J. King Saud Univ., Vol. 19, *Eng. Sci.* (2), pp. 175-194, Riyadh (1427H./2007)

Experimental Evaluation of Drying Shrinkage and Mechanical Properties of Repair Materials for Concrete Structures

Tarek H. Almusallam
Civil Engineering Department,
College of Engineering, King Saud University,
P.O. Box 800, Riyadh 11421, Saudi Arabia

(Received 12 November 2005; accepted for publication 07 November 2006)

Abstract. The potentially aggressive environments in some parts of Saudi Arabia have resulted in premature deterioration of many concrete structures during their service performance life. To achieve more effective and long lasting repair materials, it is essential that the properties of the repair materials and the substrate are compatible. This study aims at evaluating the mechanical properties of selected classes of repair materials that are commonly used in repair application within the Kingdom. A total of 114 specimens were cast to investigate some of the important properties of nine widely used local repair materials available in the market. The properties evaluated in this study are: drying shrinkage, compressive strength and modulus of elasticity. Out of each of the selected repair materials, six specimens for shrinkage and six specimens for compressive strength and modulus of elasticity measurements were considered in the study. Additional specimens made from cement paste were used as control samples for the study. Results of the present study show that all repair materials must be checked experimentally to confirm the properties given by the supplier before their use in any field application. The study also recommends that the selection of suitable repair material should be based on the type of application, as application changes properties requirement changes. For example, for one application compressive strength requirement may be more critical, while in another application shrinkage may be of great concern.

Keywords: Repairing materials, Cementitious, Drying shrinkage, Compressive strength, Modulus of elasticity.

Introduction

The major part of construction in the Kingdom of Saudi Arabia is concrete structures. Most of the structures were built in the absence of adequate supervision and quality control with unskilled labor under severe environmental conditions. Therefore, most of these constructions were deteriorated and needed repairs in order to increase their service life. Millions of riyals are currently being spent every year in removing and replacing deteriorated concrete. A wide variety of repair materials are available for engineers to repair the deteriorated structures. These materials are available in the local market and can mainly be categorized into three groups: cementitious mortars, polymer modified cementitious mortars, and resinous mortars

The repair of distressed or deteriorated concrete structures is an important civil engineering problem, and an efficient and a long lasting repair system is the solution. It is impossible to design and predict the future performance of a concrete system (composite material) without knowing the behavior of its constituents. The same applies to the repair system. The properties and durability of such a system are governed by the properties of the three phases: repair, existing substrate, and the interface between them. Generally, it can be said that a repaired structure is durable, that is, it will safely perform the intended use during its expected design life, when the aging of the repaired phase proportional to the aging of the existing phase of the structure is achieved. Therefore, effective and durable repairs can be realized only when a detailed diagnosis of the causes of deterioration has been made and given full consideration in the selection of materials that are both suitable for the particular environment and service conditions, and compatible with the intended substrates.

Cementitious mortars mostly consist of a conventional cement mortar often combined with special admixtures such as polymer, silica fume, fly ash or some other industrial by-products. The main advantage of cementitious materials over other types include: compatibility with cement, ease of mixing, good adhesion, quick-self curing, resistance to gas and liquid penetration, easy availability and low cost. Therefore, cementitious materials are the most widely used among other repair materials.

Concrete repair industry has witnessed an enormous growth in the Kingdom of Saudi Arabia. To the user, difficulty arises due to the lack of professionally accepted performance criteria guidelines for commercially available repair materials. The data sheets of repair materials are, in general, always reporting favorable performance by their manufacturer, and, therefore, need to be checked against the reported physical and mechanical properties. Limited research is carried out on the actual performance of various repair materials and their compatibility with the deteriorated concrete.

The purpose of this study is to investigate some of the important properties of most commonly used cementitious concrete repair materials from three main suppliers. These properties include: drying shrinkage, compressive strength, and modulus of elasticity of the selected repair materials. The results of this study provide a certain level of confidence for the engineers when using these repair materials.

Previous Studies

Over the past years, the number of researchers investigating the properties of repair materials has increased considerably. Some of the engineering properties of repair materials can be found in the literature [1-3] and in data sheets furnished by the manufacturers. However, very little is known about their performance in actual applications. The selection of the repair materials and repair execution must be evaluated in the light of the in-service conditions. Some systematic rules and guidelines need to be set for using the repair materials such that the properties of the repair materials and methods of their selection are clearly identified. Rules and guidelines can only be prepared after conducting some extensive laboratory and field tests. Several countries have already specified some performance criteria and guidelines for selecting the repair materials [4]. Table 1 shows typical values for some important properties of the three groups of repair materials [5]. For a given mechanical property, a large difference in the values for the three different groups of repair materials can be observed.

The guidelines [6] limits on some engineering characteristics such as bond strength, drying shrinkage are significantly influenced by the environmental and site conditions, modulus of elasticity, compressive strength and tensile strength.

Table 1. Typical mechanical properties of repair materials [5]

Mechanical Properties	Cementitious Mortars	Polymer-Modified Cementitious Mortars	Resinous Mortars
Compressive Strength (MPa)	20 – 50	30 – 60	50 – 100
Tensile Strength (MPa)	2 – 5	5 – 10	10 – 15
Elastic modulus in compression (GPa)	20 – 30	15 – 25	10 – 20
Coef. of thermal expansion ($°C^{-1}$ x 10^{-6})	6 – 10	10 – 20	25 – 30
Water absorption (percent by weight)	5 – 15	0.1 – 0.5	1 – 2
Maximum service temperature (°C)	> 300	100 – 300	40 – 80

The repair materials generally should have a compressive strength at least to that of existing concrete substrate. Emmons *et al*. [6] reported that no significant correlation exists between compressive strength and dimensional stability of the field repairs, which means a requirement for compressive strength is not included in the performance criteria for non-structural repair.

The modulus of elasticity of a repair material should be similar to that of the concrete substrate to achieve uniform load transfer across the repaired section. The difference in the modulus of elasticity of the substrate concrete and repair material causes cracks [7]. When using repair material with a modulus of elasticity higher than that of concrete, the weaker point in the repaired section may be the bond line itself. Also, with vertical repair, the material with higher modulus will carry most of the load. That may result in stress concentration and as a consequence to a total failure of the repair system and probably to the whole structure [1].

Since the modulus of elasticity is considered as the rigidity of the repair materials; low modulus materials deform more than those of high modulus under a given load. When the external load is applied parallel to the bond line, materials with different elastic moduli will transfer stresses from the low modulus material to the high modulus material, leading to stress concentration, and failure of the high modulus material [8]. When the external load is applied perpendicular to the bond line, the difference in stiffness between both materials is less problematic if the external load is compressive. However, if the perpendicularly-applied external load is tensile, mismatching elastic moduli is likely to cause adhesion failure. Therefore, when selecting a repair material, designers should ensure that both substrate concrete and the repair material possess similar elastic moduli [9].

