Cement & Concrete Composites 23 (2001) 93–101

Cement & Concrete Composites

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Compatibility of repair mortars with concrete in a hot-dry environment

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Received 10 February 2000; accepted 6 November 2000

Abstract

Strengthening, maintenance and repair of concrete structures are becoming more recognised in the field of civil engineering. There is a wide range of repair mortars with varying properties, available in the market and promoted by the suppliers, which makes the selection of the most suitable one often difficult. A research programme was conducted at Leeds University to investigate the properties of cementitious, polymer and polymer modified (PMC) repair mortars. Following an earlier publication on the intrinsic properties of the materials, this paper presents results on the compatibility of these materials with concrete. The dimensional stability is used in this study to investigate the compatibility of the repair mortars and the parent concrete. Composite cylindrical specimens (half repair mortar/half concrete) were prepared and used for the measurements of modulus of elasticity and shrinkage. The results of the different combined systems were obtained and compared to those calculated using a composite model. The variations between the measured and calculated values were less than 10%. The paper attempts to quantify the effect of indirect differential shrinkage on the permeability and diffusion characteristics of the different combined systems.

Keywords: Compatibility; Concrete; Dimensional stability; Modulus of elasticity; Oxygen diffusion; Oxygen permeability; Repair mortars; Shrinkage

1. Introduction

Deterioration of concrete structures is a major problem in civil engineering, which is mainly associated with contamination, cracks and spalling of the cover concrete. In many instances, the serviceability of the deteriorated structure becomes an important issue and therefore the most cost-effective solution is often to use patch repair, which involves the removal of the deteriorated parts and reinstatement with a fresh repair mortar (Fig. 1). The effectiveness of this approach is influenced by the intrinsic properties of the selected repair material (to eliminate the cause of initial deterioration), the chloride contamination level of the concrete adjacent to the repaired zone [1,2] and the compatibility of the combined system (concrete/repair).

Compatibility in a repair system is the combination of properties between the repair material and the existing concrete substrate which ensures that the combined system withstands the applied stresses and maintains its structural integrity and protective properties in a certain exposure environment over a designated service life [3,4]. Dimensional stability, chemical, electrochemical, and transport properties of the repair material and the parent concrete are the main aspects of compatibility.

The dimensional stability is probably the most important factor which controls the volume changes due to shrinkage, thermal expansion, and the effects of creep and modulus of elasticity [5–7]. The chemical and electrochemical properties include attack due to alkali silica reaction, sulphate content, pH, electrical resistivity, chloride and carbonation induced corrosion, whereas the permeability and diffusion characteristics of both materials and at the interface between them are the main consideration for a durable combined system.

Previous studies [5,6] compared properties of various repair mortars and then used finite elements analysis to study the performance of axially loaded reinforced concrete. In this study the compatibility of five repair mortars and concrete, in terms of modulus of elasticity and shrinkage, was investigated (Table 1). The paper reviews a simple model describing the modulus and

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0958-9465/01/$ - see front matter
PII: S0958-9465(00)00073-1

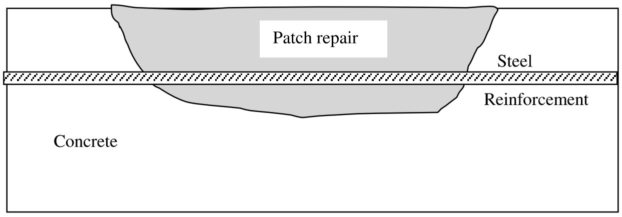

Fig. 1. Schematic diagram of patch repair.

Table 1
Repair materials used in the study

Code	Description
OPC	*Ordinary Portland cement*: OPC (BS 12) and sand in the weight ratio of 1: 2.33. Water/cement of 0.33. Superplasticizer: naphthalene sulphonated polymer based admixture (3 litres per 100 kg of binder)
FA	*Fly Ash* mortar: similar to the OPC mortar with replacing 30% of OPC with FA. Water/binder of 0.30
SF	*Silica Fume* mortar: similar to the OPC mortar with replacing 10% of OPC with SF. Water/binder of 0.33
PMC[a]	*Polymer Modified* mortar: a commercial two component (A and B) fibre reinforced polymer modified mortar. Component A: acrylic copolymer and component B: blend of cements/aggregates/admixtures
EP[a]	*Epoxy resin* mortar: a commercial three component epoxy resin-based repair mortar (A: resin, B: hardener and C: aggregate)

[a] Supplied by the manufacturer.

shrinkage behaviour of composite materials and presents an experimental programme on the application of the model. It emphasises the indirect effect of differential shrinkage on the transport properties of the different combined systems.

