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Effect of hot-dry curing environment on the intrinsic properties of repair materials

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Abstract

The paper examines the properties of five different types of repair materials, including conventional cementitious, polymer and polymer-modified repair mortars. Assessment was carried out on the basis of the engineering properties (compressive strength, tensile strength and modulus of elasticity), pore structure (porosity and pore size distribution), transport properties (permeability and diffusion) and shrinkage. These properties were measured up to the age of 28 days after curing in a hot-dry environment.

The epoxy resin repair mortar showed superior strength and transport characteristics with a very fine pore structure; however, its modulus of elasticity was remarkably low when compared with that of normal- and high-strength concretes. A hot-dry curing environment adversely affects the shrinkage and performance-related properties of conventional repair mortars; however, small improvements could be achieved by the use of mineral admixtures (fly ash and silica fume). The paper discusses also the different testing techniques which could be used to assess the potential performance of concrete repair mortars. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Corrosion of reinforcements is still a major cause of deterioration in concrete structures. The high cost incurred in repairing and strengthening faulty structures makes it essential that the materials used will provide the durability to match the residual design life of the structure. This is, of course, a strong reason for investigating and developing improved repair materials and testing methodologies.

Depending on the type of exposure environment and the condition of the deteriorated structure, selection of the appropriate repair mortar can be based on its intrinsic properties as well as its compatibility with the existing structure. Conventional repair mortars made using cements and sand will be similar to the existing concrete structure in terms of engineering and performance properties, cost and appearance. However, a high level of shrinkage and cracking can be expected, especially when cured in a hot-dry environment [1,2].

Manufacturers prepare specially formulated "shrinkage-compensating" mortars, designed to combat these problems (polymer-modified mortars, PMC). These mortars often contain polymer in the range of 5–10%, additives and polypropylene fibres to yield improved properties and reduced cracking [3]. They are considered as very effective repair materials [4] due to their improved performance properties (high resistance to the penetration of chloride ions, oxygen and carbon dioxide). However, their shrinkage deformation is significantly affected by the curing environment [5].

Only polymer mortars offer real independence from elevated temperatures, as their resin base is immune to moisture loss. These products can be formulated to gel and cure rapidly over a wide temperature range. They provide excellent strength and bond to concrete, with low shrinkage and permeability [2,3]. However, their structural and thermal compatibility are significantly different from those of conventional concrete [6,7].

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This paper focuses on the intrinsic properties of five common types of repair materials, whereas the compatibility of these materials with concrete is investigated in another study [8]. Measurements of pore structure are obtained and used for the interpretation of the engineering, transport and shrinkage properties under a hot-dry curing environment.

2. Repair materials

Five repair materials were selected in this study. These include conventional cementitious, epoxy resin (EP) and PMC. Table 1 gives details of the repair materials.

The conventional repair mortars were proportioned on the basis of minimum porosity by achieving maximum packing of the binder and sand particles. A dosage of 3% (weight of binder) of a melamine formaldehyde-based superplasticiser was used, and the amount of mixing water was adjusted to have similar workability values as those obtained by the flow-table test according to BS 4550. Table 1 shows also the workability values for the different repair mortars. The commercial pre-packed PMC and EP repair mortars were mixed and cast according to the manufacturer's instructions.

3. Testing programme

After mixing the repair materials, they were cast, compacted in their moulds on a vibrating table and left overnight covered with wet hessian and polyethylene sheets. On the following day they were de-moulded and transferred to a hot-dry environmental chamber maintained at 35°C, 45% relative humidity and 3 m/s wind velocity. These conditions were selected to examine the effects of extreme curing on the properties of repair materials.

Compressive strength, modulus of elasticity and tensile strength testing were carried out to study the engineering properties of the different repair mortars. Cubes (50 mm sides) were used for the measurement of compressive strength at 1, 3, 7 and 28 days. The static compressive modulus of elasticity test was performed on 100 mm^3 cubes at 28 days. Strain gauges were fitted on the side of the cube specimens, and the modulus was calculated for each material from the stress–strain relationship up to 1/3 of the failure load. Previous work [9] indicated that specimen size has no influence on the stiffness and the stress–strain curve. The direct tensile strength was measured using bobbin-shaped specimens (75 mm diameter and 325 mm height) at 28 days [10], using the Instron 8500 Series Digital testing instrument.

