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Properties and applications of magnesia–phosphate cement mortar for rapid repair of concrete

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Abstract

Magnesia–phosphate cement (MPB) was prepared by mixing MgO powder (M) with $NH_4H_2PO_4$ powder (P) and $Na_2B_4O_7{\cdot}10H_2O$ powder (B). In field applications, MPB mortar is usually used for rapid repair. Effects of many parameters, such as sand/MPB ratio, water/MPB (W/MPB) ratio, kind of sand, fly ash replacement of MPB, specimen volume, temperature and moisture on mechanical properties, and fluidity of MPB mortar were investigated in this paper. Some systematic information on the various field applications of MPB mortar was also discussed.

Keywords: Phosphate cement; Magnesia; Mortar; Repair of concrete; Strength

1. Introduction

The deterioration of many concrete structures, such as pavements, airport runways, bridge decks, wharves, etc., causes a serious problem, and it costs millions of dollars to renovate them. Some problems come from the fact that repair operation interrupts the use of structures for a long time when traditional materials are applied [1]. By using rapid-setting cementing materials, this delay can be greatly shortened. Among various rapid-hardening cements available for concrete repair, magnesia–phosphate cement-based binders (MPB) are of considerable interest [2].

MPB provides many essential requirements for such applications, namely quick setting, development of high early strength, high bond strength with old concrete, etc. [3,4]. There are a few papers discussing the durability of the material [5,6], which is a very important property for the successful application of the repair material.

In field applications, MPB is usually used as a mortar. Besides the parameters of MPB itself, there are many other parameters, such as types of sand, mineral admixtures, moisture of old concrete surface, temperature, etc., which have great influence on the successful repair.

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2. Experimental

2.1. Materials

Magnesia (MgO) powder with specific surface of 1560 and 3000 cm^2/g, calcined at >1500°C, from Taishan Refractory Plant of Shanghai, was used. Its specific gravity is about 3.48, and the content of MgO is higher than 95%. The specific area of MgO used for making MPB mortar is 1560 cm^2/g. Industrial grade mono-ammonium phosphate ($NH_4H_2PO_4$), borax ($Na_2B_4O_7{\cdot}10H_2O$), and potable water were used. A Class I fly ash, according to the Chinese standard JGJ 28-86, was used. The specific surface of the fly ash is about 750 m^2/kg, and its CaO content is about 2.72%.

MPB powder was prepared by mixing MgO and $NH_4H_2PO_4$, with and without borax and fly ash, and then MPB mortar was made by mixing water into MPB powder and sand. MPB proportion was P/M/B = 1:3:0.15 or 1:4:0.20, which has initial setting time of about 20 min at 20°C.

Five kinds of sand were used for MPB mortar, i.e., standard quartz sand with 98% SiO_2 and size of 0.1–1 mm, river sand, limestone with about 92% $CaCO_3$, slag with 39.6% CaO, and granite of 0.2–3-mm size. The kind of sand for making MPB mortar was standard quartz sand.

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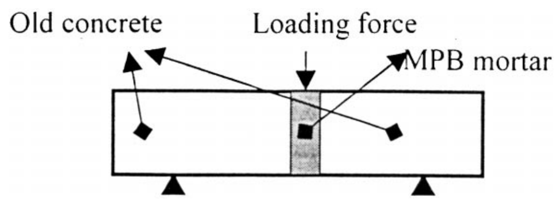

Fig. 1. The test method for measuring bond strength.

2.2. Interfacial bond strength test

Interfacial bond strength of MPB mortar with old concrete was indirectly measured with the flexural strength due to lack of the test condition (see Fig. 1). The old concrete, with size of $4 \times 4 \times 16$ cm, is a mixture of ordinary portland cement, water, quartz sand, and marble stone, with size of 5–10 mm in a proportion of 1:0.50:1.58:2.66 by weight, and has a 28-day compressive strength and flexural strength of 49.1 and 8.6 MPa, respectively. Concrete specimens were broken in the middle before test, then MPB mortar was placed into a gap of about 10 mm in thickness between two broken surfaces. The mould was vibrated about 1 min after casting, and the surplus mortar was squeezed and cleared out by hand.

All specimens above were demoulded within 1 h after casting and air-cured at 20 ± 5°C until testing. The bond strength is the value of measured flexural strength when the broken place is at the bond interface, or else is larger than the measured strength.