2. Model theory

Let the combined system of parent concrete and repair mortar be subjected to an external stress (σ_0), have a modulus of elasticity – E_0, Poisson's ratio – μ_0 and shrinkage – S_0. The corresponding properties of the two phases are shown in Fig. 2 (parent concrete: symbol "c" and repair mortar: "m").

Assumptions are:
(a) Strain is constant over any cross section.
(b) Stress is proportional to strain.
(c) Unit volume (volume = 1) of combined material.
(d) Effect of creep is neglected (creep of concrete is considered equal to the creep of repair materials).

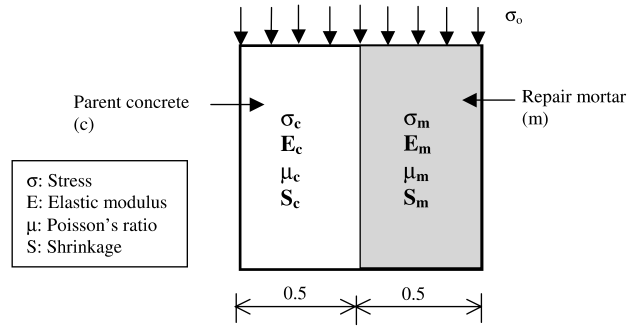

Fig. 2. Stresses and strains of a composite system.

(e) Effect of autogenous shrinkage is neglected.
(f) Thermal effects on volume change are neglected.
For equilibrium of forces:

$$\sigma_0 \times 1 = \sigma_c \times 0.5 + \sigma_m \times 0.5 \quad (1)$$

or

$$2\sigma_0 = \sigma_c + \sigma_m. \quad (2)$$

For equality of strain:

$$\frac{\sigma_0}{E_0}(1-2\mu_0) + S_0 = \frac{\sigma_c}{E_c}(1-2\mu_c) + S_c = \frac{\sigma_m}{E_m}(1-2\mu_m) + S_m. \quad (3)$$

From which

$$\sigma_c = \left[\frac{\sigma_0}{E_0}(1-2\mu_0) + (S_0 - S_c)\right]\frac{E_c}{1-2\mu_c} \quad \text{and}$$

$$\sigma_m = \left[\frac{\sigma_0}{E_0}(1-2\mu_0) + (S_0 - S_m)\right]\frac{E_m}{1-2\mu_m}. \quad (4)$$

Substitute (4) in (2)

$$2\sigma_0 = \frac{\sigma_0}{E_0}(1-2\mu_0)\left[\frac{E_c}{1-2\mu_c} + \frac{E_m}{1-2\mu_m}\right] + S_0\left[\frac{E_c}{1-2\mu_c} + \frac{E_m}{1-2\mu_m}\right] - S_c\frac{E_c}{1-2\mu_c} - S_m\frac{E_m}{1-2\mu_m}. \quad (5)$$

For modulus of elasticity, $S_0 = S_0 = S_m = 0$. Then from Eq. (5)

$$E_0 = 0.5(1-2\mu_0)\left(\frac{E_c}{1-2\mu_c} + \frac{E_m}{1-2\mu_m}\right). \quad (6a)$$

With

$$E_0 = 0.5 - \frac{E_c + E_m}{2(E_c/1-2\mu_c + E_m/1-2\mu_m)}. \quad (6b)$$

For shrinkage, $\sigma_0 = 0$. Then from Eq. (5)

$$S_0 = \frac{S_c E_c(1-2\mu_m) + S_m E_m(1-2\mu_c)}{E_c(1-2\mu_m) + E_m(1-2\mu_c)}. \quad (7)$$

Emberson and Mays [8] concluded that the Poisson's ratio has only a second-order effect on the stress distribution in patch repair. If the differences in Poisson's ratios are neglected, i.e. $\mu_0 = \mu_c = \mu_m$, then Eqs. (6a) and (7) become:

$$E_0 = 0.5(E_c + E_m), \quad (8)$$

$$S_0 = \frac{S_c E_c + S_m E_m}{E_c + E_m}. \quad (9)$$

3. Experimental work

3.1. Parent concrete

The control concrete mix had the composition of OPC:sand:gravel in the weight ratio of 1:2.33:3.5, with a cement content of 325 kg/m^3. The sand grading conformed to zone M of BS 882 [9], and the gravel had a maximum size of 10 mm. The w/c used was 0.55, which resulted in a slump value of 55 mm.

