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Improving the Compatibility between Polymer-, Pozzolanic Cement-Based Repairing Materials and Concrete Substrate

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ABSTRACT

In this study, the compatibility of five different cement based repair materials and substrate concrete was investigated in three stages. First stage includes studying the individual properties of repair materials, and also two types of concrete, such as compressive strength, flexural strength, and dry shrinkage using BS 1881: part 116, ASTM C78-06, ASTM C157 -06 test procedure respectively. Second stage includes evaluating the bond strength of composite cylinder for different combinations of repair materials and substrate concrete. Third stage includes investigating the compatibility using a composite beam of repair material and substrate concrete under third point loading.

The experimental results show that one individual property has no crucial effect on the success of concrete repair system. Bond strength and dry shrinkage however has a strong indication about the compatibility.

Keywords: Bond Test; Compatibility; Concrete Repairing Materials; Polymer; silica fume.

تحسين التوافق بين مواد الإصلاح البوليمرية- البوزولانية السمنتية والجسم الخرساني

الخلاصة

في هذه الدراسة تم التحري عن التوافق بين مواد الإصلاح البوليمرية- البوزولانية السمنتية والجسم الخرساني وعلى ثلاث مراحل .الأولى :التحري عن الصفات الذاتية لكل من مواد الإصلاح البوليمرية- البوزولانية السمنتية وكذلك لنوعين مختلفين من الجسم الخرساني ,مثل مقاومة الانضغاط ,مقاومة الانثناء، وانكماش الجفاف وباستعمال المواصفة BS1881: 116 ,ASTM C78-11part ,ASTM C157-06 06 بشكل متتالي. الثانية :تقييم مقاومة الربط للاسطوانة ألمركبه والمصنوعة من أنواع مختلفة من مواد الإصلاح والخرسانة .ثالثا :التحري عن التوافق باستخدام عتبه مركبه مصنوعة من الخرسانة ومواد الإصلاح وفحصها بطريقة التحميل بنقطتين.

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تبين نتائج الجزء العملي بانة لاتوجد خاصية منفردة لمواد الاصلاح ذات تاثيرحاسم لنجاح نظام
الإصلاح الخرساني .بينما توفر مقاومة الربط و وانكماش الجفاف مؤشرا قويا عن مدى التوافق.

INTRODUCTION

Deterioration of the infrastructure has become the most significant challenge facing the engineer and the construction industry. Therefore, the concrete repair has become one of the most industry's emerging sectors. Numerous repairs have been completed in the Gulf Region but, unfortunately, not well documented as regards to the long-term performance. Not only that but very little has been done to establish a methodology of design for durability and performance criteria for durable repair materials and repair system. Furthermore, manufacturers' data sheets, the only resource available in the market about the properties of the repair materials, do not contain all the essential data required about the properties of the repair materials. They tend to use different tests and standards to evaluate the performance of their products. Also, many standard tests used to prepare the sheets are modified arbitrary; some modifications are deficient or provide unrealistic results [1]. This situation resulted in controversy and confusion about the information provided in the manufacturer's data sheets. In addition, test methods, specimen size, restrain conditions, curing procedure; time of initial readings, temperature and humidity limits, and test duration further complicated the comparison between the information provided in the data sheets from different manufacturers [2].

On the other hand, a wide variety of repair materials are now available for the design engineer, however, it seems very difficult to select the right repair material. The difficulty, in addition to the aforesaid points, also arises from the lack of generally accepted performance criteria guidelines to the repair technology and the advanced engineering concepts. The main factors that should be considered to select durable repair materials and system include but not limited to: properties of the repair materials, type of application (structural or non structural repair), the degree of adhesion, shrinkage, thermal movement, cracking characteristics, chemical passivation of embedded steel, ease of application, chemical resistance, overall performance, material cost and labour. Some of these are discussed in brief details in the next sections [3-5].