3. Results and discussion

3.1. Sand/MPB ratio

Because the bond strength with concrete and volume stability of MPB are high, it is very suitable to be used for rapidly repairing small volume or thin section damages, such as surface scaling, crack, and pothole on pavements or runways. MPB mortar is commonly used in these cases.

Results on effects of sand/MPB ratio and P/M ratio on the compressive strength of MPB mortar are shown in Table 1 and Fig. 2. From Table 1 and Fig. 2, it can be seen that the compressive strength of MPB mortar decreases with the increase in sand/MPB ratio regardless of the curing age. However, the rate of strength reduction is different for MPB mortars with different P/M ratios.

Fig. 2 shows that P/M ratio has no obvious influence on the relationship between 1-h compressive strength and sand/MPB ratio, but has great influence on the relationship between 28-day compressive strength and sand/MPB ratio. The 28-day compressive strength is quickly reduced only when the sand/MPB ratio is over 1.5:1 for MPB, with P/M ratio of 1:2, i.e., 1.5:1 is the optimized sand/MPB ratio for the MPB. For MPB with P/M ratio of 1:3, the sand/MPB ratio is 1:1. However, the 28-day compressive strength obviously decreases with the increase of sand/MPB ratio in a linear fashion for MPB with P/M of 1:4. Moreover, Fig. 2 also indicates that this sand/MPB ratio is changed from 1:1 to 1.5:1, when the specific area of MgO in MPB with P/M ratio of 1:3 is enhanced from 1560 to 3000 cm^2/g.

For MPB paste, the optimal P/M ratio is about 1:4–1:5, i.e., the amount of hydrates is optimal matching with the amount of unhydrated MgO [7]. It is predictable that this optimal matching is lost when the quartz sand is added into MPB paste, which may occur since the hydrates cannot surround unhydrated grains of MgO and quartz sand thoroughly. The strength of MPB mortar is significantly reduced with the sand/MPB ratio, in case the hydrates cannot surround unhydrated grains of MgO and quartz sand thoroughly. Of course, the higher the P/M ratio in MPB, the more the amount of hydrates, therefore, more sand can be surrounded by the hydrates. Consequently, the higher sand/MPB ratio can be used for MPB mortar with lower P/M ratio or larger specific area of MgO.

Table 1
Effect of sand/MPB ratios on compressive strength of MPB mortar (cubic specimens with 2 cm)

		Compressive strength (MPa)					
P/M ratios	Mix proportions MPB/S/W[a]	1 h	3 h	1 day	3 days	7 days	28 days
1:2	1:0.5:0.125	17.8	40.4	62.6	70.3	72.2	73.8
	1:1.0:0.173	9.2	34.6	54.5	61.4	68.9	70.7
	1:1.5:0.222	7.0	31.5	46.1	54.2	62.4	66.1
	1:2.0:0.270	4.9	25.5	31.8	37.7	42.4	48.8
1:3	1:0.5:0.125	21.2	49.5	68.5	73.1	75.1	76.9
	1:1.0:0.173	9.5	35.0	54.1	62.3	69.6	72.4
	1:1.5:0.222	6.8	25.0	32.1	37.4	42.5	52.6
	1:2.0:0.270	4.5	12.4	14.5	15.2	27.1	30.8
	1:3.0:0.366	2.0	5.5	6.5	9.5	11.7	15.5
1:4	1:0.5:0.125	15.5	31.4	49.5	63.4	70.5	72.8
	1:1.0:0.173	9.0	23.4	40.5	44.2	46.5	49.5
	1:1.5:0.222	7.2	19.5	27.5	29.6	30.7	35.5
	1:2.0:0.270	4.2	9.5	12.4	14.6	18.3	21.7

[a] S, sand; W, water.