Cylindrical specimens (150 mm diameter and 300 mm height, and 75 mm diameter and 265 mm height) were cast for the dimensional stability study. Additional cubes (100 mm) and slabs ($400 \times 250 \times 40$ mm^3) were also cast for studying the properties of the parent concrete. The specimens were demoulded after 24 h and cured in a fog room maintained at 20°C and 99% relative humidity (RH). The properties of the control concrete substrate, measured at the age of 28 days, are given in Table 2.

The cylindrical concrete specimens were kept in the fog room for 3 months. This long curing period was chosen to provide a relatively old concrete substrate for the repair mortars. The cylinders were then split along their longitudinal axis into two halves following the procedure of BS 1881: Part 117 [10] for tensile splitting strength. The loose particles were removed and the fractured surfaces were cleaned using a wire brush. The split cylinders were transferred to the hot dry environmental chamber controlled at 35°C, 45% RH and 3 m/s wind velocity, and kept there for 7 days before casting the repair mortars.

3.2. Repair mortars

Five repair materials were selected in this investigation. These include: conventional cementitious, epoxy resin (EP) and polymer modified mortars (PMC). Table 1 gives details of the repair materials. The repair mortars used in the study are the same investigated in [11], where their intrinsic properties are reported.

Table 2
Properties of the parent concrete (substrate) measured at 28 days

Compressive strength (MPa)	55
Compressive modulus of elasticity (GPa)	31.8
Porosity (%)	11.2
Intrinsic coefficient of oxygen permeability (m^2)	1.0×10^{-17}
Coefficient of oxygen diffusion (m^2/s)	1.5×10^{-7}

3.3. Combined specimens

The half cylinder specimens were sprayed with water and placed again into their original moulds. The other halves of the moulds were cast with the different repair mortars to produce combined specimens. The specimens were compacted and kept covered overnight with wet hessian and polyethylene sheets. After 24 h, the combined specimens were demoulded and cured for 27 days in the same hot dry environment (35°C, 45% RH and 3 m/s wind velocity).

The 75-mm diameter cylinders were used for the measurements of shrinkage strains between 3 and 28 days. Demec points were attached to the combined cylinders, on both sides (concrete/repair material), at a gauge length of 200 mm. After 28 days, cores (50-mm diameter) were drilled to have one half of the repair mortar and the other of the parent concrete. These cores were used for studying the effect of differential shrinkage on the transport properties of the combined systems. Fig. 3 shows details of the shrinkage cylinder with locations of the Demec points and the drilled cores.

The (150-mm) cylinders were used for the measurements of compressive modulus of elasticity and strength at 28 days. Flat loading surfaces were produced by grinding the opposite faces of each cylinder. Strain gauges (20-mm length) were fixed on each side of the repair mortar and the parent concrete as shown in Fig. 4. The specimens were tested using the Tonipact-3000 (cube crushing machine), with a loading rate of 0.2 N/mm^2/s. The top loading plate of the machine is initially free to level with the test specimens (up to 5 kN load), then locked automatically to minimise the effect of load eccentricity. Load-strain readings were recorded automatically using a computer data acquisition system.

Duplicate specimens were used for each test and the average values were used in presenting the results. The variation of results was less than 10% for the engineering and shrinkage properties, and less than 25% for the

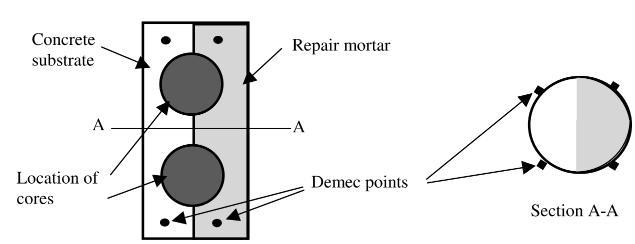

Fig. 3. Details of the combined shrinkage specimen (75 mm diameter).

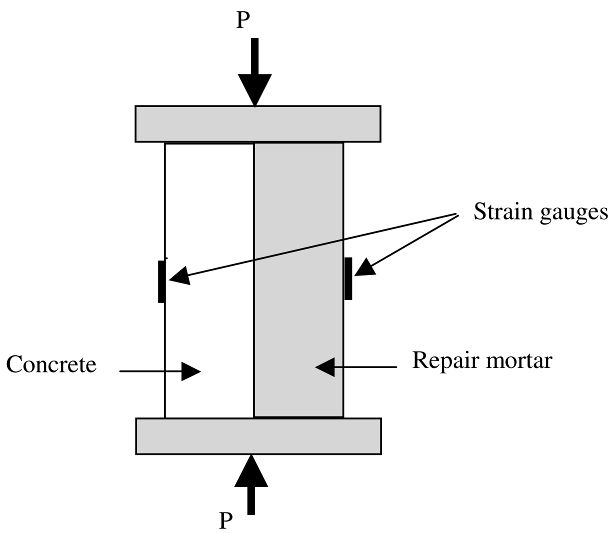

Fig. 4. Details of the elastic modulus and strength specimen (150 mm diameter cylinder).

transport properties. The testing procedures used for measuring shrinkage, modulus of elasticity and transport properties were similar to those used for testing the individual repair materials in [11].

