Pergamon

Cement and Concrete Research 32 (2002) 165–168

CEMENT AND CONCRETE RESEARCH

Deicer-scaling resistance of phosphate cement-based binder for rapid repair of concrete

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Received 17 April 2000; accepted 6 August 2001

Abstract

In this paper, a magnesium phosphate cement-based binder (MPB) was prepared by mixing MgO with mono-ammonium phosphate, borax and fly ash. The deicer-scaling resistance of MPB mortar and concrete and the bond strength loss between MPB paste and mortar with ordinary Portland cement (OPC) concrete were investigated. Experimental results show that MPB materials themselves have high deicer–frost resistance, which is not lower than that of OPC concrete with the air content of 4.5–6.5%. The bond strength loss between MPB materials and OPC concrete with the air-entraining agent is obviously lower than that between MPB and OPC concrete without the air-entraining agent, and the higher the air content in OPC concrete is, the smaller the loss is. Furthermore, the air-bubble parameters were analyzed, which indicate that MPB mortar and concrete can also obtain a reasonable air-bubble structure by chemical reactions.

Keywords: Phosphate cement; Deicer scaling; Bong strength; Air-bubble parameter; Repair

1. Introduction

Rapidly setting cementing materials are usually applied for repairing the surface damage of many concrete structures such as pavements, airport runways, bridge decks, etc., in order to quickly restore the service of these structures. Phosphate cement-based binders (MPBs) are such special repair materials.

The scaled deterioration of these concrete structures always occurs on their surfaces in the cold climate and is aggravated by deicer chemicals at the same time [1,2]. This kind of damage is difficult to be rehabilitated with traditional materials. It is very important to repair the damage in order to prevent even greater deterioration. A repair material has to possess high frost/deicer–frost resistance, besides good bond and compatibility with the old concrete.

Many research efforts have been carried out on phosphate cement-based materials for rapid repair of concrete. Popovics et al. [3], Abdelrazig et al. [4], Sarkar [5] and Yang and Wu [6] mainly studied chemical compositions and mechanical properties of the materials. The results obtained by Yoshizaki et al. [7] and Emmons et al. [8] showed that MPBs had good bond and compatibility with old concrete, and high volume stability (low shrinkage). There are only a few papers addressing the durability of this material [7,9], which is a very important property for the successful repair.

2. Experimental

2.1. Raw materials and mix proportions

MgO powder with specific surface of 250 m^2/kg, calcined at > 1500 °C, was bought from Taishan Refractory Plant of Shanghai. Its specific gravity is about 3.48, and the content of MgO is higher than 95%. Industrial grade mono-ammonium phosphate ($NH_4H_2PO_4$) and borax ($Na_2B_4O_7 \cdot 10H_2O$), NaCl and potable water were used. A low-calcium Class I fly ash according to the Chinese standard JGJ 28-86 with a specific surface area of about 750 m^2/kg was used.

MPB powder was prepared by mixing the MgO (M) and $NH_4H_2PO_4$ (P) powder with borax (B). In this form, it could be conveniently applied like ordinary Portland cement

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PII: S0008-8846(01)00651-2

Table 1
Mix proportions of MPB materials and OPC concretes

Types of material		Water/MPB/ Sand/Aggregate/SJ-2	Slump (mm)	Air content (%)	Mixing time (min)
MPB	Paste	0.10:1:0:0:0	/	/	3.5
	Mortar	0.14:1:1:0:0	/	9.1	3.5
	Concrete	0.16:1:0.63:1.47:0	175	6.9	3.5
OPC	Concrete-1	0.55:1:1.71:3.01:0	155	1.2	3.5
	Concrete-2	0.55:1:1.61:2.88:0.0002	180	4.8	3.5
	Concrete-3	0.55:1:1.55:2.79:0.0003	195	6.5	3.5

(OPC). The MPB proportion is P/M/B = 1:3:0.15. In order to enhance the workability of MPB materials and to reduce the color difference between MPB material and OPC concrete, 15 wt.% of MPB was replaced with fly ash. The density of the MPB powder is about 3.21.