For repair materials, drying shrinkage value of zero percent is considered excellent. Nevertheless, some repair materials tend to expand as well as shrink. If the drying shrinkage of repair material is high, this means the relative movement between the substrate and the repair material is high which will affect the durability of the repair. Therefore, drying shrinkage (volume change) is one of the most vital parameter to be investigated. Arguably, the most frequently investigated repair material property is drying shrinkage, or more correctly, volume change, as some repair materials have a tendency to expand as well as shrink. Emmons *et al.* [7] reported that shrinkage in the repair material can affect the durability of the repair patch along with the load carrying capacity of the repair patch. Shrinkage cracking on the surface of a repair material greatly affects the appearance of the repair patch. When cracking occurs in a repair material, remedial works may be required to seal the cracks to restrict the ingress of chlorides and carbon dioxide to the steel reinforcement level. This occurred with some repair materials monitored in the field studies of the present investigation.

In cement-based materials, most of the shrinkage occurs when the cement paste dries out after setting and hardening. In resin-based materials, shrinkage is a result of cooling following the exothermic reaction, particularly for patches with a thickness exceeding 15 mm. When shrinkage is restrained, permanent tensile stresses develop in the repair material and may cause tensile cracking in the material itself, or delamination at the interface of the repair material and the substrate. Since most repair materials are applied to an older substrate concrete that has negligible shrinkage, the repair material which will begin to shrink soon after casting must have very low shrinkage potential [10].

Previous investigators [11] emphasized that drying shrinkage of repair materials is the major problem of concrete repair. This is so because of the role it plays in determining the durability of the repair system. Their study indicated that the shrinkage of the majority of the repair materials far exceeded the shrinkage strain value of a normal concrete (about 500 microstrain at 30 days). This indicated that repair products are not being designed to minimize shrinkage, despite the claim that the materials available commercially are non-expansive, non-shrinkage or shrinkage compensating. These studies indicate that a repair mortar or concrete which is durable leads to a durable concrete repair and failure of a concrete repair occurs due to the incompatibility between the repair layer and the concrete substrate, resulting due to essentially a high free shrinkage strain characteristics of the repair layer. Compressive strength for repair material is also an important property and high compressive strength materials are necessary for some applications; but for most applications, they are not only unnecessary but harmful. Most of the high strength is achieved with high cement contents. Consequently, these materials have a high drying shrinkage value, a higher modulus of elasticity, lower creep, produce more internal heat, and become more brittle. Repairs from these mixtures will have more cracking and will perform poorly.

Morgan [12] presented the results of shrinkage tests carried out on 46 different proprietary repair materials in Canada which were obtained using the ASTM C157 test method. Only one of those materials showed a slight expansion at 30 days. From this research, 15% of the materials showed less shrinkage value as compared to that of plain concrete, whilst 50% of the materials displayed twice the value of shrinkage. The UK Department of Transport's 1987/88 maintenance program [13] included the use of shrinkage-compensated flowable concretes on two concurrent trial repair contracts on the Midland Links Motorway viaducts. The repair materials were based on their specifications document, BD 27/86 [13]. With regards to the shrinkage of the repair materials, the *New Civil Engineer* [14] argues that these materials should show no sign of cracking after 56 days. This is a stringent requirement of a repair material. However, it is helped by the fact that most of the total shrinkage in a flowing repair material occurs in the first 24 hours when the degree of restraint is low.

Experimental Program

Material selection

The study in this paper consists of nine selected cementitious repair materials in addition to another cement paste material considered as a control (reference) material. The nine repair materials were selected from three major suppliers in the local market. The repair materials from the three suppliers were equivalent to each other. Thus, material one from supplier one is equivalent to material one from the other two suppliers and so on. The considered nine repair materials were selected from the main three different suppliers in the local market. These are:

1. Master Builders Technologies agent (MBT).
2. Sika supplier agent (SIKA).
3. Fosroc supplier agent (FOSROC).

The designations of all selected repair materials for this study are given in Table 2a. Table 2b provides description of each repair material and its intended use.

Table 2a. Selected materials from different suppliers

MBT	SIKA	FOSROC
EMACO S66T (E-66)	Sika Grout 114 (S-114)	Renderoc LA (F-LA)
EMACO S88CT (E-88)	Sika Mono Top 614 (S-614)	Renderoc HF (F-HF)
EMACO R101 (E-101)	Sika Mono Top 612 (S-612)	Renderoc S (F-S)

Table 2b. Description and intended use of each selected repair material

Repair Material	Description	Intended Use
EMACO S66T (E-66)	Shrinkage compensated, sulphate resistant repair cementitious mortar	General repair and renovation of decayed, defective or damaged concrete such as: Columns, walls, beams, honey combed concrete and floors.
EMACO S88CT (E-88)	Shrinkage compensated high strength repair mortar	All types of structural repair which can be applied by trowel or wet spray.
EMACO R101 (E-101)	Shrinkage compensating, low permeability, water proof	Repair of damaged, decayed, weak or debonded concrete.
Sika Grout 114 (S-114)	Non-shrinkable cement grout, non-corrosive, iron free material	suitable for grouting in the machine foundations, columns in pre-cast in construction, concrete anchors, cavities, gaps and recesses and base plates.
Sika Mono Top 614 (S-614)	Cementitious, silica fume containing, fiber reinforced, polymer modified one-component repair mortar. Pot life (50-60 mins at 25^0C)	For concrete repairs, especially for overhead and vertical applications, specially suitable for wet-spray method.
Sika Mono Top 612 (S-612)	Cementitious, silica fume containing, fiber reinforced, polymer modified one-component repair mortar. Pot life (40-60 mins at 25^0C)	For concrete repairs, especially for overhead and vertical applications, specially suitable for wet-spray method.
Renderoc LA (F-LA)	Single component free-flowing low alkali micro-concrete. Initial set (6.5 hrs @ 20^0C), final set(9 hrs @ 20^0C)	The highly fluid nature of the product makes it ideal for many smaller locations where difficulties of access make hand or trowel-applied mortars impractical.
Renderoc HF (F-HF)	High performance non-shrink cementitious micro concrete, initial set (5.5 hrs @ 20^0C), final set (7.5 hrs @ 20^0C)	For large volume repairs, particularly where access is restricted and where vibration of the placed material is difficult or impossible.
Renderoc S (F-S)	Single component structural grade polymer modified concrete reinstatement mortar, initial set 15 mins and final set 30 mins.	For the reinstatement of large areas of concrete and for small, localized patch repairs.

