PERFORMANCE EVALUATION OF REPAIR MATERIALS

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ABSTRACT

Reduction in the useful service-life of reinforced concrete construction, mainly due to reinforcement corrosion, is a major problem facing the construction industry worldwide, in general, and the Arabian Gulf in particular. Deteriorating structures need to be repaired not only to utilize them for their intended service-life but also to assure the safety and serviceability of the associated components. While several repair materials are used for repair and rehabilitation of the deteriorated concrete structures worldwide, their performance in the Arabian Gulf environment, dominated by the extreme temperatures and aridity, has not been thoroughly investigated. This paper reports the results of a study conducted to evaluate the performance of repair materials available in the local market. Based on the data developed in the study, criteria for the selection of repair materials are recommended.

Keywords: *Carbonation, Cement-based repair mortar, Chloride permeability, Compressive strength, Elastic modulus, Polymer-based repair mortar, Shrinkage, Thermal expansion.*

الملخص

إن نقص العمر الافتراضي للمنشآت الخرسانية بسبب صدا حديد التسليح يعد مشكلة رئيسة تواجه صناعة الإنشاء في العالم بشكل عام ، وفي منطقة الخليج العربي بشكل خاص . إن تدهور المنشآت الخرسانية بمنطقة الخليج العربي يتفاقم بسبب الظروف البيئية للمنطقة المتمثلة في ارتفاع نسبة الرطوبة ودرجات الحرارة . المنشآت المتدهورة تتطلب الإصلاح والترميم ليس فقط من أجل المحافظة على العمر الافتراضي لها ولكن لتأكيد سلامة وصلاحية جميع الأجزاء المكونة للمنشآت . الترميم الجيد يؤدي إلى تحسين مستوى أداء البناء ويزيد من قوته وصلابته ومقاومة نفاذية الماء ويمنع من تسرب العناصر الضارة إلى قضبان الحديد وبالتالي يرفع من متانة المنشأة . بالرغم من توافر العديد من مواد الإصلاح في السوق المحلي والمنتجة في عدد من دول العالم ، إلا أن كفاءة أداءها في منطقة الخليج العربي لم تختبر بشكل مكثف. هذه الورقة تقدم بعض النتائج التي تم الحصول عليها من دراسة أجريت لتقييم أداء عدد من مواد الإصلاح المختارة والمتوفرة محلياً . وبناءً على نتائج هذه الدراسة تم إعداد واقتراح مواصفات لبعض الخصائص الهامة لمواد الإصلاح .

1. INTRODUCTION

Reduction in the useful service-life of reinforced concrete construction is a major problem confronting the construction industry worldwide. Concrete deterioration due to reinforcement corrosion is evident in the mild climatic conditions of the world due to the use of deicer salts while in the hot and arid regions this problem is caused due to a combination of environmental conditions, marginal aggregates and inappropriate construction methods. Considerable resources are expended to repair and rehabilitate the deteriorated concrete structures.

Repair and rehabilitation of the deteriorated concrete structures are essential not only to utilize them for their intended service-life but also to assure the safety and serviceability of the associated components. A good repair improves the function and performance of the structure, restores and increases its strength and stiffness, enhances the appearance of the concrete surface, provides water tightness, prevents ingress of the aggressive species to the concrete/steel interface, and improves its durability.

Several repair materials are marketed for the repair of deteriorating concrete structures. These repair materials are classified into different types, such as cement-based, epoxy resins, polyester resins, polymer latex, and polyvinyl acetate. Cement-based materials and polymer/epoxy resins are the most widely used among the repair materials [Allen et al.; 1994, Dehwah; 1990, Shaw, 1985]. These materials mostly consist of a conventional cement mortar often incorporating special waterproofing admixtures. These admixtures are commonly impregnated with one or more additives, such as polymer, silica fume, fly ash or some other industrial by-products.