Mortar slabs ($400 \times 250 \times 50$ mm^3) were prepared for the measurement of transport properties and pore size distribution at similar testing ages to those of the compressive strength. Porosity, oxygen permeability, water permeability and oxygen diffusion testing were conducted on 50 mm diameter cores, whereas 20 mm diameter cores were used for the measurement of pore size distribution using the technique of mercury intrusion porosimetry. Porosity testing was carried out using the method of vacuum-saturation with water [11]. For the oxygen permeability testing, the specimens were prepared and tested as described in Ref. [12]. The same specimens were also used for the measurement of oxygen diffusion and water permeability. Details of the permeability and diffusion cells with the testing procedures are described in Refs. [11–13].

Unrestrained shrinkage of the repair mortars was carried out using cylindrical specimens (75 mm diameter and 265 mm height) from two days after casting the specimens up to the age of 28 days. Demec points were attached to the curved surface of each cylinder across a length of 200 mm as described in ACI 209R-92 [14].

4. Results and discussion

4.1. Mechanical properties

4.1.1. Compressive strength

The compressive strength results of the different repair mortars are presented in Fig. 1. In general, EP

Table 1
Repair materials used in the study

Code	Description	Flow-table spread (mm)
OPC	**Ordinary Portland cement**: OPC and sand in the weight ratio of 1:2.33. Water/cement of 0.33. Superplasticiser: naphthalene sulphonated polymer-based admixture (3 litres per 100 kg of binder).	210
FA	**Fly Ash** mortar: similar to the OPC mortar, replacing 30% of OPC with FA. Water/binder of 0.30.	200
SF	**Silica Fume** mortar: similar to the OPC mortar, replacing 10% of OPC with SF. Water/binder of 0.33.	200
PMC[a]	**Polymer-modified** mortar: a commercial two-component (A and B) fibre-reinforced polymer-modified mortar. Component A: acrylic copolymer; component B: blend of cements/aggregates/admixtures.	190
EP[a]	**Epoxy** resin mortar: a commercial three-component epoxy resin-based repair mortar (A: resin, B: hardener and C: aggregate).	110

[a] Supplied by the manufacturer.

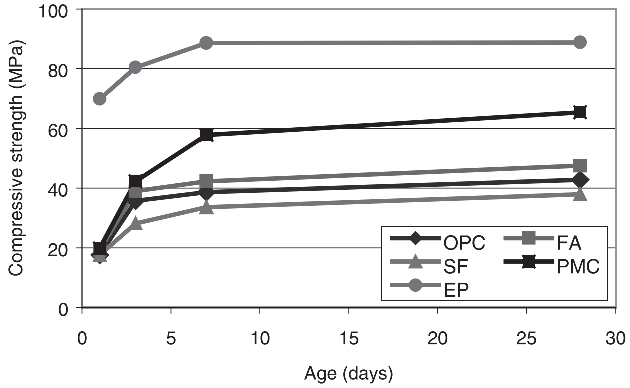

Fig. 1. Compressive strength of the different repair mortars.

(polymer repair mortar) showed the highest compressive strength at all ages, whereas the conventional repair mortars (OPC, FA and SF) gave the lowest values. PMC (polymer-modified repair mortar) showed values intermediate between the polymer and the conventional repair materials.

The effect of curing environment on the 28-day compressive strength is presented in Table 2, which gives also the compressive strength of the conventional mortars when cured at 20°C and 99% relative humidity [15]. By comparing the results, it can be seen that the curing environment has only little effect on the strength of both PMC and EP mortars. The case was different for the conventional repair mortars, where the hot-dry environment (35°C and 45% RH) has adversely affected the strength. A reduction of about 50% of the strength occurs for the same mortars when cured under a hot-dry environment.

4.1.2. Tensile strength

Fig. 2 and Table 2 present the 28-day results of the direct tensile strength for the different repair materials. The conventional mortars showed a tensile strength value of about 4 MPa, which is approximately 1/10 of their compressive strength values. PMC showed improved tensile strength (6 MPa), with almost the same ratio (1/10) to its compressive strength. A superior strength was found for the polymer repair mortar (EP), which is only 1/5 of its compressive strength value and about four times higher than that of the conventional mortars.