Method of Mixing and Casting

The method of mixing for all repair materials was the same throughout the study. The drum of the mixer was cleaned by means of spraying water while it was in motion. When the mixer stopped the standing water poured out by turning the drum upside down, the mixer was ready for an immediate cast. The temperatures of the material and water were noted down along with the laboratory temperature and humidity. Proper care was taken to control the temperature of water because some of the repair materials were required to be mixed with relatively cold water. Some materials had coarse aggregates. Prior to weighting, the material was collected in a wide plastic bucket and was mixed throughout and weighed as per the calculations.

The practice was to put 80% of the calculated water initially into the mixer and introduce the repair material. The mixing operation lasted for 5 to 8 minutes and the workability of the mix was then checked. If the mix, by inspection, showed a relatively good workability, it was poured out and the casting carried out. If the mix did not have good workability, more water was added into the mix from the remaining 20% water and the quantity added was noted down. The final material was collected in wheel-barrows and then moved to the casting area.

Table 3. Comparison of the recommended and used quantity of water

Designation of Material	Recommended Quantity of Water	Actual Quantity of Used Water
MBT (E-88)	4.0 liters per 25 kg bag	3.5 liters per 25 kg bag
MBT (E-101)	4.10 – 4.75 liters per 25 kg bag	4.75 liters per 25 kg bag
MBT (E-66)	3.5 liters per 25 kg bag	3.325 liters per 25 kg bag
SIKA (S-614)	3.5 liters per 25 kg bag	3.94 liters per 25 kg bag
SIKA (S-612)	3.25 liters per 25 kg bag	4.36 liters per 25 kg bag
SIKA (S-114)	4.0 – 4.2 liters per 40 kg bag	4.2 liters per 40 kg bag
FOSROC (F-LA)	4.0 liters per 30 kg bag	4.0 liters per 30 kg bag
FOSROC (F-HF)	4.3 – 4.5 liters per 25 kg bag	4.7 liters per 25 kg bag
FOSROC (F-S)	2.5 – 3.0 liters per 25 kg bag	3.0 liters per 25 kg bag

The shrinkage prisms were cast in a single layer by vibrating them on an external table vibrator for 15 seconds, for every mix. The cylinders for compressive strength were cast in two layers with a vibration of 20 seconds per layer. The specimens were tampered with a rubber mallet to remove any entrapped air. The surfaces were smoothed by a trowel and were covered by plastic sheet. All specimens were demolded after 22 ± 4 hours. The comparison of the rate of water recommended by the manufacturer and the actual used for all mixes are tabulated in the Table 3. For some of the mixes, the quantity of water was slightly modified in order to achieve appropriate workability. However, this deviation is insignificant and well expected due to the change of working environment.

Specimen Details and Measurements

The experimental program was designed as follows:

1) Drying shrinkage specimens

For measuring the drying shrinkage, each of the selected repair materials was mixed according to the manufacturers specifications and six prisms of dimensions (50 × 50 × 285 mm) were cast. Three specimens were kept in the lab under the temperature of 23 ± 2°C and relative humidity of about 30% and the other three specimens were kept outside the laboratory to represent the actual conditions of Riyadh City. Table 4 shows the average monthly temperature and relative humidity of Riyadh around the year. Control specimens of cement paste were cast using Type I Portland cement and kept in similar conditions as repaired specimens.

Table 4. Average Riyadh monthly dry bulb temperature (DBT) and relative humidity (RH) around the year

Month	DBT Min °C	DBT Max °C	RH Mean %
Jan.	8.79	19.58	57.22
Feb.	11.40	22.04	46.74
March	13.86	24.49	47.23
Apr.	18.28	29.93	39.28
May	23.98	37.53	17.21
June	26.35	40.30	11.30
July	28.09	41.28	11.21
Aug.	27.52	41.93	11.50
Sep.	23.28	38.04	14.79
Oct.	19.44	33.65	20.98
Nov.	13.17	25.37	35.41
Dec.	10.21	19.80	62.05

After demolding (22 ± 4 hours) all specimens were properly designated and immersed in lime saturated water having a temperature of nearly 23 ± 2°C. Then the specimens were taken out, one by one, after 30-60 minutes of immersion. They were tested for "initial comparator dial gauge reading" in the saturated surface dry condition. This condition was achieved by using a dry cloth on the surface of the wet prisms. After noting down the initial readings, the specimens were transferred to their designed storage and curing conditions. The intervals for the readings were recorded after demolding and immersion in water for one hour (1^{st} reading; initial reading was recorded). Then two readings per day were taken for the following 14 days followed by one reading per day for the next 14 days and then continued as one reading per week for the next 400 days. 400 days were selected for the study in order to cover a full year environmental conditions.

2) Compressive strength and modulus of elasticity specimens

Six cylindrical specimens from each repair material were prepared for compressive strength testing. The dimensions of specimens were 100×200 mm. All specimens were cured with intermittent water spraying. Three of the specimens were tested, according to ASTM [15], after 7 days of water spraying and the other three were tested at the age of 28 days. Elastic modulus was obtained from the stress-strain behavior of all tested cylinders under compression. The failure pattern of all the tested cylinders showed cohesive type of failure. Figure 1 shows the typical failure pattern of some of the tested cylinders. Similar failure patterns were observed for other specimens too. Due to the space limitation, however, photos of all the failed specimens are not shown in this paper.

Fig. 1. Typical failure cracking pattern of some of the tested cylinders.

Test Results and Discussions

Shrinkage strain results for all repair materials

The comparison between all shrinkage strain values for all materials subjected to lab and outside atmosphere exposure, up to the age of 400 days are shown in Figs. 2 to 11. For specimens cured inside the lab at room temperature (23 ± 2°C + 30% RH), the materials SIKA (S-614, S-612) and MBT (E-101) showed the highest shrinkage strain of about 2000-2600 microns. The second highest shrinkage specimens were FOSROC (F-HF), MBT (E-88 and E-66) with strain values of 1400-1800 microns, followed by FOSROC (F-LA and F-S) with 1000-1100 microns. Whereas, the material SIKA-114 showed the lowest shrinkage of 680 microns. The shrinkage strains for the control specimens for the same period was about 800 microns (inside the lab). For the specimens subjected to outside exposure, the highest shrinkage values were recorded for SIKA (S-