Polymer modified cement repair materials are used to overcome the problems associated with the cement-based repair materials, particularly the need for a longer curing period and enhanced shrinkage. Over the years, many polymers have been used in a range of applications in the repair and maintenance of buildings and other structures. Such polymer mortars provide the same alkaline passivation protection to the reinforcing steel, as do conventional cement materials. Polymers are usually used as admixtures; they are supplied as milky white dispersions in water and in that state are used either as a whole or as a partial replacement of the mixing water. The polymer also serves as a water-reducing plasticizer that produces a mortar with a good workability and lower shrinkage at lower water-to-cement ratios. Polyvinyl acetates (PVA), styrene butadine rubber (SBR) and polyvinyl dichlorides (PVDC) are some of the polymers commonly used in the cement mortars. A recent development in the field of polymers are redispersible spray-dried polymer powders, which may be factory blended with graded sand, cement, and other additives to produce mortars and bonding coats simply by adding water on site.

For the repair to be successful there should be compatibility between the repair material and the base concrete. Physical and chemical compatibility are some of the criteria considered in the selection of a repair material.

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During the initial stage of casting a repair layer over a hardened concrete substrate, stresses resulting from restrained shrinkage cause tensile cracking through the repair layer or delamination at the interface of the repair layer and the substrate or both. Loss of integrity in the early stages in the repair systems is primarily due to stresses resulting from restrained shrinkage.

Dehwah et al. [1994] and Basunbul et al. [1994] examined the durability performance of some cement and epoxy-based repair materials by measuring the water and chloride permeability and resistance to reinforcement corrosion. The results indicated that the water permeability in all repair materials was less than that in the non-repaired concrete. However, the permeability increased significantly in all the specimens when they were subjected to thermal variations.

The study reported in this paper was conducted to evaluate the mechanical properties and durability characteristics of cement- and polymer-based repair mortars.

2. TEST PROCEDURES

2.1. Selection Of Repair Materials

Seven proprietary repair materials were selected to represent the generic type of repair mortars presently utilized in the repair of deteriorated concrete structures. Three of the selected proprietary repair mortars (CB3, CB4 and CB5) were cement-based while the other four (PB1, PB2, PB3 and PB4) were polymer-based. In addition to proprietary repair mortars two cement-based repair mortars (CB1 and CB2) prepared in the laboratory were also evaluated. Table 1 summarizes the composition of the repair mortars evaluated in this study.

2.2. Mechanical Properties

The selected repair mortars were tested to evaluate the following mechanical properties:

i) Compressive strength, according to ASTM C 109,
ii) Tensile strength, according to BS 6319,
iii) Elastic modulus, according to BS 6319,
iv) Drying shrinkage, according to ASTM C 157, and
v) Thermal expansion, according to ASTM C 531.

2.3. Durability Characteristics

The durability characteristics of the selected repair mortars were evaluated by measuring chloride permeability, electrical resistivity, and depth of carbonation. For this purpose, specimens of varying sizes were prepared and tested. Details of the test procedures are discussed in the following paragraphs.

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2.3.1 *Chloride permeability*

Cylindrical specimens measuring 75 mm in diameter and 50 mm high were prepared using the selected repair mortars and the chloride ion permeability was determined as per the procedure described in ASTM C 1202.

2.3.2 *Electrical resistivity*

Cylindrical specimens, 75 mm in diameter and 150 mm high were prepared using the selected repair mortars. The electrical resistivity was measured using a SG ABEM Terrameter SAS 330 C precision digital electrical resistance meter.

Since electrical resistivity is a function of the moisture content, resistance measurements were conducted after immersing the specimens in water for various time periods. These data were utilized to determine the relationship between moisture content and the electrical resistivity for each repair mortar.

2.3.3 *Carbonation*

The carbonation-resistance of the repair mortars was determined using a non-standard test method. For this purpose, cylindrical specimens, 50 mm in diameter and 72 mm high, were prepared. They were then exposed to an accelerated carbonation environment (6% CO_2, Temperature 55 °C, and 70% RH) in a purpose built chamber. These specimens were retrieved from the exposure chamber after 2, 4, 6, and 12 months of exposure and cut at mid height to obtain two freshly broken surfaces. Phenolphthalein was sprayed on these surfaces, and the depth of carbonation measured at 12 locations equally spaced on each surface. The average of 24 measurements was noted as the depth of carbonation.