OPC, standard quartz sand and 5–10 mm limestone were used for making mortar and concrete. Their bulk densities are 3.1, 2.62 and 2.7, respectively. A new SJ-2 saponin-based air-entraining agent [10] was used for air-entrained OPC concrete.

The mix proportions are shown in Table 1. The air content and the void spacing factor in the hardened materials were measured. The flowability of the fresh MPB materials significantly increased with the mixing time. The minimum mixing time was always 3–4 min.

Specimens with $4 \times 4 \times 16$ cm dimensions were used. Two types of samples were prepared.

(1) MPB and OPC monolithic samples for the deicer–frost scaling — MPB mortar and concrete were demolded within 1 h after casting, and then stored in air with about 65–75RH%. The OPC concretes were demolded within 1 day, and then stored in water at 20 ± 5 °C.

(2) OPC concrete–MPB paste/mortar composite samples for the bond strength — the OPC concrete specimens at 28 days were taken out of water and stored in air with about 65–75RH% for 3 days, and then broken in the middle. The MPB paste/mortar was used to rejoin the broken pieces by filling a gap of about 10–20mm thickness between the two broken surfaces. The mold was vibrated about 1 min after casting. All composite specimens were demolded within 1 h and then cured in air at 20 ± 5 °C.

Other test conditions are given in the section of test methods.

2.2. Deicer–frost test

The sketches of the deicer-scaling test are seen in Fig. 1. The single surface immersion method in Fig. 1(a) is for evaluating the scaling resistance of the MPB material itself. MPB mortar/concrete or OPC concrete specimens are used in Fig. 1(a). The whole soaking method in Fig. 1(b) is for investigating the effect of the combined action of frost and deicer on the bond between MPB and OPC concrete. The regime of freeze–thaw cycling was achieved with the cooling rate of about 0.5 °C/min for 4 h at -20 ± 2 °C and then thawed for 4 h at 20 ± 5 °C [11]. A 3% NaCl solution was used as the deicer solution.

Specimens were treated according to the following conditions before the deicer–frost test:

1. OPC concrete specimens — soaked in water for 14 days + stored in air with about 65–75RH% for 11 days + soaked in water for 3 days.
2. MPB or repaired specimens — stored in the air with about 65–75RH% for 7 days + soaked in water for 3 days.

2.3. Interfacial bond strength

The interfacial bond strength of MPB paste/mortar and old concrete was indirectly measured and was expressed as the flexural strength of the composite sample. OPC concretes in Table 1 were used as old concretes.

The interfacial bond strength is the value of the measured flexural strength when the broken site is at the bond interface, or else is larger than the measured flexural strength when the broken site is not at the bond interface [12].

3. Results and discussion

3.1. Deicer scaling

The deterioration of roads/pavements, airport runways, bridge decks is mainly caused by frost action in northern China. It is severely amplified by the use of deicer chemicals. Repairing the scaled concrete requires that the repair material possess high frost/deicer–frost resistance.

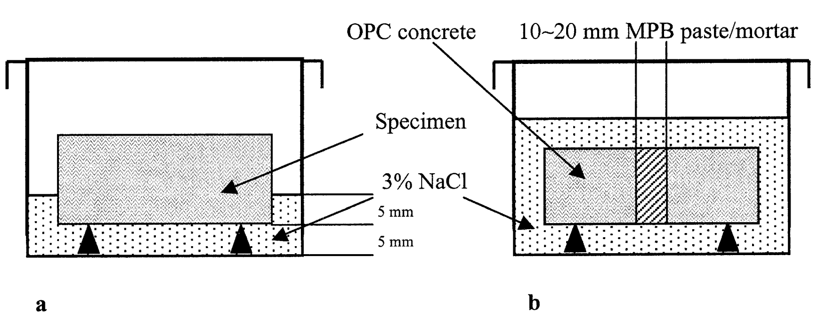

Fig. 1. The sketch of the deicer–frost test. (a) Single surface immersion method. (b) Whole soaking method.