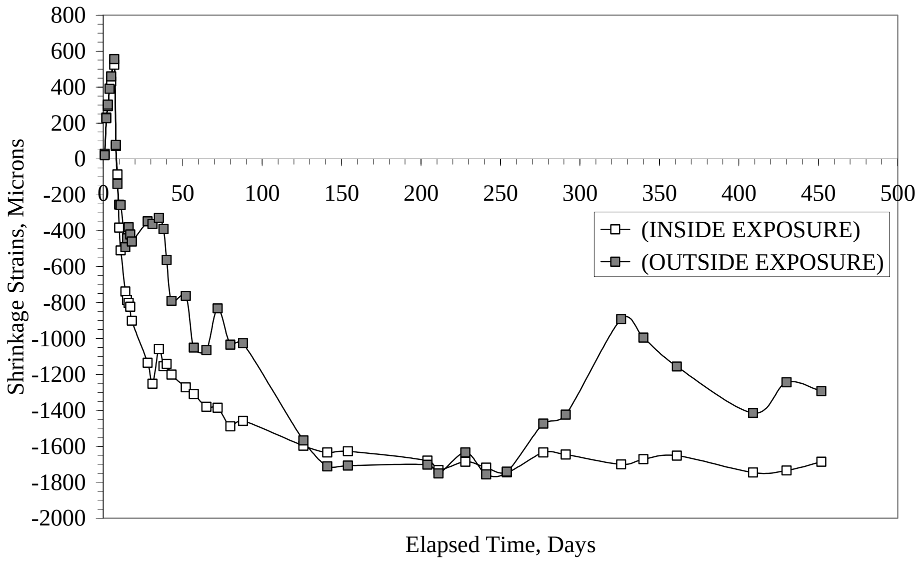

Fig. 2. Comparison of shrinkage strains of prisms prepared from MBT (EMACO- S88CT) for inside (23 ± 2°C and 30% RH) and outside exposure.

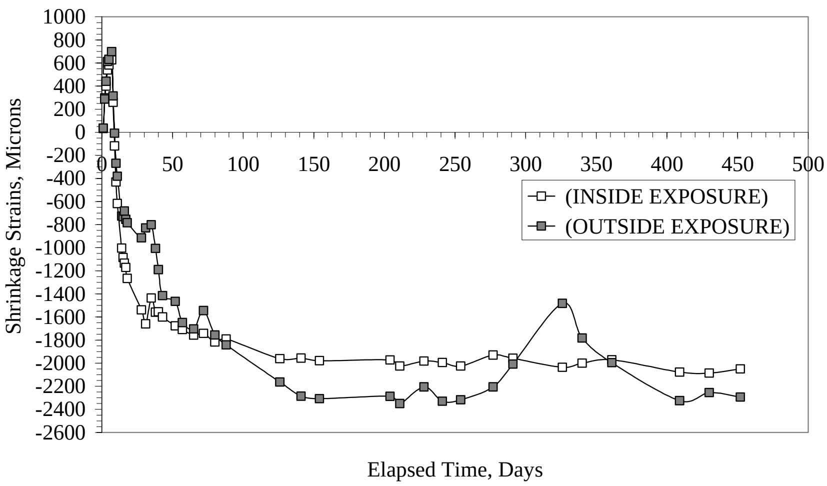

Fig. 3. Comparison of shrinkage strains of prisms from MBT (EMACO-R101) for inside (23 ± 2°C and 30% RH) and outside exposure.

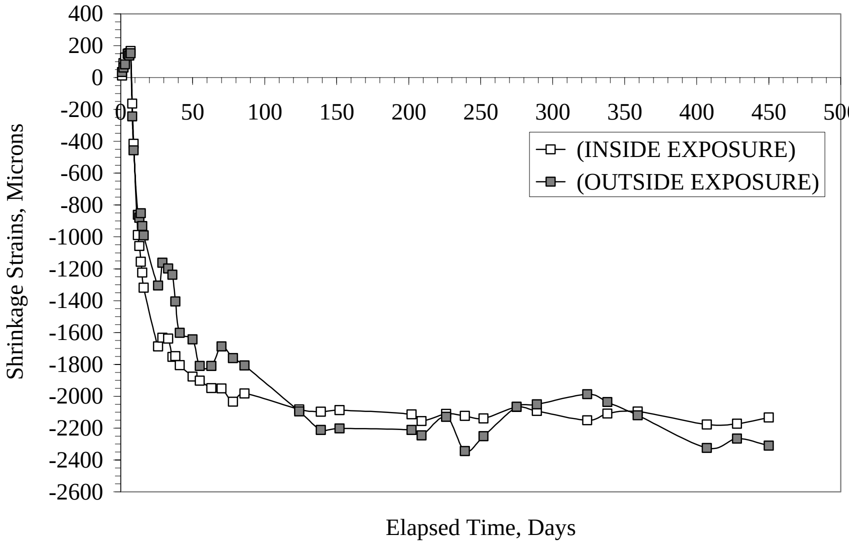

Fig. 4. Comparison of shrinkage strains of prisms from SIKA (614) for inside (23 ± 2°C and 30% RH) and outside exposure.

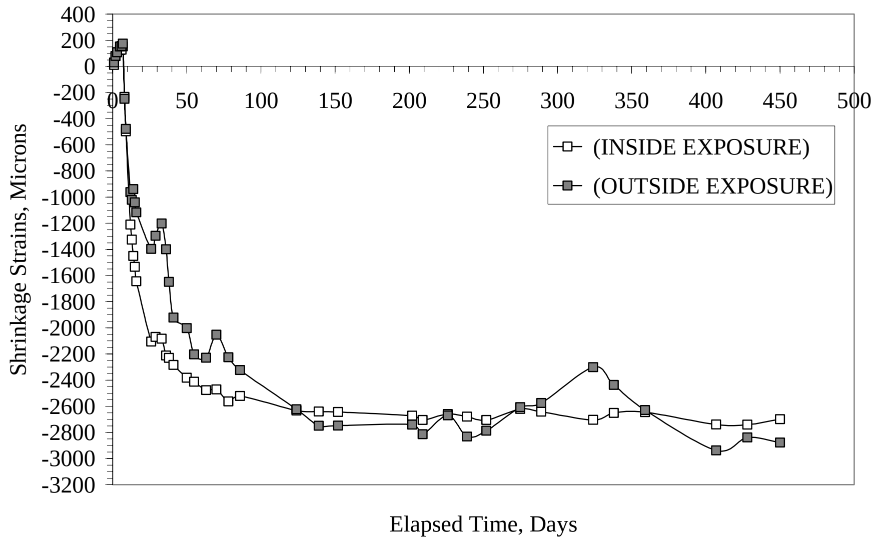

Fig. 5. Comparison of shrinkage strains of prisms from SIKA (612) for inside (23 ± 2°C and 30% RH) and outside exposure.

