Mechanical Properties of Polymer-, Pozzolanic Cement-Based Repairing Materials

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ABSTRACT

In this study, the mechanical properties of five different cement based repairing materials were evaluated. These materials were classified into two groups: laboratory made materials with or without admixtures (3 types), and other two types of commercial proprietary pre-packaged with additives. Mechanical properties, such as compressive strength, modulus of rupture and drying shrinkage were studied.

Results show that these mechanical properties were varying significantly from each other. The drying shrinkage of the commercial proprietary repair materials was less than that of the conventional mortar. This will lead to a reduced cracking risk in the former repair materials compared to the latter. Through the regression analysis on the experimental data collected, power relation with coefficient of determination of 0.766 is obtained between compressive and modulus of rupture.

Keywords: Polymer-modified cement mortar; Concrete repair materials; Mechanical properties; Silica fume.

الخواص الميكانيكية لمواد الاصلاح البوليمرية - البوزولانية السمنتية

الخلاصة

تم في هذا البحث تقييم الخواص الميكانيكية لخمسة انواع مختلفة لمواد الاصلاح السمنتية. هذه المواد تم تصنيفها في مجموعتين: مواد اصلاح مصنعة مختبريا (3 انواع)، ونوعان اخران من مواد الاصلاح التجارية بماركة عالمية وجاهزة التعبئة والحاوية على المضـــافات. تشـــمل الخواص الميكانيكية التي تم دراستها مقاومة الانضغاط، معاير الكسر و انكماش الجفاف.

بينت النتائج ان الخواص الميكانيكية تتباين فيما بينها بشكل واضح. وان قيم انكماش الجفاف للمواد التجارية كان اقل من قيمه لمواد الاصلاح التقليدية. ويقود ذلك الى التقليل مـــن مخـــاطر التشقق في مواد الاصلاح التجارية مقارنة بمواد الاصلاح التقليدية. لقد اظهر تحليل الانحـــدار للبيانات التي تم جمعها مختبريا بوجود علاقة اسية بمعامل تحديد قدره 0.766 بـــين مقاومـــة الانضغاط و معاير الكسر.

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List of Symbols		
Symbols	**Description**	**Units**
f_{ts}	Splitting tensile strength/ modulus of rupture	MPa
f_{cs} , f_{cs}	Compressive strength,	MPa
A , B	Regression coefficients	
E	Modules of elasticity	GPa
f_{c^-}	Equivalent cylinder compressive strength	MPa
f_{cu}	Cube compressive strength	MPa
f_{ts}	Tensile strength	MPa
ε_{sh}	Drying shrinkage strain	micro-strain
IAE	Integral absolute error	
Qi	Experimental result	
Pi	Prediction result	
R^2	Coefficient of determination	

INTRODUCTION

Reduction in the functional service-life of reinforced concrete construction is a major problem related to the construction sectors. Concrete deterioration due to reinforcement corrosion is evident in the damp climatic conditions of the world. In the hot and dry regions this problem is caused due to a mixture of environmental conditions, marginal aggregates and inappropriate construction methods. Repairing and rehabilitation of damaged concrete structures are essential not only to utilize them for their intended service-life but also to guarantee the safety and serviceability of the associated members.

A successful repairing improves the performance and function of the structure, restores and increases its stiffness and strength, enhances the appearance of the concrete face, provides water-resistant, protect the concrete against ingress of the aggressive species, and improves its durability. Several repairing materials are marketed to repairing the deteriorating concrete structures. These repairing materials are classified into different types, such as cement, 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 [1–3].These materials mostly consist of a conventional cement mortar often without any admixture, polymer modified cement repair materials and pozzolanic (such as silica fume, fly ash or other industrial by- products) modified cement repair materials. Polymer modified cement repairing materials are used to overcome the problems associated with the cement-based repairing materials, particularly the need for a longer curing period and also to enhance the bond between old substrate concrete and new repairing materials [4, 5]. Polymers are usually used as admixtures; they are supplied as milky white dispersions in water and in that state are used 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. Styrene butadiene rubber (SBR) is one of the polymers commonly used in the cement mortars. A recent development in the field of polymers are re-dispersible spray-dried polymer powders, which may be factory blended with graded sand, cement, and other additives to produce mortar sand 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. The study reported in this paper was conducted to evaluate the mechanical properties of five cement- and polymer-based repair materials. These repair materials were classified into two groups; laboratory made and commercial proprietary repairing materials. More details about these two groups will be explained in section 3.