4. Presentation of results

4.1. Modulus of elasticity

The modulus of elasticity is the property which controls the load distribution of a combined system composed of two materials. The elastic stress–strain behaviour (up to 1/3 of the failure load) of the individual repair mortars, concrete, and the average values of the combined systems (labelled as Comb) are presented in Figs. 5(a)–(e). The individual values are given in Table 3 together with the measured average of the combined systems. Table 3 gives also the moduli for the different combined systems (E_0), as calculated from Eq. (8) using the individual values of E_c and E_m.

The results show that, except for the PMC and EP, the modulus values of the cementitious repair mortars are quite similar to that of the parent concrete. Consequently, when combined together, the modulus of OPC, FA and SF combined systems did not change much, indicating only a slight effect on the load distribution of the combined systems and hence modulus compatibility. In contrast to the cementitious mortars, the PMC and the EP mortars had different modulus values to that of the concrete. As a result of the combined action, the PMC repair mortar increased the modulus of concrete, whereas the EC mortar caused a reduction in the concrete modulus.

When the values of modulus are compared, the combined (measured) modulus agrees with the average modulus of the individual materials (E_0) to within 10%. This is in compliance with the theory of combined modelling when there is no discontinuity of strain at the interface, for example, cracking and a transitional zone effect. It also suggests that the effect of Poisson's ratio as considered in the derivation of Eq. (6a) is not significant for the materials used.

4.2. Compressive strength

Fig. 6 shows the stress–strain relationships for the different combined cylinders up to failure, whereas the numerical values of the 28 days compressive strength for the individual repair mortars and the combined cylinders are given in Table 4. Although the PMC showed a relatively higher modulus than that of the concrete, its stress–strain behaviour when combined with the parent concrete was found to be quite similar to those of the cementitious mortars. In fact the compressive strength value for the PMC/concrete was slightly higher than that of the parent concrete. The EP/concrete system showed a different behaviour and exhibited a strength value of 38.4 MPa. This value is relatively low when compared with the individual materials and also when compared to the other combined systems. However, its strain capacity was the greatest (Fig. 6).

4.3. Shrinkage

Shrinkage is another important property regarding the dimensional stability of combined systems. Incompatibility due to drying shrinkage causes internal stresses, which might lead to failure at the interface or within the lower strength material. The shrinkage results of the different combined systems are presented in Figs. 7(a)–(e), where the average combined values (Comb) are plotted with values of the individual materials.

The results indicate that long moist curing (3 months) significantly reduces the shrinkage of the control concrete even when exposed to the hot dry environment. Most of the shrinkage strains developed within the first 2 weeks, after which it levelled off to show an overall low shrinkage value at the age of 28 days. In contrast to the modulus results, the EP/concrete system (Fig. 7(e)) showed similar behaviour to that of the parent concrete indicating compatibility of shrinkage behaviour. The PMC repair mortars usually incorporate expanding additives which reduce the shrinkage at early age. This can be seen in Fig. 7(d), where the PMC/concrete system showed low shrinkage values within the first 10 days, after which the rate of shrinkage development was relatively higher than that of the parent concrete.