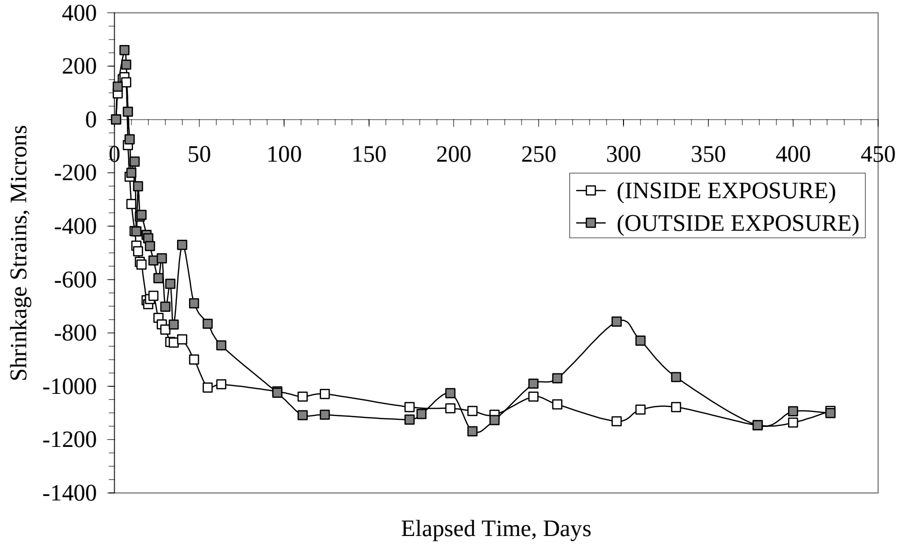

Fig. 6. Comparison of shrinkage strains of prisms from FOSROC (RENDEROC-S) for inside (23 ± 2°C and 30% RH) and outside exposure.

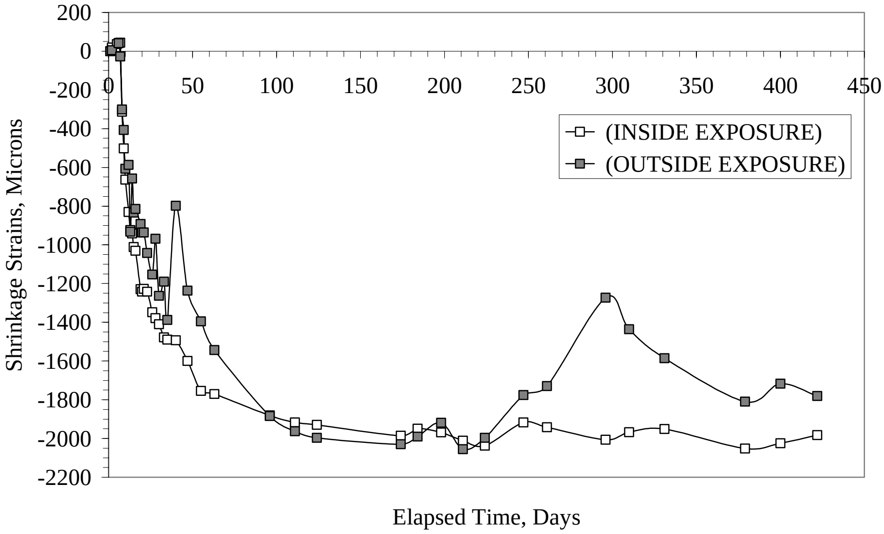

Fig. 7. Comparison of shrinkage strains of prisms from FOSROC (RENDEROC-HF) for inside (23 ± 2°C and 30% RH) and outside exposure.

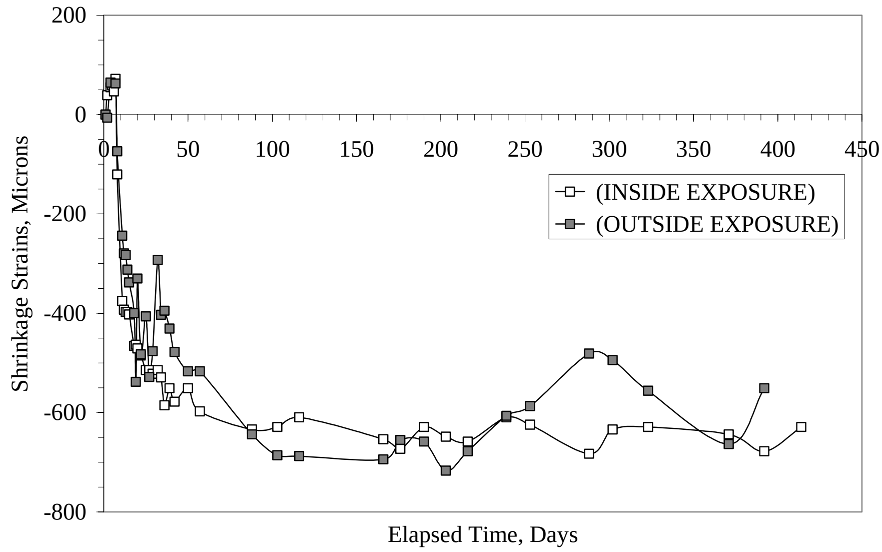

Fig. 8. Comparison of shrinkage strains of prisms from SIKA (114) for inside (23 ± 2°C and 30% RH) and outside exposure.

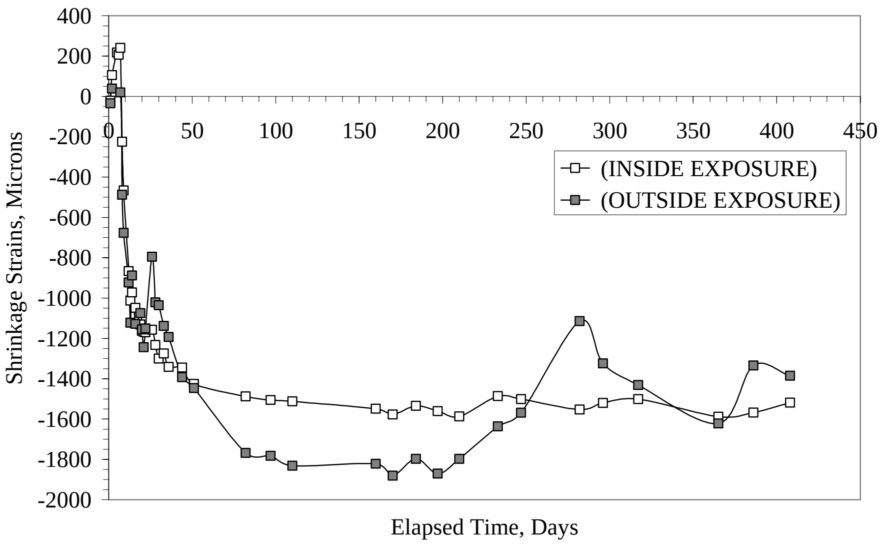

Fig. 9. Comparison of shrinkage strains of prisms from MBT(EMACO S66T) for inside (23 ± 2°C and 30% RH) and outside exposure.