Table 2
Strength and modulus properties at 28 days

	Compressive f_c (MPa)		Tensile f_t (MPa)	f_t/f_c (%)	Modulus E (GPa)
Curing	35°C	20°C	35°C	35°C	35°C
OPC	42.8	(83.6)	4.08	9.5	32.3
FA	47.6	(88.6)	3.84	8.1	28.6
SF	39.0	(90.7)	3.48	8.9	31.4
PMC	65.4	[>55.0]	5.94 [7.6]	9.1	41.4
EP	88.8	[>80.0]	17.51 [18]	19.7	13.2

( ): at 20°C and 99% relative humidity, Ref. [15]; [ ]: at 20°C and 65% relative humidity, supplied by the manufacturers.

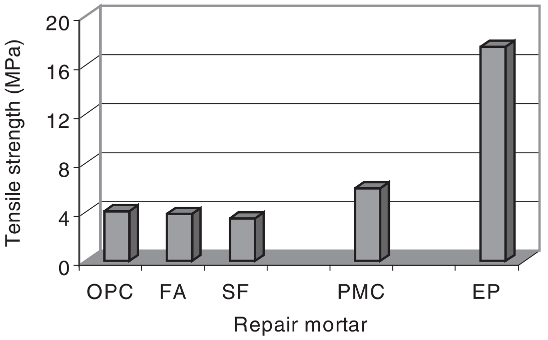

Fig. 2. 28-day tensile strength of the different repair mortars.

4.1.3. Modulus of elasticity

The modulus of elasticity is an important property regarding the deformability of repair materials under load conditions. The compressive static moduli of elasticity of the different repair materials are graphically illustrated in Fig. 3, and also given in Table 2. In contrast to the strength results, the EP repair mortar showed the lowest modulus value of 13 GPa. The highest value was obtained for PMC (41 GPa), while the conventional repair mortars (OPC, FA and SF) showed almost similar values between 29 and 32 GPa.

4.2. Porosity and pore size distribution

The results of total porosity, as obtained from the vacuum saturation test, are illustrated in Fig. 4. The porosity values varied widely (0.5–15%) for the different types of repair mortars used in this study. The polymer repair mortar (EP), which showed the highest strength properties, exhibited the lowest porosity values. In fact, the porosity of EP was extremely low (<1%) at all tested ages. The highest porosity values were obtained for the conventional repair mortars, which exhibited higher porosity values than the PMC. Among the conventional mortars, the SF gave the lowest compressive strength and also the lowest porosity.

Measurements of pore size distribution combined with total porosity are essential for the pore structure analysis of repair mortars. There are many parameters that can be used to represent the pore size distribution results. In this study, the median pore diameter (MPD), which corresponds to the pore size at 50% intrusion, was used. Fig. 5 shows the MPD for the different repair materials up to 28 days. The polymer repair mortar exhibited not only the lowest porosity value but also the

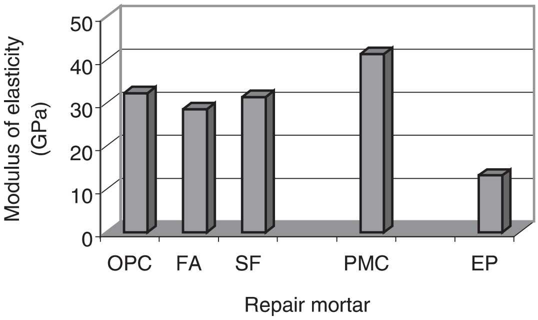

Fig. 3. 28-day compressive modulus of elasticity.

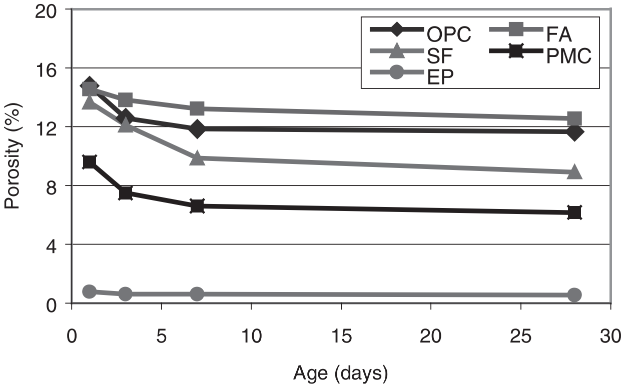

Fig. 4. Porosity vs. age for the different repair mortars.