3. RESULTS

3.1. Mechanical Properties

Table 2 shows the compressive strength, tensile strength and modulus of elasticity of selected polymer- and cement-based repair mortars. As expected, the compressive strength of specimens prepared with selected polymer- and cement-based repair mortars increased with the age of curing. After 28 days of curing, the highest compressive strength was measured in the specimens prepared with CB3. The compressive strength of CB3, CB4, and PB4 was more than 50 MPa, while the compressive strength of specimens prepared with PB3 and PB1 was in the range of 19 to 24 MPa. The compressive strength of specimens prepared with other proprietary repair mortars, Portland cement, and silica fume cement was around 45 MPa.

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The tensile strength values were in the range of 2.5 to 6.5 MPa, the maximum value being measured in the specimens prepared with PB4 and the lowest value being recorded in the specimens prepared with PB3.

The modulus of elasticity of the selected polymer- and cement-based repair mortar specimens was in the range of 25.8 to 32.6 GPa. An exception to this trend was noted in the specimens prepared with PB3, which exhibited a value of 11.3 GPa after 28 days of curing.

The coefficient of thermal expansion of the selected polymer- and cement-based repair mortar specimens is summarized in Table 3. These values were in the range of 7.99 to 10.84×10^{-6}/°C.

The drying shrinkage of the cement-based repair mortars is depicted in Figure 1. The drying shrinkage strains increased with time in all the cement-based repair mortars, increasing more rapidly at the earlier stages and slowly later. The drying shrinkage strain in the non-proprietary cement-based repair mortars (CB1 and CB2) was lower than that in the proprietary cement-based repair mortars, particularly CB3 and CB4. As shown in Figure 2, the drying shrinkage strain in the polymer-based repair mortars also increased with time. Further, the ultimate drying shrinkage strain in the proprietary cement-based repair mortars, particularly CB3 and CB4, was more than that in most of the polymer-based repair mortars. The lower drying shrinkage in the polymer-based repair mortars compared to the cement-based repair mortars may be attributed to the addition of shrinkage compensating admixtures in the former.

The risk of cracking of a repair material, based on the assumption of a rigid concrete substrate, is defined as $\varepsilon_{sh}E/f_t$, where f_t is the tensile strength, E is the modulus of elasticity, and ε_{sh} is the drying shrinkage. In this relationship, the ratio E/f_t is extremely important with the lowest values being more preferable. Table 4 compares the E/f_t values of selected polymer- and cement-based repair mortar specimens after 7 and 28 days. The comparison between the proprietary polymer and cement-based repair mortars indicates that PB3 has the lowest E/f_t, while this value is the highest in CB1 repair mortar. The low E/f_t noted in PB3 may be attributed to the presence of polymers in this repair material. It should be stated that most polymers increase the tensile strength whilst moderately influencing the ductility – thus the frequent use of polymer modified cement mortars. It is not surprising that the three materials with E/f_t on the lower scale are all polymer-modified mortars. Further, the two non-proprietary cement-based repair mortars (CB1 and CB2) exhibit higher risk of cracking compared to the other cement- and polymer-based proprietary repair materials.

Table 4 also shows the risk of cracking after 7 and 28 days. The risk of cracking varies from 1.5 to 4.1 after 7 days, and 4.1 to 5.4 after 28 days. The higher risk of cracking after 28 days, compared to that at 7 days, indicates that unless there is a substantial relief of tensile strain, by creep mechanism, the risk of cracking increases with the age. This may well explain why drying shrinkage cracking is commonly noticed in structures after 7 days of exposure.

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3.2. Durability Characteristics

3.2.1 *Chloride permeability*

The chloride permeability of the selected polymer- and cement-based repair mortars is summarized in Table 5. This table also provides the chloride permeability classification according to ASTM C 1202. Chloride permeability of the selected polymer- and cement-based repair mortars was in the range of 158 to 1368 Coulombs and is therefore classified as very low-to-low, as per ASTM C 1202 criterion. The results show that there is no clear difference between the cement-based and polymer-based repair mortars with regard to the chloride permeability. Since the chloride permeability indirectly provides an indication of the electrical resistivity of concrete, these data indicate that both the cement- and polymer-based repair mortars would be effective in reducing reinforcement corrosion.

