is maintained with time and the deflection reaches 20 mm ($f/l = 1/12.5$) with little sign of deterioration.

For OPC reinforced by A.R. glass fibers (Fig. 9), the strength reaches its maximum value after 7 days of hydration, and this value is maintained with time. After 90 days of hydration, the deflection at MOR is close to 4 mm, about the same as that obtained for MPC reinforced by E-glass fibers. The ultimate deflection is also 10 mm.

From Figs. 7–9, it can also be concluded that:

(1) E-glass fibers are not chemically attacked in MPC matrices for up to 90 days of age;
(2) A.R. glass fibers maintain their performance in OPC matrices for up to 90 days;i
(3) polypropylene fibers behave very well in MPC matrices; some interactions between these fibers and the matrix such as improved adhesion and fibrillation under pull-out may occur and enhance the bending response with time.

Typical toughness indices and residual strength factor values are reported in Table 4 for the different series of tests undertaken. As per ASTM C1018, when the residual strength factor $R_{10,20}$ reaches 100 the composite can be considered elastic–perfectly plastic. When $R_{10,20} > 100$, the composite is considered strain-hardening, and when $R_{10,20} < 100$, the composite is considered rather brittle. Note that the control OPC composite presents some ductility till the deflection reaches 5.5 times the deflection at first crack load ($I_{10} = 10$). Over this value, some embrittlement appears and the residual strength factor is smaller than 100.

For MPC based composites, three types of behavior were observed and are classified according to the above definition:

- brittle, when either polyester or polyamide fibers were used;
- elastic–plastic with polypropylene fibers, in this case the recorded ultimate deflection was 20 mm, which means a deflection to span ratio of 1:12.5, a remarkable result;
- strain-hardening when E-glass or metallic fibers were used, however, embrittlement or softening of the composite started when the deflection exceeded about 4 mm, which corresponds to a deflection to span ratio of 1:62.5.

Behavior of composites after immersion in hot water at 60°C

The main characteristics of the various composites after immersion in hot water for 28 days are shown in Table 5.

From Tables 3–5, it is observed that:

- the OPC composites embrittle when immersed in hot water, their MOR value decreases and their toughness indices are about half those of the specimens cured in air at 20°C;
- the MPC composites maintain their mechanical performance, except when E-glass fibers are used, this is likely due to the poor behavior of E-glass in hot water, as reported by Dejean;[6]
- the MPC composites reinforced by polypropylene and metallic fibers not only retain their strength levels but also remain ductile after 28 days of immersion in hot water.

Behavior of composites subjected to wetting–drying cycles

As shown in Table 6, the results of composites tested after exposure to 25 wetting–drying cycles correlate well with those observed after 28 days of immersion in hot water, namely the OPC composite embrittles after wetting–drying cycles, while the MPC composites reinforced by either polypropylene or metallic fibers remain ductile.

CONCLUSIONS

Based on this limited investigation, the following conclusions can be drawn.

(1) Magnesia–phosphate cements (MPC) reinforced with fibers, tested at 3 h of

age, develop mechanical properties comparable to ordinary Portland cement (OPC) composites tested at 28 days.

(2) Of the different fiber composites tested in this study, polypropylene and metallic fiber (made from amorphous cast iron) reinforced composites showed stable behavior when exposed to cycles of wetting and drying or when immersed in hot water (60°C) for 28 days.

(3) The use of the proper type and amount of fibers with MPC matrices led to composites with elastic–plastic or strain-hardening behavior in bending. Such behavior was achieved in this study with 1.09% by volume of polypropylene fibers and 0.69% by volume of metallic fibers.

(4) Based on 1 to 3 above, it can be concluded that MPC composites are ideally suitable as fast repair materials, where not only fast setting and high early strength are essential requirements but also high strain capacity and environmental durability are needed to guarantee the long life of the repair.

(5) The limited investigation carried out in this study indicates that the behavior of MPC cements with fibers (E-glass, polypropylene and metallic) is better than that of OPC reinforced by A.R. glass, for lower or equivalent fiber volume fractions.

(6) Some fibers like polypropylene and amorphous cast iron (tested in this investigation) have excellent potential to improve the mechanical properties of rapid set materials such as MPC. They provide ductility and durability in severe environments and could be effectively used to improve the performance of the repairs

(7) While this study provided preliminary results on the feasibility of fiber reinforced MPC composites for repairs, a large number of variables are yet to be investigated and include: optimization of the matrix, determination of the best fiber volume fraction, study of the microstructure and interfaces under short- and long-term environmental exposure, and the cost of the final product.

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