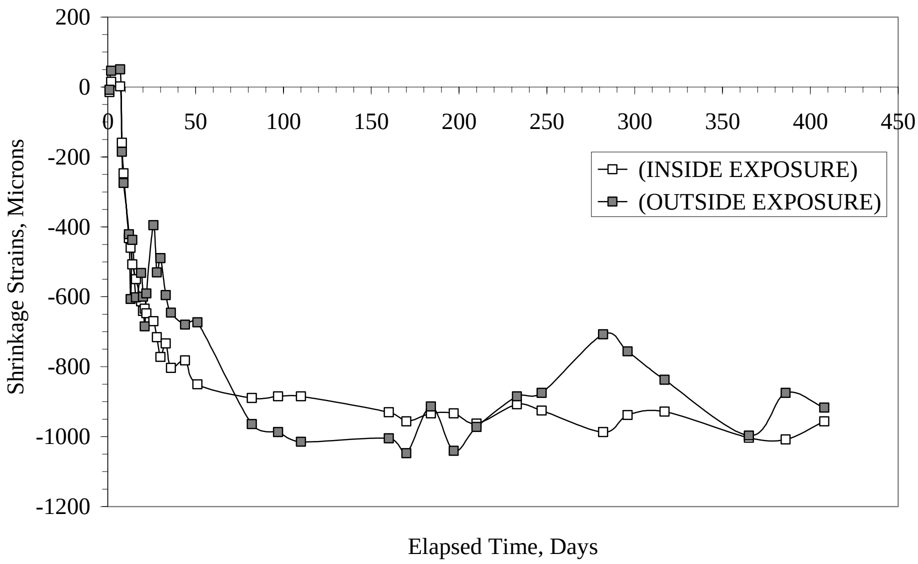

Fig. 10. Comparison of shrinkage strains of prisms from FOSROC (RENDEROC-LA) for inside (23 ± 2°C and 30% RH) and outside exposure.

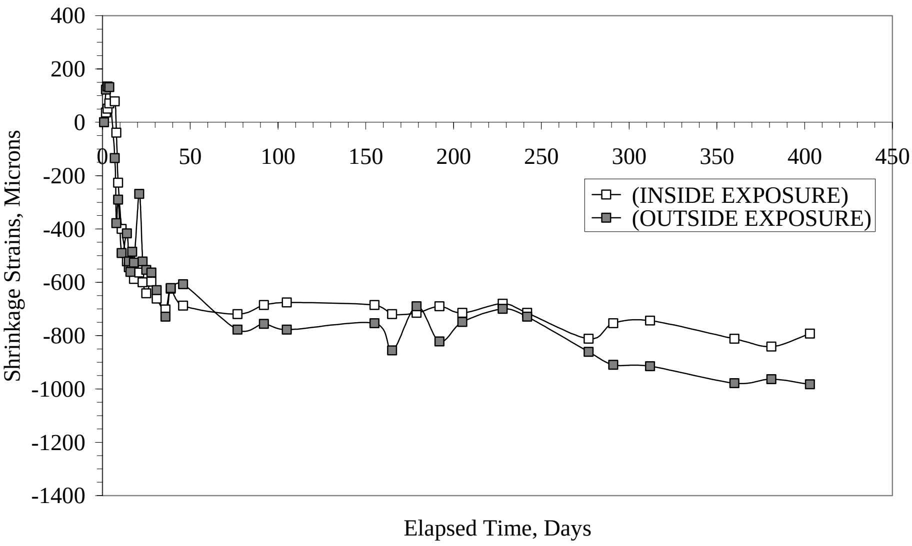

Fig. 11. Comparison of shrinkage strains of prisms from CONCRETE CONTROL for inside (23 ± 2°C and 30% RH) and outside exposure.

614, S-612) and MBT (E-101) with shrinkage strains of about 2200–2900 microns. The second highest values were recorded for FOSROC (F-HF), MBT (E-88 and E-66) with shrinkage strains of about 1800-2000 microns. The lowest shrinkage strain among all types was for the specimens from SIKA (S-114) specimens with just 715 microns, whereas the materials FOSROC (F-S and F-LA) experienced shrinkage strains in the range of 1050–1150 microns. It is noted that most of the repair materials in the outside exposure exhibited change in shrinkage after about 300 days and this is due to some weather change at that period of time.

It is worth mentioning that some manufacturers specify in their leaflet that their repair materials are “shrinkage compensated”. The only repair material which support this statement up to certain extent is SIKA (S-114) in which it experienced a shrinkage strain lower than the control cement paste. The other repair materials considered for this study showed higher shrinkage strains compared to the control specimens and this violates the claim made by suppliers.

Compressive strength results

The test results of the compressive strength values for all specimens tested at 7 and 28 days are given in Table 5. The corresponding strengths values given by the manufacturers are also reported in Table 5. The later are also plotted in Figs. 12 and 13 for 7 and 28 days, respectively. It is evident from the results of 7 days strength that the material E-88 gives the highest value of 54 MPa followed by E-66, S-114 and F-HF with values above 40 MPa. The next lower strength values of 30-40 MPa were obtained by F-S and F-LA. The lowest material strength values were for E-101 and S-114 with about 20 MPa.