3.2.2 *Electrical resistivity*

The electrical resistivity of concrete or mortar is a major factor affecting the corrosion process of embedded steel reinforcement. The electrical resistivity depends on the moisture content in the concrete or mortar. To evaluate this effect the mortar specimens prepared with polymer- and cement-based repair mortars were immersed in a water bath and retrieved at varying time periods, and their weight and electrical resistivity were measured after surface drying them. This has resulted in generation of data depicting the relationship between moisture content and electrical resistivity of all the selected materials.

The variation of the electrical resistivity with moisture content of the selected cement- and polymer-based repair mortars are depicted in Figs. 3 and 4, respectively. The electrical resistivity of the cement-based repair mortars decreased with the increase in moisture content, as shown in Fig. 3. With the exception of CB5, all the cement-based repair mortars have similar electrical resistivity, particularly at higher moisture content. The higher electrical resistivity noted in CB5 compared to the other cement-based repair mortars, indicates the significance of the type and quantity of admixtures in the repair mortars. Most of the available cement-based repair mortars contain admixtures, such as water reducing and shrinkage compensating agents. Another observation is the variation in the amount of moisture each material can take. The repair mortar CB5 showed the ability to absorb more than 9% water compared to less than 6% by the other cement-based repair mortars.

The data in Figure 4 show that the electrical resistivity values of the polymer-based repair mortars, with the exception of PB1, decrease with an increase in the quantity of water. Further, the electrical resistivity of polymer-based repair mortars is higher than that of cement-based repair mortars. Electrical reisistivity of polymer-based repair mortars also show large variation. The electrical resistivity of PB1 is more than five times that of the other three polymer-based repair materials. This may be attributed to the type and amount of polymer material used in the repair mortar. Similarly, the amount of water each material can absorb varies substantially. This was evidenced by the lowest and largest water absorption shown by PB1 and PB3 where the maximum water absorption values were 2.3 and 8.6 %, respectively.

3.2.3 *Carbonation*

The variation of carbonation depth in the selected cement- and polymer-based repair mortars with the period of exposure is depicted in Figs. 5 and 6, respectively. As expected the depth of carbonation increased with the exposure period for all the tested repair mortars. As shown in Fig. 5, the in-house prepared repair mortars (CB1 and CB2) showed almost constant rate of carbonation during the 6-month exposure period, and increased by almost three times afterwards. Also the in-house prepared repair mortars showed the smallest depth of carbonation in the first six months of exposure among the cement-based repair mortars. The rate of carbonation of the other three cement-based proprietary repair mortars CB3, CB4, and CB5 decreased substantially after 6 months of exposure. After 12 months of exposure, the best and worst performance in terms of carbonation was exhibited by CB3 and CB5, respectively.

Carbonation to full depth, i.e., 25 mm was noted in the specimens prepared with PB1 and PB3 after 2 and 4 months of exposure, respectively, as depicted in Fig. 6. PB2 and PB4 showed much better resistance to carbonation than PB1 and PB3. These results suggest the role of polymer type on the carbonation resistance of repair mortars.

After twelve months of exposure to CO_2 environment, the depth of carbonation in the selected cement- and polymer-based repair mortars, except PB1 and PB3, was in the range of 4.9 to 11.8 mm. The low carbonation in some of the tested repair mortars may be attributed to the dense structure of these specimens, presumably due to the addition of silica fume, fibers and/or other additives.

4. DISCUSSION

Over the years, several types of cement- and polymer-based repair mortars have been developed and used in repair and rehabilitation of different concrete structures. These repair mortars have wide variations in physical as well as durability properties. Although these repair materials have adequate and some times high strength, they may develop premature deterioration problems when used in hot or harsh environments. This is attributed to incompatibility in properties between the repair mortar and the substrate concrete of the repaired structure. Such properties like drying shrinkage strain and thermal expansion may cause tensile cracking through the repair layer and/or delamination at the interface between the repair layer and the substrate.