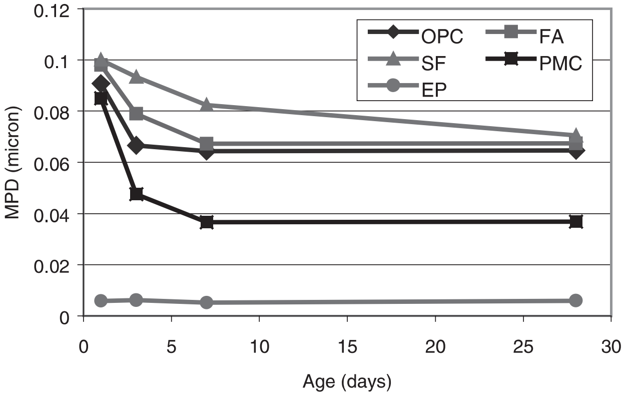

Fig. 5. Median pore diameter of the repair mortars.

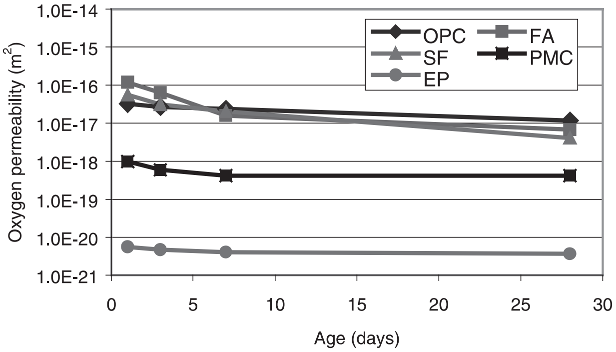

Fig. 6. Variation of oxygen permeability for the different repair mortars.

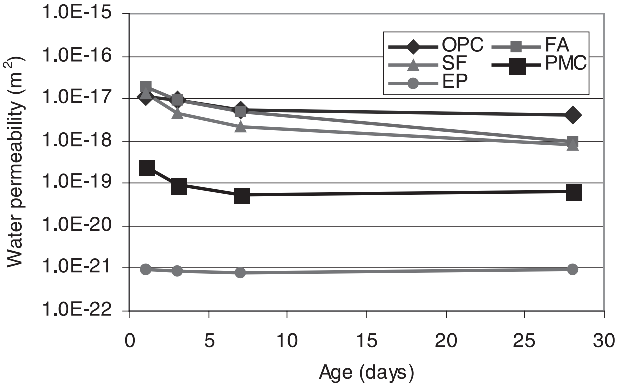

Fig. 7. Water permeability vs. age for the different repair mortars.

finest pore structure, which is at least 10 times smaller than that of conventional repair mortars. For PMC, the MPD reduced sharply within the first week, indicating the refinement of pore sizes even under hot-dry environmental conditions. The effect of pore structure on the performance properties of the repair materials is discussed in the following sections.

4.3. Transport properties

4.3.1. Permeability

Permeability is a property which defines the resistance to the penetration of aggressive substances under the influence of differential pressure and is fundamental regarding concrete durability and long-term performance. The values of oxygen and water permeability are shown in Figs. 6 and 7, respectively.

In general, the results varied widely (3–4 orders of magnitude) for the different repair materials. The EP repair mortar, with its fine pore structure, showed the lowest permeability values. These values are extremely low when compared to high-performance concrete [16]. The permeability of PMC was about one order of magnitude lower than that of the conventional repair mortars.

4.3.2. Oxygen diffusion

Diffusion is another transport property describing the rate of movement of aggressive substances due to a concentration gradient. The oxygen diffusion values measured for the different materials are presented in

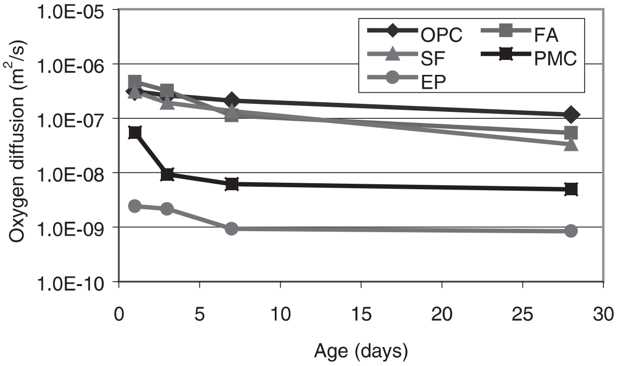

Fig. 8. Oxygen diffusion of the different repair mortars.