Table 5. Comparison between the compressive strengths ($f_c^{'}$) of test results and values presented by manufacturer

Material Designation	$f_c^{'}$ from company (MPa)		Avg. $f_c^{'}$ from Tests (MPa)	
	at 7 Days	at 28 Days	at 7 Days	at 28 Days
MBT (E-88)	60	70	54	70
MBT (E-101)	N/A	35	20	29
MBT (E-66)	45	65	45	55
SIKA (S-614)	N/A	55-60	25	35
SIKA (S-612)	N/A	45-50	21	37
SIKA (S-114)	N/A	65	43	54
FOSROC (F-S)	N/A	55	31	43
FOSROC (F-HF)	44	64	43	56
FOSROC (F-LA)	45	60	37	46

N/A: Not Available

For the 28 days strength values, the trend was nearly the same. Material E-88 showed the highest compressive strength of 70 MPa among the tested materials followed

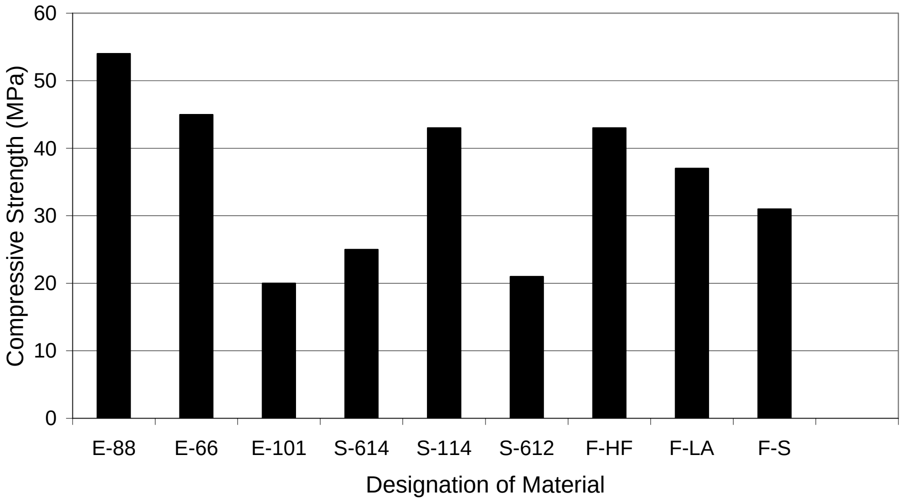

Fig. 12. Compressive strength at 7 days for all considered repair materials.

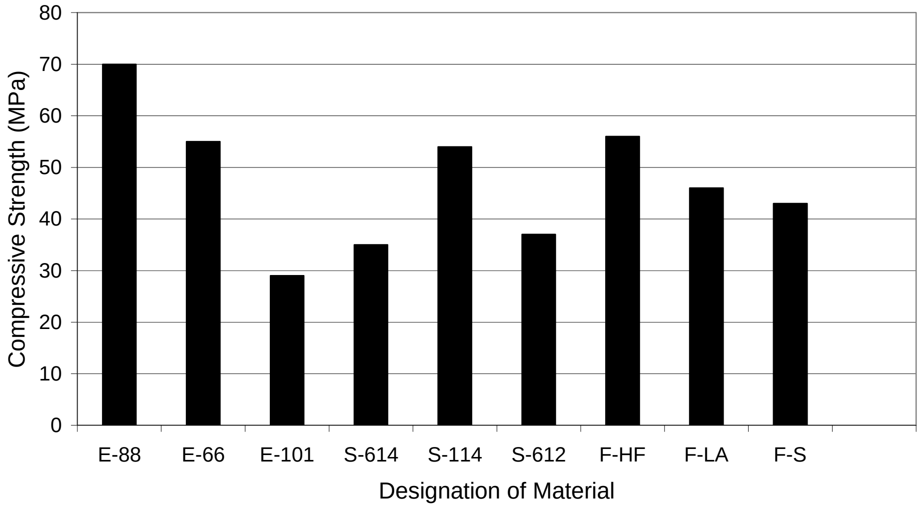

Fig. 13. Compressive strength at 28 days for all considered repair materials.

by E-66, S-114 and F-HF, in the range of 50-60 MPa. The material F-LA along with the S-612 and F-S were in the range of 35-45 MPa. The material with the least compressive strength was E-101 with the strength around 30 MPa.

Most of the compressive strength test values were lower than the values reported by the material's data sheet. This proves that the values provided by suppliers should always be checked and confirmed before using them in any field application.

However, the results of the measured compressive strengths almost for all considered materials, as reported in Table 5, are equal or greater than that of the normal strength concrete. Therefore, the selection of the repair material should not be based mainly on its compressive strength value. Other engineering characteristics, e.g. rupture strain, thermal expansion, creep etc., may be more critical to the repair system than the strength.

Elastic Modulus Evaluation

The stress-strain relationships of all materials studied are shown in Fig. 14 for 28 days. The curves were used for the calculations of the modulus of elasticity of all materials and the values obtained are given in Table 6. The calculations for the modulus of elasticity of the tested specimens were calculated according to ASTM C469 [16].

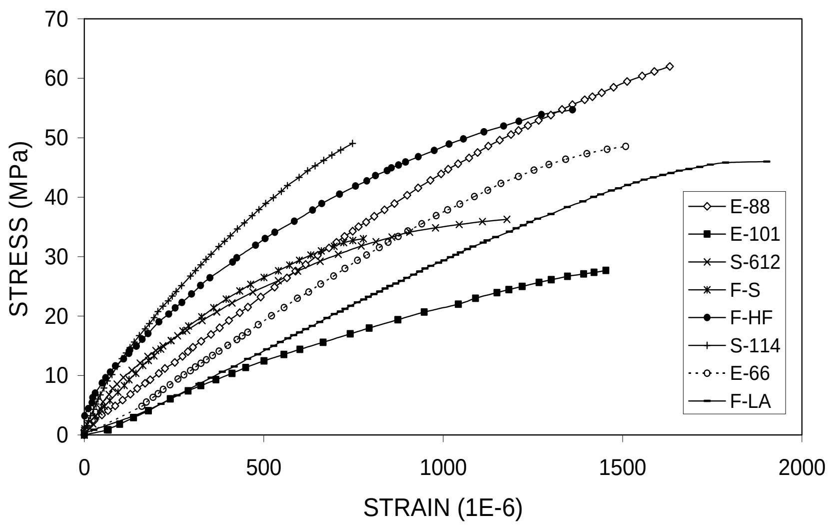

Fig. 14. Stress-strain relationship for all repair materials after 28 days curing.

Table 6. Modulus of elasticity for the tested materials

Designation of Materials	Modulus of Elasticity at 28 Days (GPa)
MBT (E-88)	46.0
MBT (E-101)	27.0
MBT (E-66)	43.7
SIKA (S-612)	46.0
SIKA (S-114)	78.0
FOSROC (F-S)	49.0
FOSROC (F-HF)	57.6
FOSROC (F-LA)	29.0

Table 6 shows that the highest modulus of elasticity value was obtained for the repair material SIKA (S-114) with a value of 78 GPa. The lowest values were obtained by MBT (E-101) and FOSROC (F-LA) with values of 27 and 29 GPa, respectively. The value for modulus of elasticity for the repair material SIKA (S-614) was not obtained due to some difficulties that were experienced during testing.