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4.1. Mechanical Properties

The data developed in this study have shown a wide variation in the mechanical properties of the selected cement- and polymer-based repair materials. Further, the variation in the properties was noted within materials of similar generic type. However, it should be noted that the mechanical properties of the selected repair materials were within the acceptable range.

No clear distinction could be established between the cement- and polymer-based repair mortars with regard to the compressive, tensile and flexural strength, drying shrinkage and coefficient of thermal expansion. The elastic modulus of the polymer-based repair mortars was, however, less than that of cement-based repair mortars. This indicates that these materials tend to be more ductile than the cement-based repair mortars. This could be attributed to the addition of polymers and/or fibers. The lower elastic modulus also results in a lower risk of cracking due to drying shrinkage.

4.2. Durability Characteristics

The data generated in this study indicate the possibility of having large variation in some of the durability related properties of different pre-packed cement- and polymer-based repair mortars, due to the vast differences in their composition. This raises the important issue of the compatibility between the repair materials and the existing substrate concrete of repaired structure.

The chloride permeability of the selected repair materials was very low to low as per ASTM C1202 classification. This indicates that to start with the evaluated repair mortars may provide adequate resistance to chloride penetration required for protection against reinforcement corrosion if the repair mortars are adequately mixed and placed.

A wide variation in the electrical resistivity was noted between the selected repair mortars. More importantly, the tested repair mortars showed different levels of absorption ability that dictates the electrical resistivity value. Therefore, a repair mortar with high electrical resistivity may isolate the repaired portion of the concrete structure from the undamaged areas, thereby providing an efficient protection to the steel in the repaired area.

Carbonation in some repair mortars, such as PB1 and PB3 was surprisingly very rapid compared to the other repair mortars. This indicates that when such materials are used as repair mortar the chances of carbonation related reinforcement corrosion are very high. The data developed in this study indicate the need to obtain information on the durability indices, such as those developed in this study, to ascertain the suitability of the repair materials for the exposure conditions.

5. CONCLUSIONS

The following are the main conclusions that can be drawn from the tests conducted to evaluate the mechanical properties and durability characteristics of selected cement- and polymer-based repair mortars:

- No clear distinction was noted between the mechanical properties of the cement- and polymer-based repair mortars.
- There was no clear difference between the cement-based and polymer-based repair mortars with regard to the chloride permeability. The chloride permeability of the selected repair mortars was very low to low, as per ASTM C 1202 criterion.
- The electrical resistivity of the polymer-based repair mortars, with the exception of PB4, was higher than those of the cement-based repair mortars. Large differences in electrical resistivity values were observed between the polymer-based repair mortars compared to the cement-based repair mortars. The electrical resistivity of PB1 was more than five times that of the other two polymer-based repair mortars.
- The specimens prepared using polymer-based repair mortars PB1 and PB3 were fully carbonated (25 mm) after only 2 and 4 months of exposure, respectively. After twelve months of exposure to CO_2 environment, the depth of carbonation in the selected cement- and polymer-based repair mortars, except PB1 and PB3, was in the range of 4.9 to 11.8 mm. The low carbonation in some of the tested repair mortars may be attributed to the dense structure of these specimens, presumably due to the addition of silica fume, fibers and/or other additives.
- The risk of cracking, electrical resistivity and enhanced carbonation appear to be the criteria that differentiates between the performance of the repair mortars. Therefore, it is necessary to request for information on tensile strength, drying shrinkage and elastic modulus from strength point of view and electrical resistivity and carbonation from the durability perspective.

Based on the data developed in this study, the following criteria for the selection of polymer- and cement-based repair materials for hot conditions are suggested:

Property	Performance criteria
Compressive strength	Min. 40 MPa after 28 days
Tensile strength	Min. 3 MPa after 28 days
Modulus of elasticity in compression	20 GPa after 28 days
Coefficient of thermal expansion	8 to 10 X 10^{-6} / °C
Shrinkage measure at 25 °C (ASTM C 157)	Max 500 μ after 7 days
Chloride permeability (ASTM C 1202)	Low (1000 to 2000 Coulombs)
Elecrical resistivity	More than 200 Ohm·m in saturated surface dry condition.