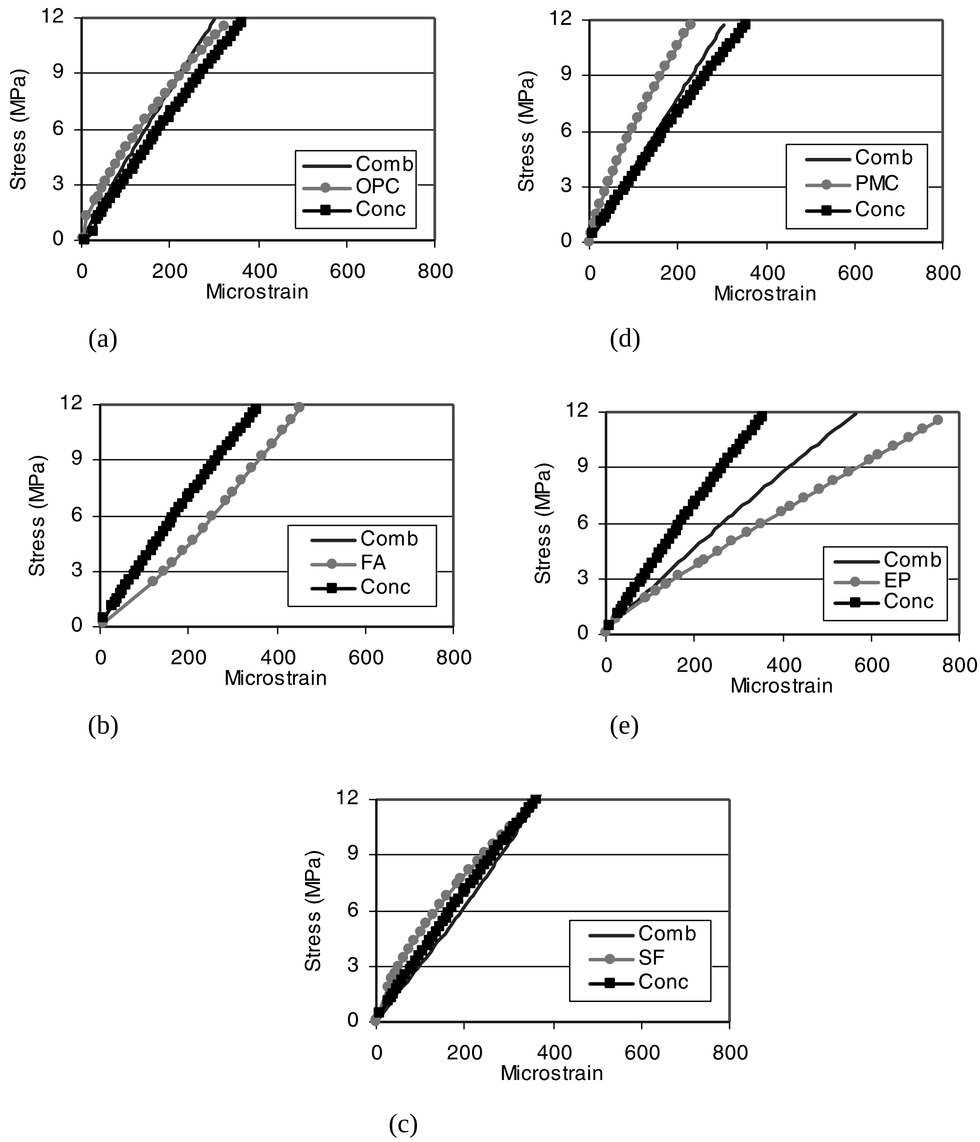

Fig. 5. Stress–strain relationships for the different combined systems: (a) OPC/concrete system; (b) FA/concrete system, the comb curve falls behind the conc curve; (c) SF/concrete system; (d) PMC/concrete system; (e) EP/concrete system.

Table 3
Values of the modulus of elasticity (GPa)

	Individual		Combined	
	Concrete (E_c)	Repair (E_m)	Average[a] (E_0)	Average (measured)
OPC	31.8	32.3	32.1	32.3
FA	31.8	28.6	30.2	33.7
SF	31.8	31.4	31.6	32.7
PMC	31.8	41.4	36.6	38.6
EP	31.8	13.2	22.5	20.6

[a] Calculated from Eq. (8).

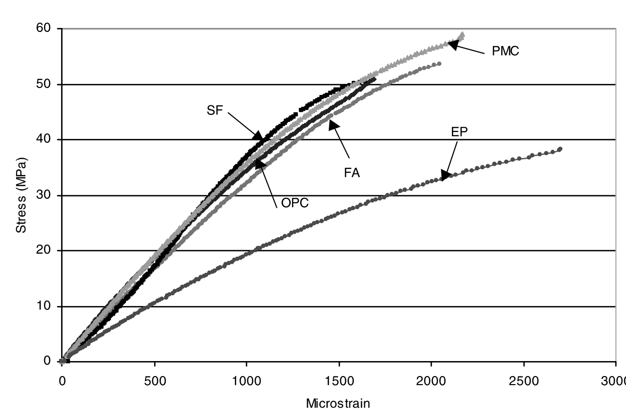

Fig. 6. Stress–strain relationships of composite samples up to failure.