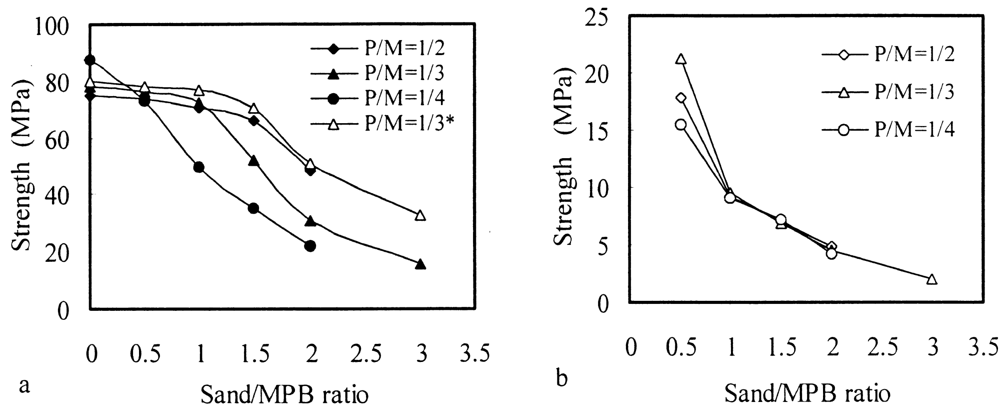

Fig. 2. Effects of sand/MPB ratio and P/M ratio on the compressive strength of MPB mortar, (a) 28-day strength. * MgO with the specific area of 3000 cm^2/g. (b) One-hour strength.

3.2. Size of specimen and temperature

The hydration of MPB is an exothermic reaction, so the larger the size of specimen, the higher the hydrated heat and temperature in the specimen, therefore, the quicker the development of strength of MPB mortar. Table 2 clearly shows that the development of strength of specimen with the size of 4 × 4 × 16 cm is much quicker than that of the cubic specimen of 2 cm, and the strength of the former is also greater than that of the latter, especially at early ages. In fact, the maximum temperature of the former was above 70°C, between 0.5 and 1 h after casting at 20 ± 5°C, but that of the latter was only about 42°C. Of course, the increase of hydrated heat accelerates the formation of hydrates and may affect the composition and morphology of the hydrates [4,8]. Consequently, it is reasonable to infer that the service of repaired structure can be more quickly restored when the volume of MPB mortar used is greater. However, it is necessary to be very careful for the application of MPB mortar due to its high heat of hydration when the repaired volume is large. The size of specimens used in the following tests is 4 × 4 × 16 cm if there is no special explanation.

From Table 2, it can also be seen that the strength of MPB mortar increases with the increase in the curing temperature, especially at early ages. MPB mortar can also quickly attain strength even at 0 ± 5°C, therefore, MPB is very suitable to use for repairing under cold climate. However, the strength of cubic specimen of 2 cm, evenly cured at 40 ± 5°C, is still much lower than that of specimen with the size of 4 × 4 × 16 cm before 3 h, but the strength of both is almost the same after 1 day.

Table 2
Effects of specimen size and curing temperature on the compressive strength of MPB mortar

Specimen size and curing temperature[a]	Compressive strength (MPa)					
	1 h	3 h	1 day	3 days	7 days	28 days
4 × 4 × 16 cm, 20 ± 5°C	58.7	60.9	63.2	69.3	77.1	79.6
2 × 2 × 2 cm, 0 ± 5°C	1.6	3.1	25.5	56.0	68.2	70.3
2 × 2 × 2 cm, 20 ± 5°C	9.5	35.0	54.1	62.3	69.6	72.4
2 × 2 × 2 cm, 40 ± 5°C	24.1	45.9	67.5	71.4	77.5	78.2

[a] Sand/MPB ratio = 1:1; W/MPB = 0.173.

3.3. Water/MPB (W/MPB) ratio

Just as in portland cement, the W/MPB ratio is also an important parameter for controlling properties of MPB mortar. Results on effects of the W/MPB ratio on properties of MPB mortar are shown in Table 3 and Fig. 3. They show that the strength of MPB mortar is reduced with the increase in the W/MPB ratio, but their strength values are still very high. For example, the 1-h compressive and flexural strength of MPB mortar with W/MPB ratio of 0.13 are 68.2 and 11.0 MPa, respectively, and those of MPB mortar with W/MPB ratio of 0.21 are 38.5 and 6.7 MPa, respectively. Table 3 also shows that the fluidity of MPB mortar significantly increases with the W/MPB ratio. Consequently, it is easy to meet engineering demands on strength and workability, and to restore the service of concrete structures within 1 h after repair with MPB by adjusting the W/MPB ratio.