It should, however, be stated here that this paper is aimed to evaluate factors affecting compatibility between repair materials and concrete substrate of five cement- and polymer-based repair materials. These repair materials were classified into two groups; laboratory made and commercial proprietary repair materials. More details about these two groups will be explained in section 2. The materials properties such as compressive strength, flexural strength, dry shrinkage for repair materials and substrate concrete were examined. Bond strengths of the repair materials were investigated to evaluate the compatibility between the five repair materials and substrate concrete. For this purpose, prisms of composite beam under third point loading as per modified ASTM C78-06 [6] test procedure were tested

EXPERIMENTAL WORK

Materials

Concrete Repairing Materials

Repairing materials used in this study were five types. They are conventional mortar M_C, polymer modified cement mortar M_{SBR}, silica fume modified cement mortar M_{SF}, and two commercial repair mortars (named EUCOGROUT M_{EU} and HSXtra $M_{HS)}$. Table (1) shows description of the repair materials used through this study.

Table (1) Details of the repairing materials used through this study.

Repair mortar	w/c or w/cm*	w/r.m**	Description
M_C	**0.50**	---	Portland cement mortar (sand/cement =2).
M_{SBR}	**0.38**	---	Portland cement polymer modified mortar (sand/ cement =2, polymer (SBR 15% of total cement)).
M_{SF}	**0.40**	---	Portland cement silica fume mortar (sand/ cement 2, silica fume10% replacement of total cement).
M_{EU}	---	**0.15**	Mortar based on cement with carefully graded fine aggregate in combination with selected additives. Produced by SWISS CHEM company.
M_{HS}	---	**0.18**	Shrinkage controlled, cementitious high specification repair mortar system, HSXtra is suitable for hand and spray application for repair where high load bearing is required, produced by FOSROC company.

*** Water to cementitious material ratio.**
****Water to repair material ratio.**

Substrate Concrete

Two substrate concrete mixes were used in this study. One mix considered to be normal quality substrate, while the other one considered being high quality substrate. The mix proportion of the concrete is the same, (1:1.6:2.9 by weight). The deference is only in w/c ratio, which was 0.65 for normal strength concrete, 0.4 for high strength. British standard method was adopted to design the normal quality concrete (named as C25), while the high quality concrete (named as C50) was achieved by decrease the water cement ratio by about 50% as compared to C25.

Assessment Methods

Workability

The flow of the repair materials was determined using flow table of mortar as per ASTM C230-06[7] standard practice. Flow was measured immediately after mixing, within 5 minutes from the time of addition of water into the mix.

Compressive Strength

The compressive strength of the different repair mortars was determined using 50 mm cube. The compressive strength of concrete was measured on 150mm cube in accordance with BS 1881: part 116[8] by using a standard testing machine. The compressive strength of the substrate concrete was tested at 7, 28 and 63 days age. The compressive strength of the repair materials were tested at 7, 14 and 28 days age.

Modulus of rupture

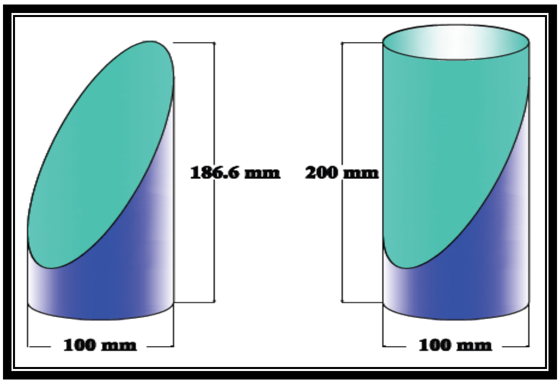
The modulus of rupture was determined using the third point loading beam method. The prism sample dimensions were 100×100×400mm, as per ASTM C78-06 [6]. The modulus of rupture of the substrate concrete was tested at 7, 28 and 63 days age. While modulus of rupture of the repair materials were tested at 7 and 28 days age.

Drying Shrinkage

The drying shrinkage of different repair mortars was measured on 285 mm length and 25*25 mm cross section area of prismatic section standard practice. The specimens dimension was adopted according to ASTM C157 -06 [9]. The drying shrinkage of the repair materials were tested at 4, 7, 14, 21, and 28 days age.