Table 4
Compressive strength (MPa) for individual and combined repair mortars

	Individual cubes	Combined cylinders
OPC	42.8	50.6
FA	47.6	50.4
SF	39.0	50.5
PMC	65.4	58.8
EP	88.8	38.4

Incompatibility of shrinkage can be seen clearly from comparing the combined systems with the cementitious repair mortars. Table 5 gives the 28-day shrinkage for the individual materials (S_c, S_m) together with the average combined measured values (S_0) and as calculated from Eq. (9). It should be noted that the values of E in Eq. (2) should strictly be effective values to account for creep. In the present analysis, the difference in creep between the repair material and the parent concrete was neglected. Also, it was assumed that no moisture transfer occurred across the interface since the fractured surface of the substrate was sprayed with water prior to the repair materials being cast.

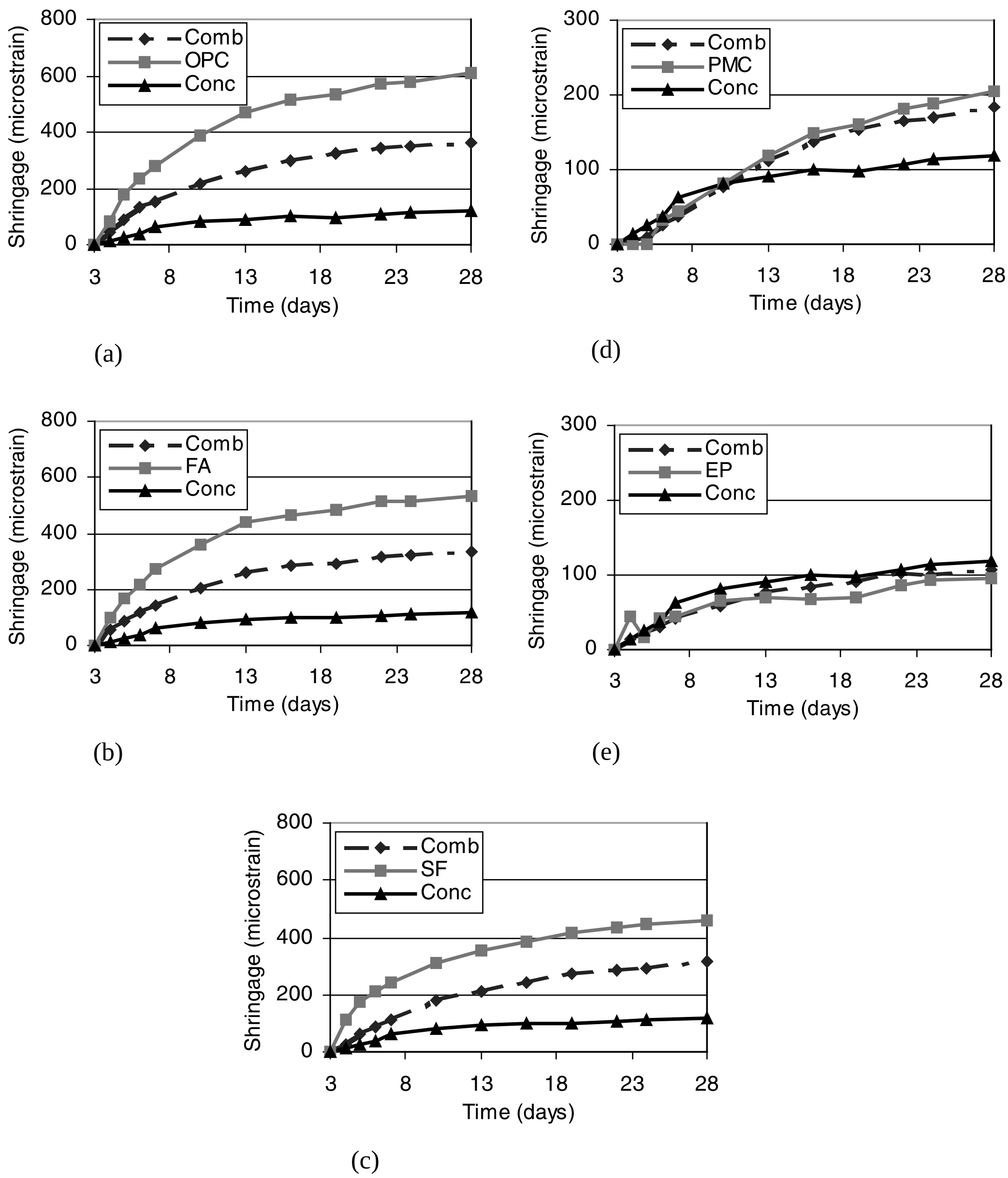

Fig. 7. Shrinkage strains for the different combined systems: (a) OPC/concrete system; (b) FA/concrete system; (c) SF/concrete system; (d) PMC/concrete system; (e) EP/concrete system.