3.4. Fly ash

Fly ash replacement of MPB is initially used to reduce the cost of the repair and to adjust the color of MPB to coincide with that of old concrete. However, it is found that the Class I fly ash has good water-reducing effect on MPB mortar after fly ash replacement of MPB. Results on effects of fly ash replacement of MPB on properties of MPB mortar are shown in Table 4 and Fig. 4. They indicate that at the same W/(MPB + F) ratio, the fluidity is enhanced with the increase in the fly ash replacement of MPB, but the strength is reduced. However, at the similar fluidity, the strength of MPB mortar is not reduced but somewhat increases after fly ash replacement of MPB. It is also found that MPB mortar with fly ash has larger cohesion than without fly ash at the similar fluidity. These

Table 3
Effects of W/MPB ratio on the strength of MPB mortar (sand/MPB ratio = 1:1)

W/MPB	Fluidity[a] (mm)	Compressive strength/flexural strength[b] (MPa)					
		1 h	3 h	1 day	3 days	7 days	28 days
0.13	110	74.2/11.0	78.3/>12	91.1/>12	92.3/>12	99.0/>12	102/>12
0.15	128	66.8/9.3	71.0/11.8	80.4/>12	83.2/>12	85.1/>12	89.3/>12
0.17	154	58.7/7.8	60.9/8.4	63.2/8.2	69.2/10.2	77.6/10.8	79.6/11.2
0.19	190	44.2/6.3	50.0/7.4	59.4/7.6	65.3/8.6	70.5/9.0	71.6/9.4
0.21	225	38.5/6.7	47.0/6.0	47.6/6.7	49.5/6.9	52.8/7.6	60.2/8.2

[a] According to the Chinese standard GB 2419-81.
[b] The symbol ">" means the flexural strength values are over the maximum value of the measuring meter (12 MPa).

results of fly ash replacement of MPB are mainly due to the dense and rolling effects of the finer grains of fly ash. These effects of fly ash, of course, are not so obvious if the specific area of MgO in MPB is larger.

In order to enhance the fluidity of MPB mortar, there are two convenient technical means, i.e., adding water and fly ash. From Fig. 5, it can be clearly seen that for the same fluidity, the reduction of strength by adding water is larger than by adding fly ash. Therefore, this type of fly ash is an important component to optimize properties of MPB mortar.

3.5. Kinds of sand

In order to utilize natural resources adequately and to select sand conveniently, it is necessary to investigate the effect of the kind of sand on the strength of MPB mortar. These results are shown in Table 5. It can be seen that the kind of sand has a big influence on the strength. The order in the strength value of MPB mortar with various kinds of sand is quartz sand > granite > river sand > slag > limestone. It shows that river sand and granite are good kinds of sand for making MPB mortar or concrete, but the sand containing minerals with high content of CaO, such as $CaCO_3$, are not suitable to be used with MPB together, for example, limestone. The main reason may be that the key component in MPB, monoammonium phosphate, can more easily react with $CaCO_3$, or Ca^{2+} in the minerals than with dead burnt MgO in MPB. Thus, calcium phosphate hydrates can be easily formed, therefore, the hydrates of MPB itself, magnesium-ammonium phosphates, are reduced. From some research results [9], it can be inferred that the strength of calcium phosphate hydrates may be lower than that of magnesium-ammonium phosphates.

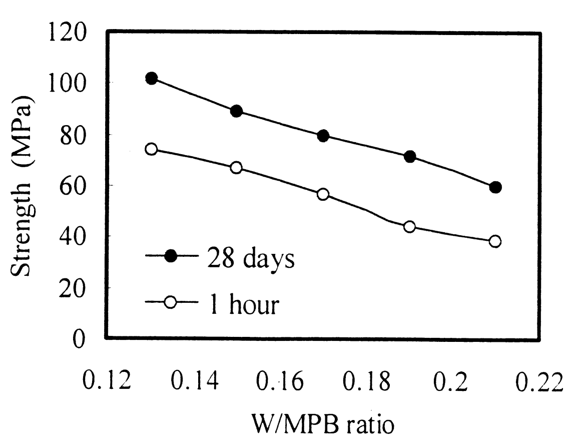

Fig. 3. Effects of water/MPB ratio on the compressive strength of MPB mortar.