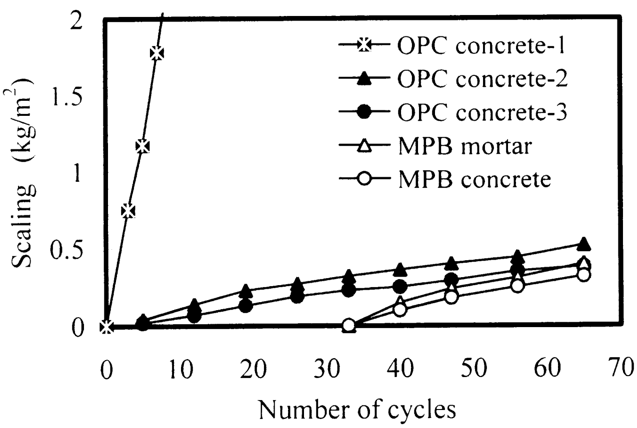

Fig. 2. Deicer-scaling resistance of various materials.

The scaling results for various materials are displayed in Fig. 2. It shows that MPB materials, regardless of mortar or concrete, have very high deicer–frost resistance. The scaling does not occur on the surfaces of MPB materials until 40 freeze–thaw cycles. After 56 cycles, the amount of surface scaling for MPB mortar, MPB concrete, OPC concrete-3, OPC concrete-2 and OPC concrete-1 is about 0.25, 0.31, 0.35, 0.44 and 9.8 kg/m^2, respectively. These results clearly show that the deicer–frost resistance of MPB mortar or concrete is equal to or better than that of OPC concrete with the air content of 4.5–6.5%.

3.2. Bond strength loss

As a repair material used, the deicer–frost resistance of the repaired specimen may be more important. The loss of interfacial bond strength between MPB and OPC concrete is used as a criterion for evaluating this resistance; the test method is shown in Fig. 1(b). Results on the bond strength are summarized in Table 2. For the repaired specimen exposed to frost in the presence of deicer, the interfacial bond strength loss between MPB and OPC concrete with the air-entraining agent is obviously lower than that between MPB and OPC concrete without the air-entraining agent. The higher the air content is, the smaller the loss is. Table 2 also indicates that the loss for MPB paste is much lower than that for MPB mortar, which is mainly due to its higher bond strength and deicer–frost resistance.

Certainly, the bond strength loss due to the combined action of frost and deicer chemical is not so big if the bond strength retrogression stored in 3% NaCl solution for the same time as 60 cycles is considered. These results are shown in Table 3.

It is necessary to notice that the loss is very big when MPB mortar is used to repair OPC concrete without the air-entraining agent. Therefore, for the repair of OPC concrete without the air-entraining agent, it is better to use MPB paste or to first treat the surface of the concrete with MPB paste. Both MPB paste and mortar can be used for repair of OPC concrete with the air-entraining agent.

Table 2
Effect of frost and deicer on the interfacial bond strength of MPB with old concrete

	Bond strength (MPa)					
	MPB paste as the repair material			MPB mortar as the repair material		
Old concrete	Before test	60 cycles	Loss (%)	Before test	60 cycles	Loss (%)
OPC concrete-1	7.5	5.1	33.3	6.8	2.1	69.1
OPC concrete-2	7.0	5.8	17.9	6.3	4.9	22.2
OPC concrete-3	6.9	> 6.0	< 9.7	6.1	5.2	14.7

Table 3
The bond strength loss of between MPB materials and old concrete after considering the bond strength retrogression stored in 3% NaCl

	Bond strength (MPa)					
	MPB paste as the repair material			MPB mortar as the repair material		
Old concrete	Stored in 3% NaCl	60 cycles	Loss (%)	Stored in 3% NaCl	60 cycles	Loss (%)
OPC concrete-1	7.0	5.1	27.1	6.1	2.1	65.6
OPC concrete-2	6.5	5.8	10.8	5.8	4.9	15.5
OPC concrete-3	6.3	>6.0	< 4.8	5.7	5.2	8.8