Table 5
Shrinkage strain at 28 days (Microstrains)

	Individual		Combined	
	Concrete (S_c)	Repair (S_m)	Average[a] (S_0)	Average (measured)
OPC	118	610	366	359
FA	118	533	315	338
SF	118	460	288	315
PMC	118	204	167	184
EP	118	96	112	108

[a] Calculated from Eq. (9).

The highest differential shrinkage was found with the OPC/concrete system. The FA and SF combined systems showed similar behaviour to that of the OPC/concrete. Similar to the modulus results, the combined shrinkage values (calculated and measured) agree to within 10%, confirming the validity of the combined model proposed and the small influence of Poisson's ratio as considered in the derivation of Eq. (7).

4.4. Transport properties

The transport properties are of great importance when considering the durability of the repair system. The combined specimens were conditioned and tested in a similar manner to the individual materials used in [11] following the procedure described in [12,13], which involve the removal of the evaporable water to eliminate the effect of moisture on the measured transport properties. The effect of differential shrinkage on the intrinsic coefficient of oxygen permeability of the combined systems is presented Table 6, whereas Table 7 gives the coefficient of oxygen diffusion results.

By comparing the results of the combined systems, it can be seen that the OPC/concrete system exhibited the highest permeability value whereas the lowest value was found with the EP/concrete system. This trend is similar to that obtained from the shrinkage results. In fact the permeability of the OPC/concrete and the FA/concrete systems were about one order of magnitude higher than the individual materials (OPC, FA mortars and parent concrete).

The results of oxygen diffusion agree with those obtained from the permeability results. The shrinkage compatibility of the EP/concrete system reduces the diffusion value to be similar to that of the parent concrete. The performance of the PMC/concrete system was adequate when compared with the EP/concrete system.

In general the trend of the transport properties of the combined specimens appears to be associated with the differential shrinkage found with the different systems. This would be expected since any weakening at the interface, and consequent increase in permeability and diffusion, would be greater for a higher differential shrinkage. Figs. 8 and 9 show the coefficients of permeability and diffusion plotted against the relative shrinkage (S_m/S_c) for the tested combined systems. The general linear relationships obtained indicate that higher differential shrinkage results in higher transport properties and therefore lower resistance to the penetration of harmful substances from aggressive environments.

Table 6
Intrinsic coefficient of oxygen permeability (m^2) for the individual and combined systems

	Concrete	Repair	Combined
OPC	1.05×10^{-17}	1.16×10^{-17}	1.19×10^{-16}
FA	1.05×10^{-17}	6.77×10^{-18}	1.15×10^{-16}
SF	1.05×10^{-17}	4.09×10^{-18}	7.64×10^{-17}
PMC	1.05×10^{-17}	4.15×10^{-19}	2.15×10^{-17}
EP	1.05×10^{-17}	3.69×10^{-21}	1.95×10^{-17}

Table 7
Coefficient of oxygen diffusion (m^2/s) for the individual and combined systems

	Concrete	Repair	Combined
OPC	5.50×10^{-8}	1.17×10^{-7}	1.33×10^{-7}
FA	5.50×10^{-8}	5.39×10^{-8}	1.29×10^{-7}
SF	5.50×10^{-8}	3.35×10^{-8}	8.51×10^{-8}
PMC	5.50×10^{-8}	4.97×10^{-9}	6.30×10^{-8}
EP	5.50×10^{-8}	8.47×10^{-10}	5.59×10^{-8}

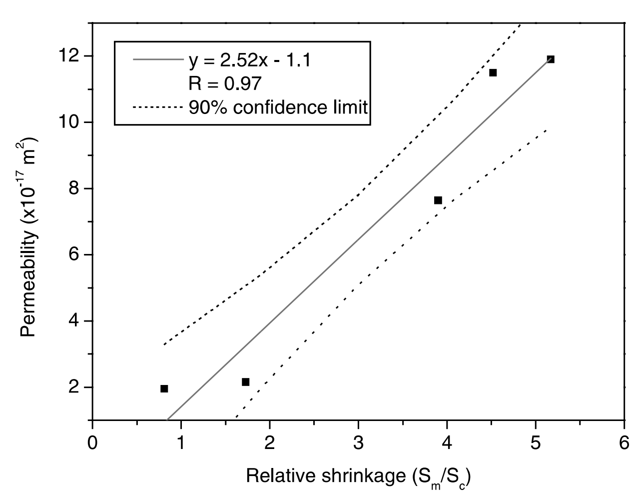

Fig. 8. Relationship between coefficient of oxygen permeability and relative shrinkage.