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Table 1. Selected cement- and polymer-based repair mortars

Repair mortar	Description
CB1*	Portland cement mortar (w/c: 0.38, sand/cement 2.5).
CB2*	Portland cement silica fume mortar (w/c: 0.38, sand/cement 2.5, silica fume 5% of total cement).
CB3	Pre-packed blend of Portland cement, fine aggregate, fillers, and additives.
CB4	Pre-packed blend of Portland cement, fine aggregate, and additives.
CB5	One component cement-based repair mortar.
PB1	Consists of Portland cement, sand, and acrylic latex admixture.
PB2	Consists of Portland cement, silica fume, fibers, and polymer.
PB3	Pre-packed blend of cement, silica fume, and polymer.
PB4	Single component polymer based-repair mortar. based on Portland cement, graded aggregate, special fillers, and chemical additives.

* prepared in-house.

Table 2. Mechanical properties of polymer- and cement-based repair mortar specimens

Repair mortar	Compressive strength MPa		Tensile strength MPa		Modulus of elasticity GPa	
	7 days	28 days	7 days	28 days	7 days	28 days
CB1	45.4	45.8	2.1	3.1	20.8	26.8
CB2	40.3	44.2	2.7	3.7	23.6	29.7
CB3	44.4	71.9	4.1	4.8	23.7	28.8
CB4	42.9	50.1	3.4	5.4	26.0	32.6
CB5	36.3	44.7	2.5	3.7	22.0	25.8
PB1	9.5	19.3	2.3	3.8	ND*	ND*
PB2	34.7	45.8	2.3	3.8	22.0	26.0
PB3	16.6	24.1	1.8	2.5	8.8	11.3
PB4	43.2	60.4	4.6	6.5	24.3	30.5

* ND: Not determined

Table 3. Coefficient of thermal expansion of polymer- and cementious-based repair mortar specimens

Repair mortar	Coefficient of thermal expansion, x10^{-6}/°C

* ND: Not determined

Table 4. Risk of cracking in polymer- and cement-based repair mortars

Repair mortar	E/f_t x 10^3		Risk of cracking in the specimens exposed at 25 °C	
	7 days	28 days	After 7 days	After 28 days
CB1	9.72	8.49	3.8	ND*
CB2	8.88	8.07	3.6	5.4
CB3	5.78	6.05	3.9	ND*
CB4	7.69	6.06	3.1	4.1
CB5	8.73	6.94	2.9	4.4
PB1	ND*	ND*	ND*	ND*
PB2	8.4	6.81	4.1	ND*
PB3	4.78	4.54	1.5	4.1
PB4	5.28	4.70	3.2	4.2

* ND: Not determined

Table 5. Chloride permeability of cement- and polymer-based repair mortar specimens

Repair mortar	Chloride permeability, Coulombs	ASTM C 1202 classification

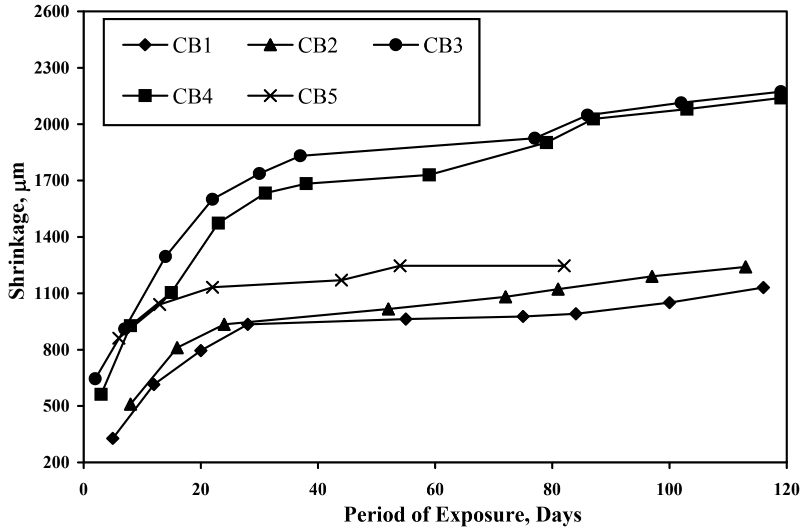

Fig. 1. Drying shrinkage in cement-based repair mortars.