Bond Strength

The bond strength of the repair materials was determined using the standard ASTM C882-06 [10] test procedure. In this test procedure, the repair material is bonded to a substrate concrete specimen on a slant elliptical plane inclined at 30° angle from vertical to form a 100×200 mm composite cylinder (see Fig 1). Before the repair material is bonded to the substrate concrete, the slant surface of the substrate concrete specimen is cleaned and dried. The test is performed by determining the compressive load required to fail the composite cylinder and the bond strength is calculated as [Max Load] / [Area of Slant Surface].

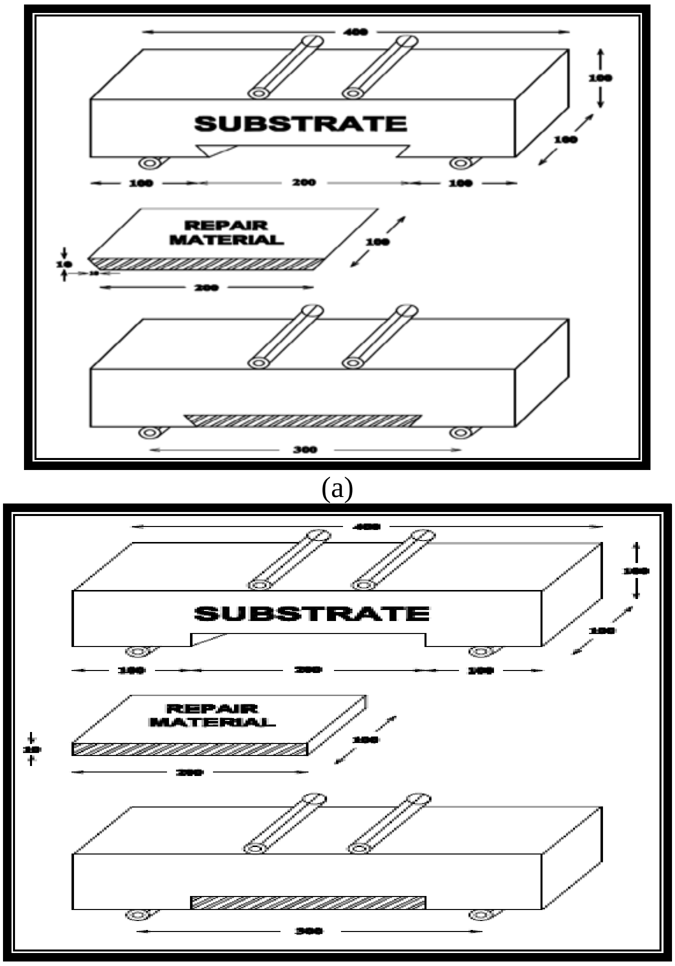


(b) (a)

Figure (1) Substrate and composite section for slant shear bond strength test. (a) Substrate; (b) Composite section.

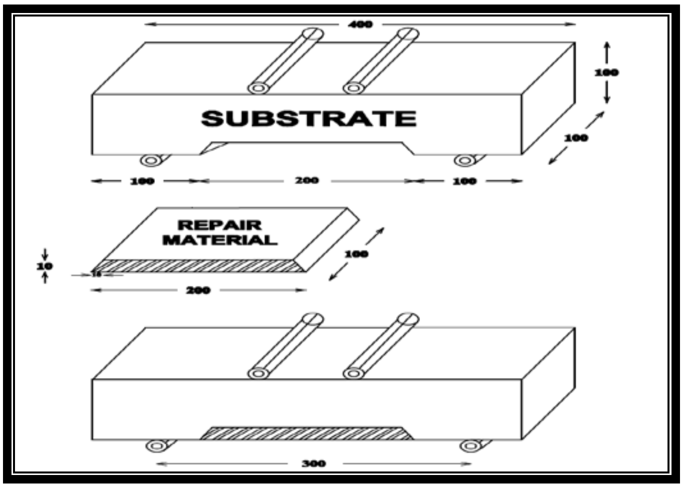
Third Point Loading Composite Prism Test