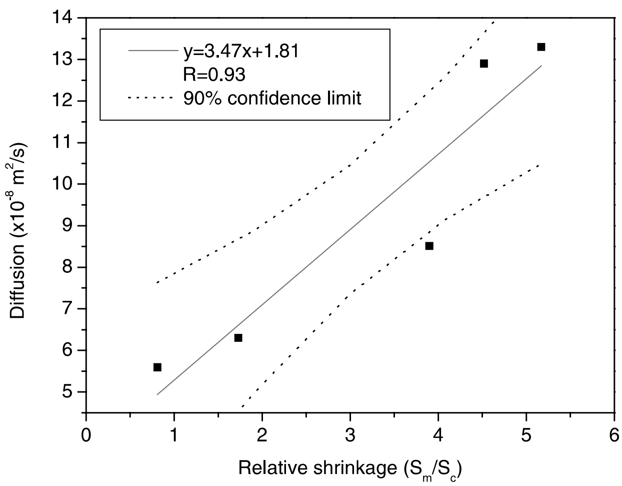

Fig. 9. Relationship between coefficient of oxygen diffusion and relative shrinkage.

5. Discussion

Compatibility of concrete and repair materials involves matching of different properties between the two systems, as mentioned earlier. Dimensional stability under load application (modulus) was one of the issues considered in this study for the different systems investigated.

Mismatch in the modulus of elasticity becomes of great concern in repairs when the applied load is parallel to the bond line in a combined system. The material with the lower modulus deforms more and, therefore, transfers the load, through the interface, to the higher modulus material [14]. If the transferred load exceeds the load-carrying capacity of the material or the bond at the interface, fracture occurs. For the design of an efficient repair, it has been recommended that the repair material should have greater modulus (>30%) than the concrete substrate [15]. Within the different repair mortars used in the study the cementitious mortars provided almost similar moduli values to that of the parent concrete, whereas the mismatch can be seen clearly with the epoxy (polymer) mortar used (Table 3). Due to the high bond strength of epoxy mortars [16], it forces the concrete to deform more under load application (Figs. 5(e) and 6), leading to an early concrete fracture and consequently failure of the combined system.

Drying shrinkage was the other parameter used to study the dimensional stability in repair systems. It is mainly influenced by the composition of the materials and the surrounding environments, and achieves a great part of its ultimate value at early ages considering the small size of the samples tested [17]. Larger specimens with a higher volume-to-surface ratio will definitely take more time to shrink. As the fresh repair material tends to shrink, the parent concrete (relatively old) restrains it. The differential movements cause tensile stresses in the repair mortar balanced by compressive stresses within the concrete. Creep in such a situation is an advantage, as it releases part of these stresses. As shrinkage proceeds, the stresses accumulate, which might cause cracks and failure if exceeded the tensile capacity of the repair material or the bond strength at the interface.

In contrast to the modulus results, the shrinkage incompatibility is more associated with the cementitious mortars, which reduces sharply with the use of PMC to reach minimum for polymer (EP) mortars. Similar trend of results was found with the transport properties of the different systems, suggesting their dependence on the dimensional stability of combined systems. A general correlation appears to exist between transport properties and differential shrinkage.

In general, the results obtained in this investigation indicate that in spite of the superior properties of the epoxy mortar, its compatibility with concrete is mainly affected by the low modulus. The high shrinkage of the cementitious mortars, especially when exposed to hot dry environments limits their compatibility. The most appropriate performance was obtained for the PMC mortar, which showed adequate compatibility in modulus and shrinkage with improved engineering and transport properties.

6. Conclusions

For the repair materials used in this study and stored under a hot-dry environment, the conclusions can be summarised as follows:

1. High shrinkage strains of the cementitious repair mortars affected their compatibility with concrete, and increased indirectly the permeability at the interface of the combined system by one order of magnitude.
2. The mismatch in modulus of elasticity between concrete and the epoxy mortar used in the study reduced the load carrying capacity of the combined system.
3. Transport properties (namely permeability and diffusion) correlated fairly well with differential shrinkage of the repair material and parent concrete.
4. The PMC repair mortar showed the most appropriate properties in terms of dimensional stability with concrete due to similar elastic modulus and low shrinkage strains when compared to the parent concrete.

Future research should investigate the dimensional compatibility, including creep and autogenous shrinkage, of repair materials with microstructural studies of the interface and transition zone.

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