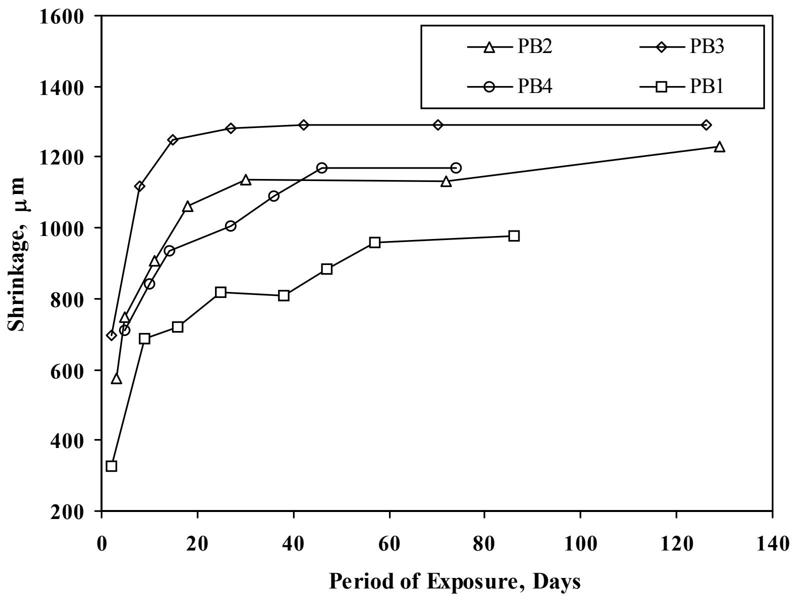

Fig. 2. Drying shrinkage in polymer-based repair mortars.

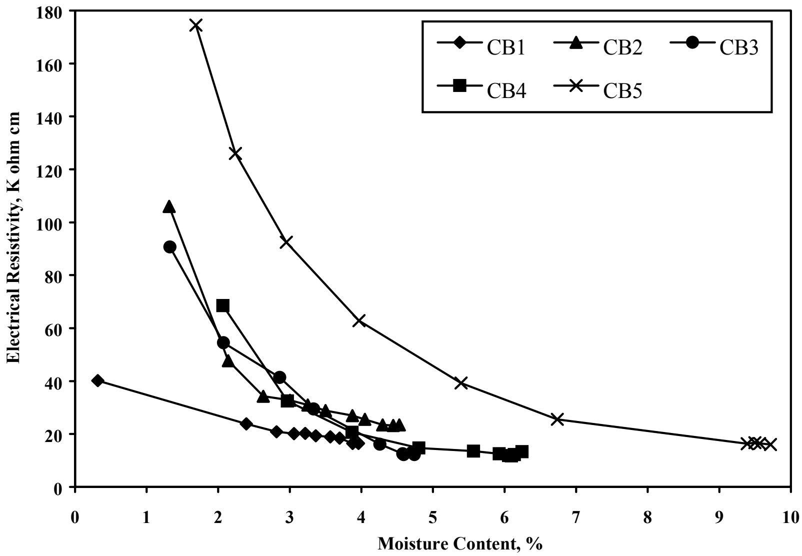

Fig. 3. Variation of electrical resistivity with moisture content in cement-based repair mortars.