CORRELATION BETWEEN MECHANICAL PROPERTIES OF CONCRETE AND REPAIRING MATERIALS

Tensile strength and compressive strength are two important rally, both are used or required in structural design. However, tensile strength is also required in structural design for some specific applications, such measurements used for describing concrete mechanical properties. Usually, tensile strength can either be determined by direct tension test, splitting tensile test or modulus of rupture test. However, splitting tensile test and modulus of rupture test have been much more popularly carried out, probably due to their simplarity. Furthermore, it has been widely reported that splitting tensile strength and modulus of rupture can be estimated from compressive strength of concrete through various empirical relations proposed by different concrete institutes and researchers [6–11]. These empirical relations can be summarized by the following general equation (1) [11]:

$$f_{ts} = A(f_{cs})^B \quad \text{…. (1)}$$

It is observed that most of the published empirical relations were proposed for normal concrete; while, few were for repair mortar.

EXPERIMENTAL WORK

SELECTION OF REPAIR MATERIALS

Five proprietary repairing materials were selected to represent the generic type of repair mortars they are: conventional repairing materials M_C, silica fume modified cement repairing mortar M_{SF}, polymer modified cement repair materials M_{SBR} and two other pre-packed blend of Portland cement repair materials commercially available in the local market, named EUCOGROUT M_{EU} and HSXtra M_{HS}. The first three types were prepared in the laboratory; while the last two types were bought from the market. Table (1) summarizes the composition of the repairing mortars evaluated in this study.

MECHANICAL PROPERTIES

The selected repairing materials were tested to evaluate the following mechanical properties:

(a) Flow, according to ASTM C190;

(b) Bleed, non-standard, visual inspection;

(c) Compressive strength, according to ASTM C109;

(d) Modulus of rupture, according to ASTM C78 and

(e) Drying shrinkage, according to ASTM C157;

RESULTS AND ANALYSIS

MECHANICAL PROPERTIES

The flow characteristics of the selected polymer- and cement-based repair mortars are summarized in table (2). While the flow of M_{EU} was beyond the measuring range, as this material was very fluid, low flow was measured in Portland cement repair material M_{HS} specimens. The flow of other polymer-and cement-based repair mortars was in the range of 80–86%.

The bleeding characteristics of selected polymer- and cement-based repair mortars are summarized in table (3). Medium bleeding was noted in M_{EU} repair mortar, while it was low in the other M_C, M_{SBR}, and M_{SF} repair mortars and no bleeding in M_{HS}. Increased bleeding in M_{EU} is expected, as these are supposed to be flowing mortar.

Table (4) shows the compressive strength development in the selected repair mortars. As expected, the compressive strength of specimens prepared with the selected repair mortars increased with the age of curing. After 28 days of curing, the highest compressive strength was measured in the specimens prepared with M_{EU}. The compressive strength of M_{HS} repair mortar was 52 MPa, while the compressive strength of the specimens prepared with M_{SBR} and M_{SF} was in the range of 27–29 MPa. The compressive strength of specimens prepared without any improvement (i.e. control specimen M_C) was the lowest value, 19.5 MPa. Table (4) also shows equivalent cylinder compressive strength using the formula ($f_{c'} = f_{cu} / 1.25$) suggested by the BS 1881[12]. These values are important to compute E value for concrete ($E= 4700 \sqrt{f_{c'}}$) [7], shown in table 4.