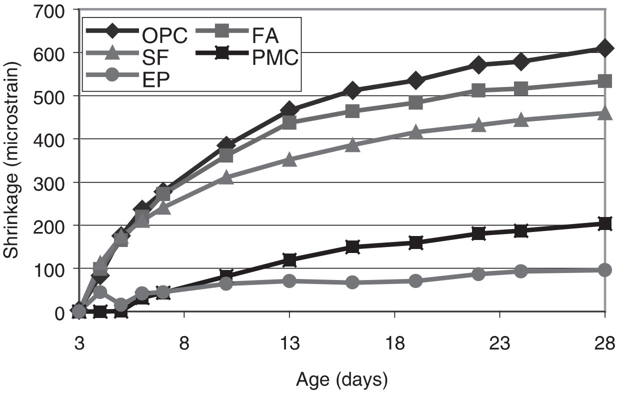

Fig. 9. Shrinkage of the different repair mortars.

Fig. 8. The polymer repair mortar (EP) showed the lowest diffusion value whereas the conventional repair mortars exhibited the highest values, similar to the permeability results.

4.4. Shrinkage

Shrinkage is a volume-change property which is measured by monitoring periodically the length changes of the specimens exposed to controlled environmental conditions. The specimen size and the exposure conditions, which vary in different standards, have a great influence on the shrinkage of repair mortars [17]. The drying shrinkage of the different repair mortars is shown in Fig. 9. The results show clearly that conventional repair mortars are more sensitive to the hot-dry environment, which accelerates the moisture loss and enhances shrinkage. Dramatic reduction in shrinkage can be obtained using polymers. PMC showed a reduction of more than 50% compared to the conventional mortars. Further reduction can be obtained using polymer mortar (EP). The latter showed less than 20% shrinkage compared to the conventional mortars.

5. Discussion

In this study, the intrinsic properties measured for the repair mortars varied widely depending on their generic types and formulations, which result in different pore structure influencing both engineering and performance properties of repair mortars. The epoxy resin (polymer) mortar, exhibiting the lowest porosity values and the finest pore sizes, showed further improved characteristics. The coarse pore structure of the cementitious mortars resulted in lower compressive and tensile strength values, which were about two and four times lower than those of the epoxy mortar, respectively. However, the difference was further enhanced in the transport properties, where the reduction was about three orders of magnitude in the permeability and two orders of magnitude in the diffusion. This indicates clearly that the transport properties are more representative of mortar pore structure and strongly supports the adoption of such properties within the performance-based criteria of repair mortars. Cabrera and Al-Hassan [18] reported that measurements of permeability and pore structure are the most rational way of assessing the quality of repair mortars.

The drying shrinkage data obtained in this study indicated the sensitivity of the conventional mortars to curing environment. The fast withdrawal of moisture due to a hot-dry environment adversely affects the drying shrinkage to give values about 6–8 times and 2–3 times higher than those of polymer and polymer-modified repair mortars, respectively. However, the use of mineral admixtures (FA and SF) was found to improve the pore structure and consequently reduce the shrinkage. A different deformation behaviour is obtained for the repair mortars under load application. Mangat and O'Flaherty [19] indicated that, for the design of efficient repair, the repair material should have greater modulus than the concrete substrate. The modulus of elasticity of the conventional repair mortars was quite similar to that of normal concrete. The epoxy mortar gave the lowest value, about 1/3 that of normal concrete, indicating much more deformation under load application.

Currently there are developments towards unified European Standards for repair materials. These standards, as reviewed by Robery and Shaw [20,21], are not limited to the strength properties but extended to different characteristics such as: composition, usability and physical (thermal compatibility, dimensional stability and pull-off adhesion) and transport (resistance to chloride, carbonation and water penetration) properties. Most of these performance tests are stated to be conducted after curing the specimens at 21 ± 2°C. However, and based on the results obtained in this study, great care should be taken with the use of repair materials, especially cementitious mortars, when exposed to hot-dry environmental conditions.

6. Conclusions

1. The intrinsic properties of the repair mortars vary widely depending on their formulations and the exposure environment.
2. Under a hot-dry curing environment, polymer and polymer-modified repair materials exhibit improved strength, permeability, diffusion and shrinkage properties when compared to conventional cementitious repair mortars.
3. Differences between the different types of repair materials studied are more pronounced in their transport properties than their strength properties, indicating the importance of the permeability and diffusion characteristics in the performance specifications of repair mortars.
4. Within the different types of repair mortars used in this study, the polymer (resin) material deforms more under load application, indicating incompatibility with normal- and high-strength/performance concretes.

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