In this test method, concrete prisms 400mm in length with a cross-section of 100mm by 100mm were cast as per standard ASTM C 78-06[6] test procedure. The composite prism for evaluating the compatibility of repair material with substrate concrete was fabricated to the same dimensions as the control prism, with the exception that a wide-mouthed notch 200mm (length), 100mm (width), 10mm (thick) was cast into the bottom of the composite prism using a 3-dimensional inset (see Fig 2). After de-molding, the prisms were moist cured for 27 days, and then the wide-mouthed notch areas were textured using dry brushing. The rough surface textured substrate specimens were air-dry cured for 7 days before batching the notched area with the repair materials. The composite sections were de-molded next day and cured in water for 27 days. After 27 days, the composite sections were tested in third point loading prism test, as per ASTM C78-06 [6] test procedure.



(a)

(b)



(c)

Figurer (2) Repairing region shape. (a) Acute angle edge; (b) Square angle edge; (c) Obtuse angle edge.

Note: All dimensions with (mm)

RESULTS AND ANALYSIS

Mechanical Properties

Table (2) shows the flow values of the five repair mortars used in this study.

The compressive strength is considered one of the most important properties of hardened concrete or mortar. Generally it is the main characteristic value to assess the concrete or mortar quality in the national and international codes. The compressive strength values at various ages for all types of repair materials and substrate concrete are presented in Table 3. The test results show that, in general, all specimens exhibit a continuous increase in the compressive strength with the progress of age. This increase in the compressive strength is attributing to the continuity of hydration process which forms a new product within the mortar or concrete mass.

Table (2) Flow values of selected five repairing materials .

Repair mortar	M_C	M_{SBR}	M_{SF}	M_{EU}	M_{HS}
w/c or w/cm*	0.50	0.38	0.40	---	---
w/r.m**	---	---	---	0.15	0.18
Flow %	80	85	86	Flowing	10

[*] Water to cementitious material ratio.
[**]Water to repairing material ratio.

Table (3) Compressive strength development of selected repair materials and concrete.

Index	w/c or w/cm*	w/r.m**	Compressive strength (MPa)				
			7 days	14 days	28 days	35 days	63 days
M_C	0.50	---	10.60	13.00	19.50	---	---
M_{SBR}	0.38	---	15.90	21.80	29.28	---	---
M_{SF}	0.40	---	14.64	18.01	27.00	---	---
M_{EU}	---	0.15	26.80	47.09	62.80	---	---
M_{HS}	---	0.18	27.00	41.00	52.00	---	---
C_{25}	0.65	---	21.00	---	27.50	27.80	28.00
C_{50}	0.40	---	36.3	---	52.00	53.80	54.50

*** Water to cementitious material ratio.**
****Water to repairing material ratio.**

The modulus of rupture values at various ages for all types of repair materials and substrate concrete are presented in Table (4). Depending on the test results, the modulus of rupture of all specimens increases gradually with the progress of age. The reason for this increasing is due to propagation of hydration progress.

The relationship between the drying shrinkage and age of specimens for all types of repair materials are represented in Table (5). The test results in Table (5) showed that, the rate of drying shrinkage of all specimens decreases with the progress of age. The reason for this is decrease the evaporation of water from the gel pores and/or the water adherent to the gel particles.

Table 4: Modulus of rupture development for selected repairing materials and substrate concrete

Index	w/c or w/cm*	w/r.m**	Modulus of rupture (MPa)		
			7 days	28 days	63 days
M_C	0.50	---	1.71	4.00	---
M_{SBR}	0.38	---	2.15	5.08	---
M_{SF}	0.40	---	4.24	7.50	---
M_{EU}	---	0.15	7.10	9.20	---
M_{HS}	---	0.18	8.42	10.0	---
C_{25}	0.65	---	3.74	3.78	3.80
C_{50}	0.40	---	5.31	5.70	5.91

*** Water to cementitious material ratio.**
****Water to repairing material ratio.**

Table (5) Shrinkage development for selected repairing materials.