The modulus of rupture of the selected repair mortars is summarized in table (5). These values were evaluated after 7 and 28 days of curing. As expected, the values at 28 days were more than those determined after 7 days of curing. After 28 days of curing, the modulus of rupture values were in the range of 4.0–10 MPa, the maximum value being measured in the specimens prepared with M_{HS} and the lowest value being recorded in the specimens prepared with M_C.

The drying shrinkage of the repair mortars is depicted in figure (1) and table (6). The drying shrinkage strain increased with time in all the repair mortars, increasing more rapidly at the earlier stages and slowly later. The drying shrinkage strain in the lab made repair materials (M_C, M_{SBR}, and M_{SF}) was more than that in the commercial proprietary cement-based repair mortars, M_{EU} and M_{HS}. Further, the ultimate drying shrinkage strain in the conventional cement-based repair mortars, M_C, was more than that in all of the lab made and commercial proprietary repair mortars.

The lower drying shrinkage in the M_{EU} and M_{HS} repair mortars compared to the lab made repair mortars may be attributed to the lower value of w/c in these materials compared to the lab made (M_C, M_{SBR}, and M_{SF}) repair mortars. This reduction in the drying shrinkage of repair material results in stress reduction at the substrate/repair material interface

The risk of cracking of a repair material, based on the assumption of a rigid concrete substrate, is defined as ε_{sh} E/ f_{ts} [13]. In this relationship, the ratio E/ f_{ts} is extremely important with the lowest values being more preferable. According to the ACI 318-05, E value can be evaluated using the formula: E= 4700 $\sqrt{f_c}$-; and since f_{ts} test data dose not available, instead, modulus of rupture results f_{fs} will be used in this study. Table (7) compares the E/ f_{fs} values of repair mortar specimens after 7 and 28 days. The comparison between the 5 different types of repair materials indicates that M_{SF} and M_{HS} have the lowest E/ f_{fs} (2.91 and 3.031 respectively), while this value is the highest in M_C repair mortar. The low E/ f_{fs} noted in M_{SF} and M_{HS} may be attributed to the presence of silica fume in the former and special additives in the later repair materials. It should be stated that most pozzolanic admixture enhance the microstructure of the concrete matrix leading to increase the tensile strength whilst moderately influencing the ductility. It is not surprising that the conventional cement-based repair mortars M_C exhibit higher risk of cracking compared to the other commercial proprietary and lab made repair materials. Table (7) also shows the risk of cracking after 7 and 28 days. The risk of cracking varies from 127.12 to 4562.2 after 7 days and 287.98 to 4037.56 after 28 days. The higher risk of cracking in the repair materials M_C after 7 days, and staying around the same level until the age of 28 days, indicates that unless there is a substantial relief of tensile strain, by creep mechanism for example, the risk of cracking will not be decreases with the age. This may well explain why drying shrinkage cracking is commonly noticed in structures between 7 days to 28 days of exposure. Lowest risk of cracking noticed in repair material M_{HS} indicates for the significant of reducing w/c ratio to reduce or may avoid such risk.

APPLICABILITY EVALUTION ON PUBLISHED EMPIRICAL RELATIONS TO CONCRETE REPAIR MATERIALS

Previously published empirical relations between modulus of rupture and compressive strength of normal concrete are presented in table (8). From table (8), it can be seen that for normal concrete, these empirical relations can be generally summarized by using equation (1). Figure (2) presents the comparison between experimental data points and prediction curves of the empirical relations shown in table (8). It can be observed from figure (2) that although when experimental data points show obviously scattered, a general trend that modulus of rupture increases with the increase of compressive strength can still be observed. When compressive strength is low (20 MPa), experimental data points are closed to the empirical relations; however, with the increase of compressive strength, experimental data points deviate more and more above the prediction curves.