As explained earlier in the literature review, there is a direct relationship between the modulus of elasticity and the interaction between the repair material and the base concrete and in particular at the bond line between the new and old materials. A major difference between the actual modulus of elasticity and the data sheet value may cause a total failure of the repair system. This calls for the urgent need to thoroughly investigate the engineering properties of repair material for the particular repair application before selecting it. In any case, the selection should not be based on the engineering characteristics reported by the manufacturer.

Conclusions

Based on the tests performed for the comparative study on the nine types of cementaious repair materials, the following conclusions can be drawn:

1) All repair materials must be checked experimentally to confirm the properties given by the supplier before use in any field application.
2) The test results show that the shrinkage strain measurements for 400 days exposures showed that the repair material designated as SIKA (S-114) exhibited the lowest shrinkage strain for inside and outside exposure. The maximum shrinkage strain was recorded for the repair material SIKA (S-612). The other repair materials falls between the above mentioned two repair materials.
3) The highest 28 days compressive strength was achieved by the material MBT (E-88) with a value of 70 MPa, followed by FOSROC (F-HF) with 56 MPa. The minimum value was obtained by MBT (E-101) with 29 MPa. All studied repair materials had reasonably higher compressive strength than the normal concrete. These materials should, therefore, be useful for vertical applications, such as columns where compressive strength is very important.

4) For modulus of elasticity comparison, the highest value was achieved by SIKA (S-114) with 78 GPa, followed by FOSROC (F-HF) with 57.6 GPa. The lowest value was obtained for MBT (E-101) with 27 GPa.
5) The selection of suitable repair material should be based on the type of application in which some of the properties become more critical than others (i.e. compressive strength or shrinkage).

It should be noted that the above conclusions are based on the author's observation and should not be considered a promotion for any of the used product (repair material). The results are liable to change under different test setup and environmental exposures.

Acknowledgements. The author wishes to express his gratitude to the Research Center, College of Engineering, King Saud University for financial support provided for the execution of this project.

References

[1] Mays, G. and Wilkinson, W. "Polymer Repairs to Concrete; Their Influence on Structural Performance." *ACI Special Publication* SP-100-22.1.1987, pp. 351-375.
[2] Emberson, N.K. and Mays, G.C. "Significance of Property Mismatch in the Patch Repair of Structural Concrete – Part 1: Properties of Repair Systems." *Magazine of Concrete Research,* 42, No. 152 (1990), 147-160.
[3] ACI Committee. *Concrete Repair Guide*, (ACI 546-96), Detroit: American Concrete Institute, 1997.
[4] Cusson, Daniel and Mailvagan, Noel. "Durability Repair Materials*." Concrete International*, 18, No. 3 (March 1996), 34-36.
[5] Emmons, P.H. and Vaysburd, A.M. "System Concept in Design and Construction of Durable Concrete Repairs." *Construction and Building Materials,* 10, No. 1 (1996), 69-75.
[6] Emmons, P.H.; Vaysburd, A.M.; McDonald, J.E.; Poston, R.W. and Kesner, K.E. "Selecting Durable Materials: Performance Criteria." *Concrete International,* (March 2000), 38-45.
[7] Emmons, P.H.: Vaysburd, A.M. and McDonald, J.E. "Concrete Repair in the Future Turn of the Century - Any Problems?" *Concrete International*, (March 1994), 42-49.
[8] Hewlett, P.C. and Hurley, S.A. *The Consequences of Polymer-concrete Mismatch, Design Life of Building*. London: Thomas Telford, 1985.
[9] Good, R.J. "Locus of Failure and Its Implications for Adhesion Measurements, Adhesion Measurements of Thin Films, Thick Films, and Bulk Coatings." In: K.L. Mittal (Ed.), ASTM STP 640, American Society for Testing and Materials, Vol. 78, 1978, pp. 18-29.
[10] Brill, L.; Komlos, K. and Majzlan, B. "Early Shrinkage of Cement Paste, Mortars and Concrete." *Materials and Structures,* 13, No. 73 (1980), 41-45.
[11] Emmons, P.H. and Vaysburd, A.M. "Factors Affecting the Durability of Concrete Repair: The Contractor's Viewpoint." *Construction and Building Materials,* 8, No. 1 (1994a), 5-16.
[12] Morgan, D.R. "Compatibility of Repair Materials and Systems." *Construction and Building Materials,* 10, No. 1 (1996), 57-67.
[13] Department of Transportation. *Specifications for the Repair of Concrete Highway Structures*. Draft standard BD 27/86, 1987/88, UK.
[14] New Civil Engineer. *Midland Links Analysis Offers Full Repair Range*. April 1987.
[15] American Standards for Testing Materials. *Evaluation of Compressive Strength for Concrete, ASTM C39*, 1992.
[16] American Standards for Testing Materials. *Calculation of Elastic Modulus, ASTM C 469*. 1992.

دراسة معملية لتحديد ا واص ا يكانيكية ومقدار الانكماش للمواد ا ستخدمة لإصلاح ا رسانة

طارق بن ود ا سلم

قسم الهندسة المدنية ، كلية الهندسة ، جامعة الملك سعود ،
ص ب ٨٠٠، الرياض ١١٤٢١ ، المملكة العربية السعودية

(قدِّم للنشر في ٢٠٠٥/١١/١٢م ؛ وقبل للنشر في ٢٠٠٦/١١/٠٧م)

ملخص البحث. تسببت الأجواء القاسية في بعض مناطق المملكة العربية السعودية في تدهور شديد في كثير من المباني الخرسانية مما أدى إلى تقليل الفترة الزمنية التشغيلية لعمر المنشأ. ولكي يتم الحصول على مواد إصلاح طويلة المدى في فعاليتها لابد أن تكون خواص هذه المواد متوافقة مع طبقة الخرسانة القديمة. ولقد تم في هذا البحث تجهيز ١١٤ عينة لدراسة بعض الخواص المهمة لتسع من مواد الإصلاح المستخدمة محلياً والتي تم الحصول عليها من عدد من الموزعين لها في المملكة. ومن الخواص التي تمت دراستها هي : مقدار الانكماش الحاصل في مواد الإصلاح ، ومقدار قوة تحملها للضغط بالإضافة إلى حساب معامل المرونة لجميع العينات المعتبرة في الدراسة. وقد تم تجهيز من كل نوع من أنواع مواد الإصلاح المعتبرة في الدراسة ٦ عينات لاختبار الانكماش ، و٦ عينات لاختبار قوة تحملها للضغط وحساب معامل المرونة و ٦ عينات إضافية تم عملها من عجينة الإسمنت لكي تكون مقياساً للمقارنة مع العينات الخرسانية التي تم قياس الانكماش الحاصل فيها.