3.6. Moisture in surface of concrete

Generally, the moisture of old concrete and curing conditions have a significant influence on the repairing quality, especially on the interfacial bond between repair material and old concrete. For common cements as repair materials, such as portland cement, aluminate cement, ferroaluminate cement, slag-alkaline cement, etc., the wet surface and wet curing are very important for successful repairing.

Table 6 gives results on effects of moisture conditions on the bond strength of MPB mortar with old concrete. The test method of the bond strength is seen in Fig. 1. Table 6 displays that the bond strength between MPB mortar and wet surface of old concrete is lower than that between MPB mortar and half-dry or dry surface of old concrete, but the effect of the moisture of surface on the bond strength at early ages is more obvious. After repair, the wet curing has no good influence on the bond strength. In actual engineering, the moisture of concrete is similar to that of the half-dry surface, therefore, for the MPB material, it is not necessary to splash water on the cleaned surface of old concrete before repairing and to cure in high moisture condition after repairing. The reason is that the amount of hydrates and the W/MPB ratio are very low, therefore, the shrinkage by moisture change is very low, and there is very low possibility to cause cracking at the repaired interface. This property makes MPB materials have very strong adaptability in fields.

4. Field applications

According to the above results and engineering demands in fields, MPB with P/M ratio of 1:3 and 0–30% fly ash was experimentally applied for repairing potholes, cracks, surface scaling, and edge spalling near

Table 4
Effects of fly ash replacement of MPB on properties of MPB mortar

Mix proportions (MPB + F)/S/W	Fluidity (mm)	Compressive strength/flexural strength (MPa)					
		1 h	3 h	1 day	3 days	7 days	28 days
(1 + 0):1:0.17	154	58.7/7.8	60.9/8.4	63.2/8.2	69.2/10.2	77.6/10.8	79.6/11.2
(0.95 + 0.05):1:0.17	173	54/6.8	58/7.0	60/8.1	63/8.4	69/9.4	77/9.6
(0.90 + 0.10):1:0.17	194	51/6.3	52/6.8	57/7.2	59/8.3	61/8.2	74/8.5
(0.85 + 0.15):1:0.17	213	47/6.0	48/6.5	50/7.0	52/7.6	56/8.0	69/8.3
(0.80 + 0.20):1:0.17	236	44/4.6	43/5.2	46/5.6	49/6.1	54/7.3	65/8.2
(0.90 + 0.10):1:0.15	153	54/7.9	61/8.0	67/9.2	64/9.1	66/9.9	77/10.5
(0.80 + 0.20):1:0.13	164	61/7.8	64/8.2	66/8.6	70/9.8	79/10.2	81/11.4
(0.70 + 0.30):1:0.11	158	52/6.6	60/8.0	68/8.5	73/10.1	77/10.6	83/11.9

cutting joints on highways and municipal roads, for surface scaling of reinforcing concrete at the splashing zone in a wharf, and so on.

4.1. Pavement

In 1996 and 1997, MPB mortars with sand/MPB ratio of 1:1 were experimentally used for repairing 11 potholes, five surface cracks with length of 2–5 m and width of 12–30 mm, 6 m^2 surface scaling, and edge spalling at six cutting joints on highways and key municipal roads in Xiamen, Fujian Province. These pavements are main municipal traffic roads, thus, the municipality requires that the traffic be restored as quickly as possible.

MPB with operable time of about 25 min was used. In order to control the operable time, the amount of retarder borax was adjusted between 5% and 15% according to the air temperature, about 15–45°C. The color of MPB mortar is similar to that of old concrete on the pavements when the amount of fly ash was about 15%. The W/(MPB + F) ratio of MPB mortar was 0.16 for satisfactory workability. Furthermore, crushed sandstone of 5–10-mm size was randomly embedded into MPB mortar when the thickness of the patching layer was larger than about 40 mm.

Two important requirements have to be considered before casting MPB mortar:

(a) To ensure as far as practicable that all defective concrete and chipping are removed, and a sound and clean surface is obtained.
(b) To ensure the best possible bond between the old concrete and MPB mortar, treatment of damages on the pavements were performed, according to Fig. 6, except for potholes. Then, the traffic on the pavements was restored within 3 h after casting and finishing.