In order to further evaluate the deviation between experimental data points and prediction curves shown in figure (2), integral absolute error (IAE) is employed [13], which is written:

$$IAE = \sum \frac{\sqrt[2]{(Qi - Pi)^2}}{\sum Qi} \times 100 \qquad \ldots..(2)$$

IAE values of the empirical relations are also presented in table (8). It can be seen that except the IAE values of empirical relations reported by ACI 363R-92[6] is less than 30%, the others are all above 50%, which verifies the inapplicability of these empirical relations to the repair materials.

COMPRESSIVE STRENGTH AND FLEXURAL STRENGTH REGRESSION ANALYSIS AND DISCUSSION

As shown in figure (3), regression analysis was carried out on these experimental data points of modulus of rupture (f_{fs}) and cylinder compressive strength (f_{cs}) of repair materials. Through regression analysis, the empirical relation obtained can be expressed:

$$f_{ts} = 0.639\,(f_{cs})^{0.709} \qquad \ldots\ ....(3)$$

R^2 of this proposed relation is 0.766, indicating a positive correlation. IAE values for Equation (3) is only 14.87% which is very small compared with the large IAE values shown in table (8), suggesting high reliability and accuracy of this proposed relation.

It is interesting to say that this formula is based on limited data and then needs for more investigation before any generalization

CONCLSIONS

The following are the main conclusions that can be drawn from the experimental program conducted to evaluate the mechanical characteristics of selected cement-based repair mortars.

1. Clear distinction could be established between the lab made and commercial proprietary cement- based repair mortars with regard to the compressive, modulus of rupture and drying shrinkage. M_{EU}, and M_{HS} were the better among them.
2. The drying shrinkage of the commercial proprietary repair mortar was less than that of the lab made repair mortar. The drying shrinkage of M_{EU} was less than ten times that of the conventional mortar M_C. This reduction in the drying shrinkage of repair material results in stress reduction at the substrate/repair material interface**.**
3. The risk of cracking appears to be the criteria that differentiate between the performances of the selected repair materials. Therefore, it is necessary to request for information on modulus of rupture, drying shrinkage as well as compressive strength from strength point of view throughout any evaluation of repair materials products.

4. Previously published empirical relations proposed for normal concrete, are inappropriate to cement- based repairing mortar; and, it is necessary to investigate the potential correlations among mechanical properties of such materials.

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Table (1) Selected repairing materials

Repair mortar	Group	Description
M_C	Laboratory made repairing materials	Portland cement mortar (w/c:0.5,sand/cement 2)
M_{SBR}		Portland cement polymer modified mortar (w/c:0.38, sand/ cement 2, polymer (SBR 15% of total cement)
M_{SF}		Portland cement silica fume mortar (w/c:0.4, sand/ cement 2, silica fume10% replacement of total cement)
M_{EU}	Commercial proprietary repairing materials	Ready to use mortar based on cement with graded fine aggregate in combination with selected admixtures, produced by SWISS CHEM company (water/ repair material = 0.15)
M_{HS}		Pre-packed blend of Portland cement, fine aggregate, fillers and additives, produced by FOSROC company (water/ repair material = 0.18)

Table (2) Flow characteristics of selected repairing materials

Repair mortar	Flow %
M_C	80
M_{SBR}	85
M_{SF}	86
M_{EU}	Flowing
M_{HS}	Low

Table (3) Bleeding in selected repairing materials

Repair mortar	Bleeding
M_C	Low bleeding*
M_{SBR}	Low bleeding
M_{SF}	Low bleeding
M_{EU}	Medium bleeding *
M_{HS}	No bleeding*