Index	w/c or w/cm*	w/r.m**	Shrinkage (micro-strain)				
			4 days	7 days	14 days	21 days	28 days
M_C	0.50	---	330	570	750	830	870
M_{SBR}	0.38	---	300	550	641	711	742
M_{SF}	0.40	---	180	369	489	575	625
M_{EU}	---	0.15	26	45	69	80	84
M_{HS}	---	0.18	28	49	71	85	95

*** Water to cementitious material ratio.**
****Water to repairing material ratio.**

Bond between repair and substrate is usually a weak link in a repaired structure [11], and the compatibility between repair and substrate materials is fully dependent on the bond strength of the repair materials [12]. The bond strength values of repair materials are presented in Table (6).

Table (6) Bond strength of composite specimens for selected repairing materials and substrate concrete.

Index	w/c or w/cm*	w/r.m**	Bond strength (MPa)	
			63 days	
			C_{25}	C_{50}
M_C	0.50	---	5.02	3.50
M_{SBR}	0.38	---	5.00	6.00
M_{SF}	0.40	---	6.00	6.14
M_{EU}	---	0.15	8.06	11.0
M_{HS}	---	0.18	8.09	12.5

*** Water to cementitious material ratio.**
****Water to repairing material ratio.**

The bond strength mainly depends on adhesion in interface, friction, aggregate interlock, and time-dependent factors. Each of these main factors, in turn, depends on other variables. Adhesion to interface depends on bonding agent, material compaction, cleanness and moisture content of repair surface, specimen age, and roughness of interface surface. Friction and aggregate interlock on interface depend on parameters, such as aggregate size, aggregate shape, and surface preparation

[11]. In addition to the above factors, the measured bond strength is highly dependent on the test method used (Size and geometry of specimen and the state of stress on the contact surface are quite dependent on the chosen test method) [13].

In the ASTM C928 specification, the bond strength between the repair materials and substrate concrete is determined using the slant shear test method as specified in ASTM C882-06 [10] test procedure. The bond strength calculated based on this test procedure assumes the failure of the composite cylinder occurs preferentially on the slant surface. Previous research studies [14, 15, and 16] have shown that, the failure on the slant plan is not necessarily the case with all the repair materials.

Pattnaik [17] found three different modes of failures. They are (as shown in Fig.(3): slant surface failure indicating of the weak bond between the repair and substrate materials. While materials failure, (either in substrate concrete or mortar), indicating weaker materials strength than the bond strength at the interface. The possible reasons for this deviation from the expected behaviour include disparity (incompatible) between the properties of the repair materials and the substrate concrete. Such disparity in properties can be expected to influence the failure mode and the bond strength determined of the composite cylinder.

The failure mode observed in this study for composite cylinder was slant surface for M_C specimens. Material failure was observed for M_{EU} and M_{HS} specimens. Mixed mode failure (i.e. slant surface and material failure) were observed in M_{SBR} and M_{SF} composite cylinder specimens test. Fig. (4) shows different types of failure mode.

(a) (b) (c)

Figure (3) Failure of the composite slant sections [17]. (a) Interface failure, (b) Substrate concrete failure, (c) Repairing material failure.

(a) Slant surface failure (b) Material failure

Figure (4) Failure of the composite slant sections of the research.

Bond strength of M_{SBR} was higher than M_C by 71.42% in the case of C_{50}, but around the same in the case of C_{25}, this increase in bond strength of M_{SBR} when used with C_{50} may be due to:

- Low w/c ratio of M_{SBR} compared with M_C, leading to increase in the density and strength of transition zone between the repairing materials and the substrate concrete;
- Reduce shrinkage by using low w/c ratio contribute to keeping on quality of bond strength[18];
- The addition of polymer leads to form a continuous three dimensional polymer network which interpenetrates the cement paste;
- The partial filling of the pores with the polymer particles reduces the porosity of transition zone between the repairing materials and the substrate concrete; and
- In addition to above factors, polymer consider good bonding agent due to the good adhesion property.