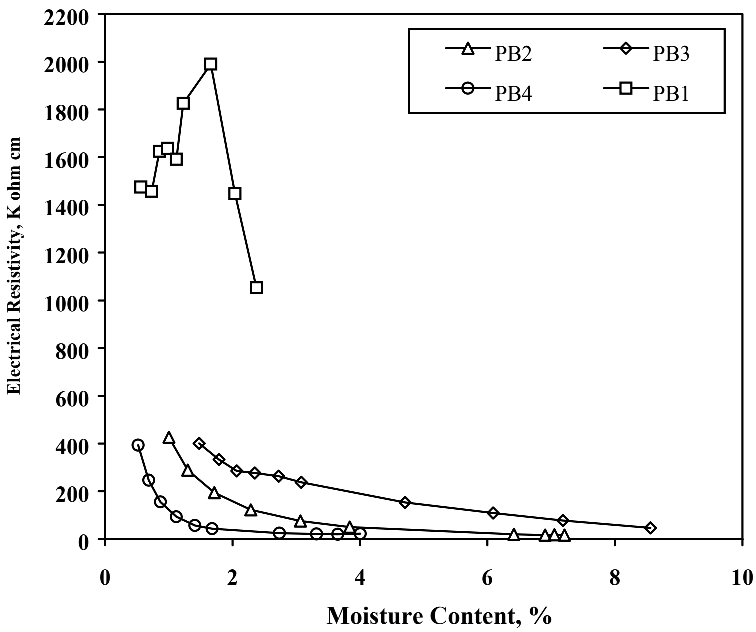

Fig. 4. Variation of electrical resistivity with moisture content in polymer-based repair mortars.

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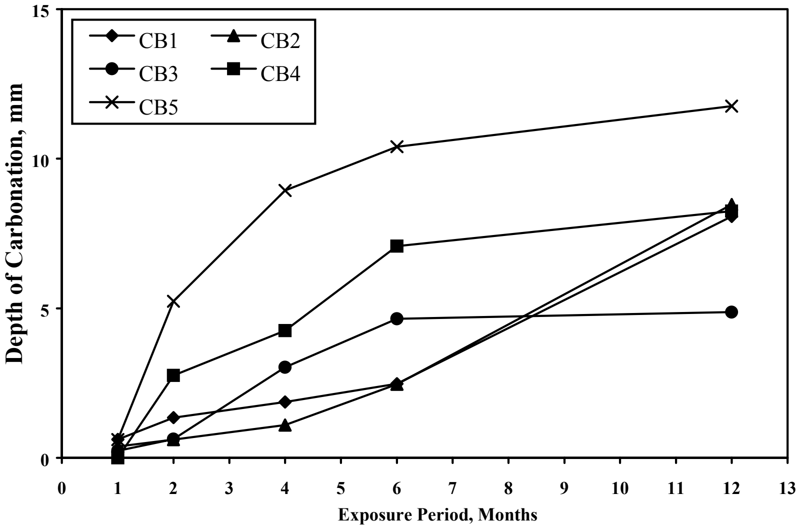

Fig. 5. Variation of carbonation depth with exposure period in cement-based repair mortars.

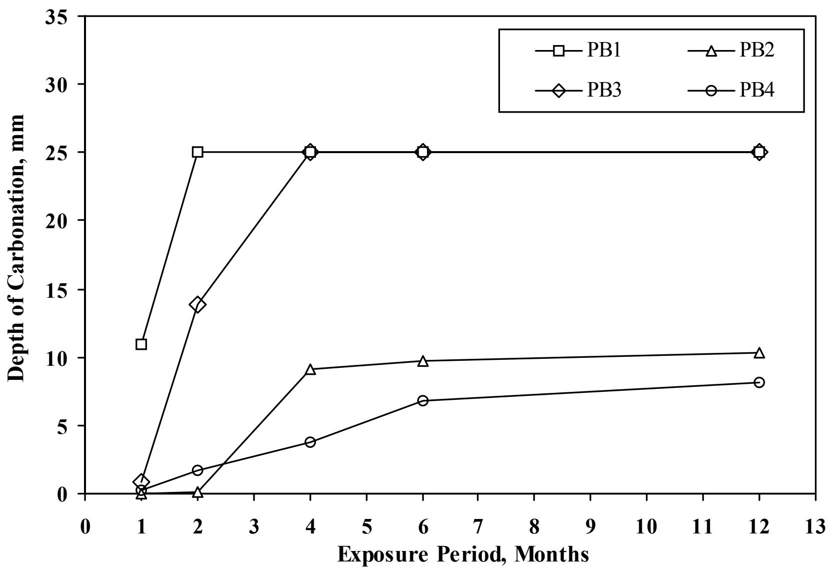

Fig. 6. Variation of carbonation depth with exposure period in polymer-based repair mortars.