*** bleed values stated by visual inspection**

Table (4) Compressive strength of selected repairing materials

Repair mortar	f_{cu}			f_c*			E [7]		
	7 days	14 days	28 days	7 days	14 days	28 days	7 days	14 days	28 days
M_C	10.60	13.00	19.50	8.48	10.40	15.60	13.68	15.15	18.56
M_{SBR}	15.90	21.80	29.28	12.72	17.44	23.42	16.76	19.62	22.74
M_{SF}	14.64	18.01	27.00	11.71	14.41	21.60	16.08	17.84	21.84
M_{EU}	26.80	47.09	62.80	21.44	37.67	50.24	21.76	28.84	33.31
M_{HS}	27.00	41.00	52.00	21.60	32.80	41.60	21.84	26.91	30.31

*** According to the BS 1881 [12], the cube to cylinder ratio is 1.25.**

Table (5) Modulus of rupture of selected repairing materials

Repair mortar	Modulus of rupture (MPa)	
	7 days	28 days
M_C	1.71	4.0
M_{SBR}	2.15	5.08
M_{SF}	4.24	7.50
M_{EU}	7.10	9.20
M_{HS}	8.42	10.0

Table (6) Dry shrinkage of selected repairing materials

Repair mortar	Dry shrinkage (micro-strain)				
	4 days	7 days	14 days	21 days	28 days
M_C	330	570	750	830	870
M_{SBR}	300	550	641	711	742
M_{SF}	180	369	489	575	625
M_{EU}	26	45	69	80	84
M_{HS}	28	49	71	85	95

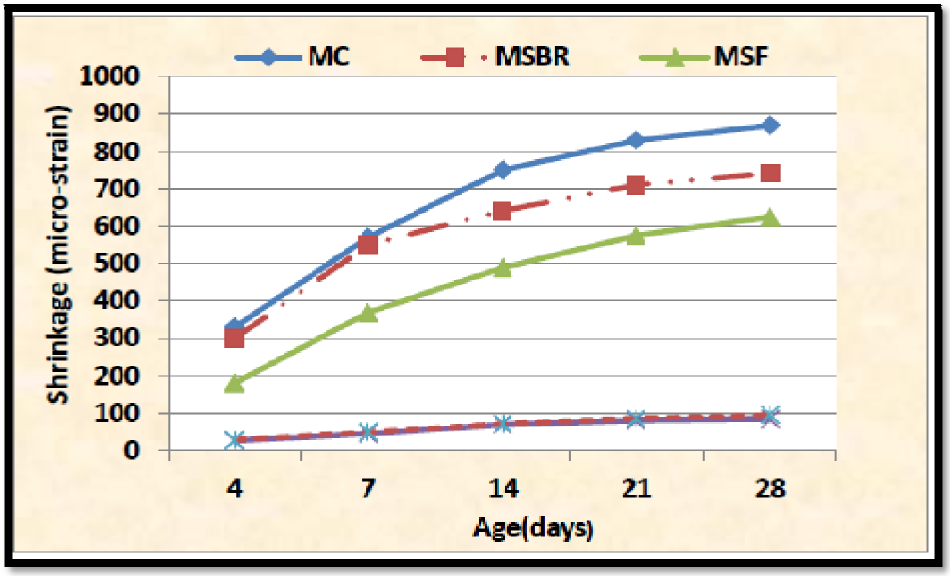

Figure (1) Dry shrinkage in repairing materials

Table (7) Risk of cracking for selected repair materials

Repair mortar	$(E/f_{ts})\times 10^3$		Risk of cracking	
	7 days	28 days	After 7 days	After 28 days
M_C	8.00	4.640	4562.20	4037.56
M_{SBR}	7.796	4.477	4288.11	3322.53
M_{SF}	3.793	2.912	1399.83	1820.30
M_{EU}	3.065	3.621	137.93	304.17
M_{HS}	2.594	3.031	127.12	287.98

Table (8) Published empirical relations between compressive strength and modulus of rupture of normal concrete, and the corresponding IAE (%)