Field observations on the repaired works during 3 years have shown 100%, 75.4%, 67.5%, and 49.3% respectively successful rehabilitation of potholes, surface scaling, surface cracks, and edge spalling at cutting joints. Furthermore, the possibility to keep the repaired works sound according to Fig. 6(b) is much greater than that according to Fig. 6(a), and the better the quality of old concrete, the greater the possibility. Most of unsuccessful repaired works are due to the thickness of MPB mortar which is lower than about 2 cm, especially for the edge spalling at cutting joints, and that those old concrete surfaces are not cleaned thoroughly or they have high moisture.

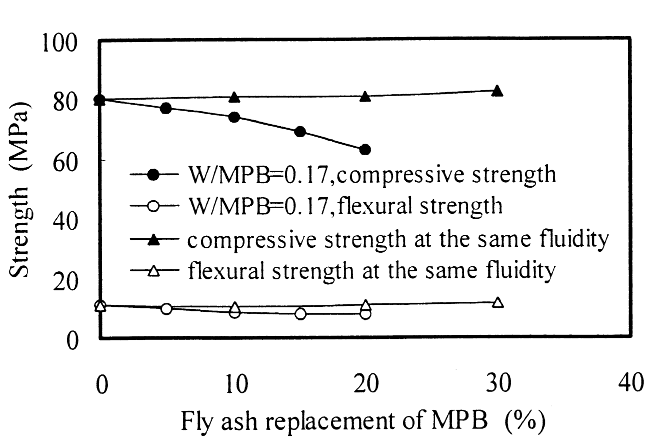

Fig. 4. Effects of fly ash replacement of MPB on the strength of MPB mortar.

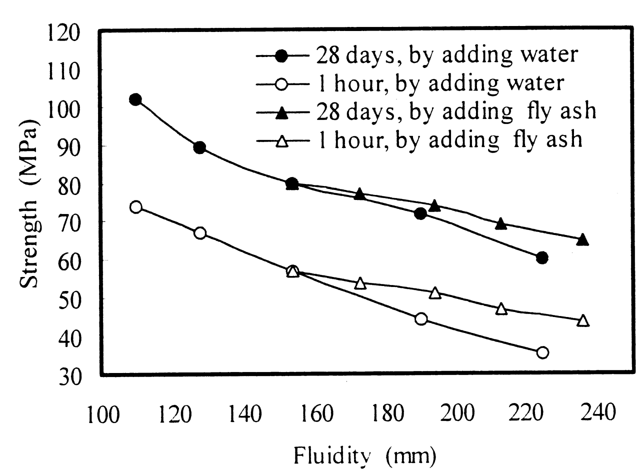

Fig. 5. Relationship between the compressive strength and the fluidity of MPB mortar due to adding water or fly ash.

Table 5
Effects of various kinds of sand on the strength of MPB mortar (W/MPB = 0.17, sand/MPB ratio = 1:1)

	Compressive strength/flexural strength (MPa)					
Sand	1 h	3 h	1 day	3 days	7 days	28 days
Quartz sand	58.7/7.8	60.9/8.4	63.2/8.2	69.2/10.2	77.6/10.8	79.6/11.2
River sand	48.4/6.4	50.8/7.9	52.8/8.1	58.4/8.5	63.3/8.9	66.4/9.1
Granite	50.8/7.1	55.2/8.60	65.6/9.3	67.0/10.1	68.8/10.4	70.6/11.0
Limestone	28.8/4.7	35.2/7.4	45.6/8.0	48.8/8.1	51.0/8.3	54.6/8.6
Slag	33.2/5.4	38.4/7.2	48.0/7.7	52.5/7.6	55.8/7.6	60.2/8.2

Table 6
Effects of moisture conditions on the bond strength of MPB mortar (W/MPB = 0.17, sand/MPB ratio = 1:1) with old concrete

Surface moisture	Bond strength (MPa)				
and curing conditions[a]	3 h	1 day	3 days	7 days	28 days
Wet surface + cured under a wet cotton cloth	1.42	3.50	4.67	5.42	7.00
Wet surface + cured in air	1.95	4.35	5.47	6.32	7.80
Half-dry surface + cured in air	2.29	5.14	7.14	7.86	8.55
Dry surface + cured in air	3.60	5.15	5.97	6.58	7.85

[a] Wet surface, the broken surfaces of old concrete specimens directly from water; half-dry surface, the broken surfaces of old concrete cured in air for 7 days after water is taken out; dry surface, the broken surfaces of old concrete dried at 105°C for 1 day after water is taken out.