3.3. Result analysis

Why do MPB materials without the air-entraining agent also possess high deicer–frost resistance? In fact, many micro-air bubbles were generated during the casting and could be seen in hardened MPB materials. This is due to the formation of much NH_3 and H_2 during the reaction of $NH_4H_2PO_3$ with MgO and adulterated iron powder during grinding. The air-bubble systems in hardened MPB mortar and concrete are measured according to ASTM C 457. The results are presented in Table 4. It is necessary to point out that the exact paste volume in MPB materials is difficult to be calculated because most of MgO is not hydrated [6] and unhydrated MgO cannot be precisely estimated. It is assumed that 50% MPB volume was attributed to the paste volume for calculation of the air void spacing factor.

Table 4
Air-bubble parameters of different materials

Types of material		Hardened air content A (%)	P/A ratio*	Specific area α (mm^2)	Spacing factor L (μm)
MPB	Mortar	9.8	3.623	18.6	195
	Concrete	7.4	3.235	19.7	164
OPC	Concrete-1	1.5	21.95	12.6	709
	Concrete-2	4.5	34.04	35.4	158
	Concrete-3	6.1	34.80	33.1	149

* P is the paste volume in hardened concrete.

From the results in Table 4, it is proved that MPB materials have high air content and the air bubbles entrained by the chemical reactions can also obtain a reasonable air void spacing factor. Therefore, the air bubbles entrained by the chemical reactions have the same effect on the deicer–frost resistance as the bubbles physically entrained by SJ-2 air-entraining agent even though the average size of chemically air-entrained bubbles is much larger than that of physically air-entrained bubbles. Furthermore, W/C ratio in the MPB materials is below 0.18, very low compared with W/C ratio of 0.55 in OPC concrete, so the freezable water in the MPB mortar or concrete is much lower. Of course, the microstructure and pore strucutre of the MPB materials are different from those of OPC, and these differences also affect the deicer–frost resistance of the materials. These are main reasons that the MPB materials have a high deicer–frost resistance.

For the repaired specimen, the bond interface is always the weakest place where water easily accumulates and therefore has a higher possibility to be damaged by the action of freeze–thaw cycles. It is necessary to have a high frost resistance for the materials on both sides of the bond interface and to get a good interfacial bond in order to get durable repair. Consequently, the cracking more easily occurs in the non-air-entrained OPC concrete near the bond interface than in the air-entrained OPC concrete, thus the bond strength loss between MPB materials and OPC concrete without SJ-2 is much bigger even though the repair material possesses high frost resistance.

4. Conclusions

(1) MPB mortars and concretes have quite high deicer–frost resistance. Scaling occurs only after 40 freeze–thaw cycles. Their deicer–frost resistance is equal to or better than that of OPC concrete with the air content of 4.5–6.5%.

(2) For the repaired specimens exposed to the combined action of frost and deicer, the bond strength loss between MPB paste/mortar and OPC concretes with the air-entraining agent is obviously lower than that between MPB and OPC concrete without the air-entraining agent. The higher the air content in OPC concrete, the smaller the loss is. The bond strength loss for MPB paste used as a repair material is much lower than that for MPB mortar, which is mainly due to its higher bond strength and deicer–frost resistance.

(3) Analysis of the air-bubble parameters shows that MPB mortars and concretes have a high air content and a low air-bubble spacing factor. Air bubbles in the MPB materials are entrained by chemical reactions. This has the same effect on the deicer-scaling resistance as those physically entrained by the air-entraining agent.

(4) MPB materials are very suitable for repair of scaled deterioration of OPC concrete caused by the frost/deicer–frost action. It is better to use MPB paste to repair OPC concrete without the air-entraining agent, but both of MPB paste and mortar can be applied for repairing OPC concrete with the air-entraining agent.

Acknowledgments

The authors deeply appreciate Foundation of Science and Technology, Shanghai Administration of Academic Education for financial support. The work described is part of the supported project JG9425.

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