Sources	ACI 318M-05[7]	ACI 363R-92[6]	Ahmad & Shah[9]
Empirical relation	$f_{fs} = 0.62(f_{cs})^{0.5}$	$f_{fs} = 0.94(f_{cs})^{0.5}$	$f_{fs} = 0.44(f_{cs})^{0.5}$
IAE(%)	53.2	29.1	66.8

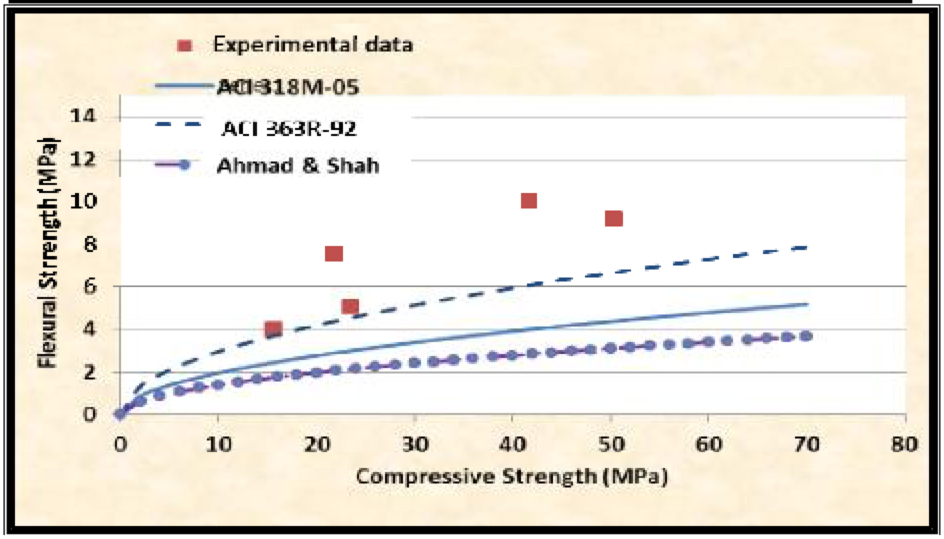

Figure (2) Comparison between experimental data points and prediction curves of published empirical relations between f_{fs} and f_{cs} of normal concrete

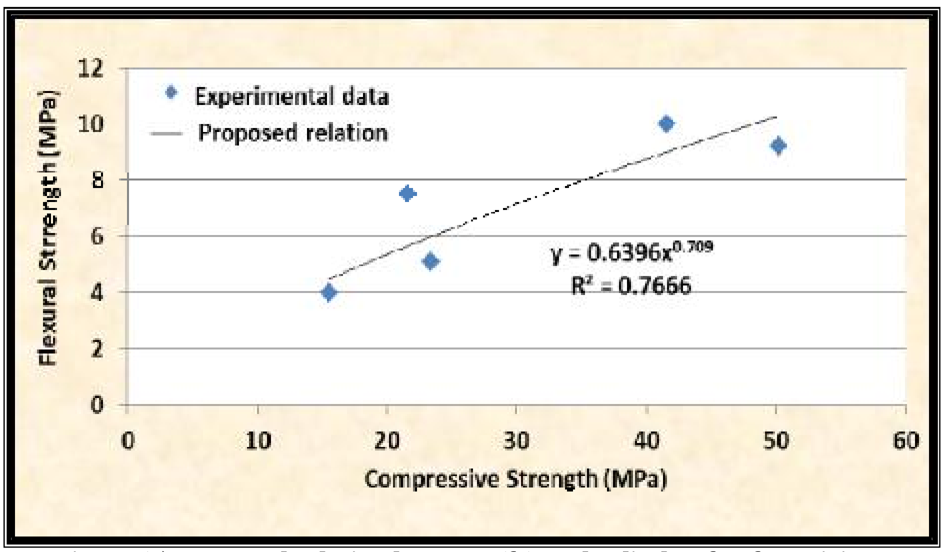

Figure (3) Proposed relation between (f_{fs}) and cylinder f_{cs} of repairing materials.