Consequently, it is best if the thickness of MPB repair mortar is at least 3 cm for surface scaling and cracks and 5 cm for the edge spalling at cutting joints.

4.2. Wharf

In 1997, MPB was experimentally used for repairing tide-zone etched surfaces of concrete frames at Nenjiang Wharf, located at Huangpu River in Shanghai. This wharf had been in service for over 50 years. The water in Huangpu River is contaminated by various types of liquid and solid. These etched surfaces are coated with some oil and lichen, and are exposed to air twice a day due to tidal action, every 2 h. Most of them are vertical surfaces, and their etched depth is about 3–10 mm. Consequently, it is necessary for the repair material to have rapid setting, quick strength development and good viscosity.

MPB with the operable time of about 20 min was used, in which the amount of fly ash was 30%. MPB mortar with fine sand of 0.1–1 mm was applied for repairing the etched surfaces. The sand/MPB ratio was 1:1 and 2:1. Because the deterioration was confined to the surface of concrete, the following measures were adopted for the best possible bond:

(a) The surface of the concrete was prepared by wire brushing, and then cleaned by water jetting.
(b) The water on the prepared surface was removed with a cotton cloth, and then MPB mortar was quickly coated on the surface and was finished with a wood spatula.

The MPB mortar can obtain enough high strength to undergo the scour attack by the river water within 1 h after finishing. Until November 1999, all repaired surfaces were still in a sound condition.

5. Conclusions

In field applications, MPB is always used as a mortar. The optimized sand/MPB ratio in MPB mortar increases with the increase in P/M ratio or the specific area of MgO in MPB, i.e., the amount of sand in MPB mortar can be optimized.

The curing temperature has a significantly influence on the strength development of MPB mortar. The higher the temperature, the greater the strength of MPB mortar, especially the strength at early age before 1 day. The hydration heat of MPB is very high, so the strength development of MPB mortar increases quickly when its volume is large.

As in portland cement, the W/MPB ratio is an important parameter for controlling the properties of MPB mortar. The higher the strength of MPB mortar, the lower the W/MPB ratio. However, the fluidity of MPB mortar increases rapidly with the W/MPB ratio.

Fly ash replacement of MPB can adjust the color of MPB mortar to coincide with that of old concrete and reduce its cost substantially. Class I fly ash is an important component to optimize properties of MPB mortar. The strength of MPB mortar is not reduced and its cohesion is enhanced after fly ash replacement. For the same W/(MPB + F), the strength of MPB mortar decreases, but its fluidity increases quickly.

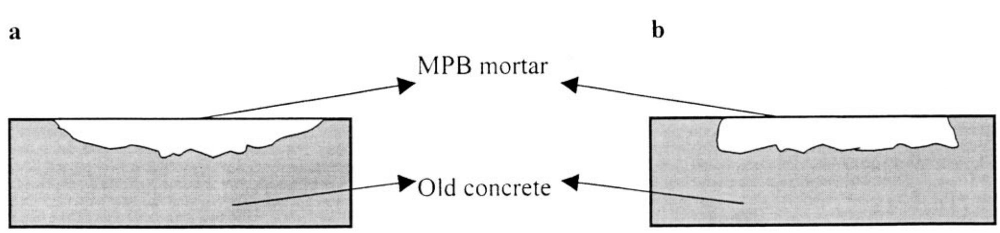

Fig. 6. Cross-section sketch of treatments on the damages of pavements. (a) Keeping the original deteriorated outline. (b) Changing the original outline.

Adding water or fly ash can increase the fluidity of MPB mortar. However, the reduction of strength due to adding water is more than that by replacing with fly ash.

The order of the strength of MPB mortar with various kinds of sand is quartz sand > granite > river sand > slag > limestone, i.e., the sand containing minerals with high CaO, such as $CaCO_3$, is not suitable for MPB mortar.

The effect of moisture of old concrete on the early bond strength between MPB mortar and old concrete is larger than on the bond strength after 7 days. It is not necessary to splash water on the cleaned surface of old concrete before repair and to cure in high moisture condition after repair when MPB mortar is used as repair material.

Results of field applications show that MPB mortar is a good material for rapid repair of concrete, and can be conveniently used. The durability of the repaired material is satisfactory enough after some simple measures are taken.

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