Decrease bond strength of M_{SBR} when used with C_{25}, May related to exist difference between mechanical properties of the repair material and the substrate. This disparity in mechanical properties can be expected to influence the failure mode and the bond strength determined in the composite cylinder.

M_{SF} performed bond strength considerably better than the corresponding M_C. This is may attributed to:

- Mineral admixtures (SF) have effect on bonding strength by improving microstructure, reduce thickness of transition zone, and densified interfacial zone due to pozzolanic activity and the fine filler effect (transition zone between the repairing materials and the substrate concrete)[19]; and
- w/c ratio is low in M_{SF} compared with M_C, this leads to increase in the density and strength of transition zone between the repair materials and the substrate concrete. At same time low w/c ratio leads to reduce shrinkage which have inverse effect on bond strength [18].

Table (6) shows further increase in the bond strength of both M_{EU} and M_{HS} specimens compared with M_C. This increase in the bond strength of the M_{EU} and M_{HS} is likely related to:

- Refinements in pore structure and denser, thinner interfacial transition zone between the repair materials and the substrate concrete, meaningless proportional loss of this weaker phase due to use low w/c ratio and some additives in mortar;
- Size and shape of aggregate used in M_{EU} or M_{HS} are different from those in M_C, and corresponding effect on friction and aggregate interlock on interface;
- Shrinkage consider influence factor on bond strength, so when reduce due to use low w/c ratio, leads to increase bond strength[18]; and
- Increase bond strength also may relate to the presence of bonding agent in M_{EU} or M_{HS}.

Compatibility Results

Criteria for Compatibility

- It is well established that [17], a prism of higher total depth value deflects less in the flexure test compared to a prism of lower depth value under the same loading. In the composite prism, if the repairing system is failed in bond, and there is a de-bonding between the batched notched area and the substrate, the total depth will be reduced, and the load deflection curve should have lesser slop than the slop of the load deflection curve of compatible composite prism (i.e without de-bonding) as shown in Fig.5. Otherwise, the load will transfer to repair material, and the composed prism consider compatible.

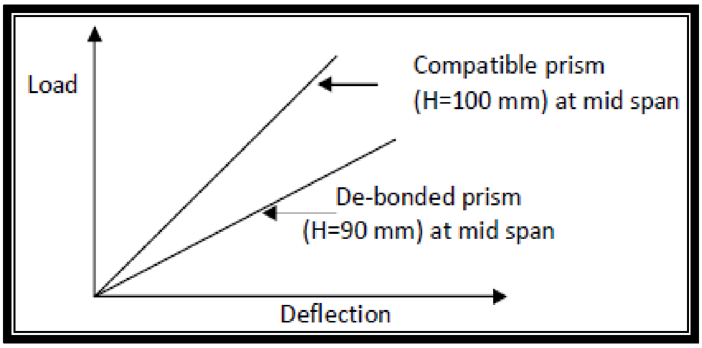


Figure (5) Typical load deflection curve of the composite and substrate beam [17].

- In case of stiffer repairing materials, flexural strength ratio, FCR (flexural strength of repair materials divided by flexural strength of substrate beam) is typically greater than 1.0; the composite section ratio (flexural strength of composite beam divided by flexural strength of substrate beam) is expected to be more than 1.0. If not, then the load transfer is not adequate and the repair material is incompatible with the substrate concrete.
- In case of weaker repairing material, FCR and composite section ratio is less than 1.0, and if the load transfer is adequate, the composite beam is forced to fail in the middle third portion of the beam or inside the repair material due to maximum stress induced. If the failure mode is on the edge of the notch or if the repair material is de-bonded, instead of failing in the middle-third of the patched beam, then the repair material is not compatible with the substrate beam.
- In case of repairing materials where composite section ratio is greater than 1.0, the load carrying capacity is more than that of the substrate concrete. Therefore, the failure mode is immaterial whether it is failing at the middle-third or at the edge of the repair section in the composite beam. The repair material can be assumed to be compatible in those cases within the maximum anticipated stress levels.

Compatibility Results and it's Analysis

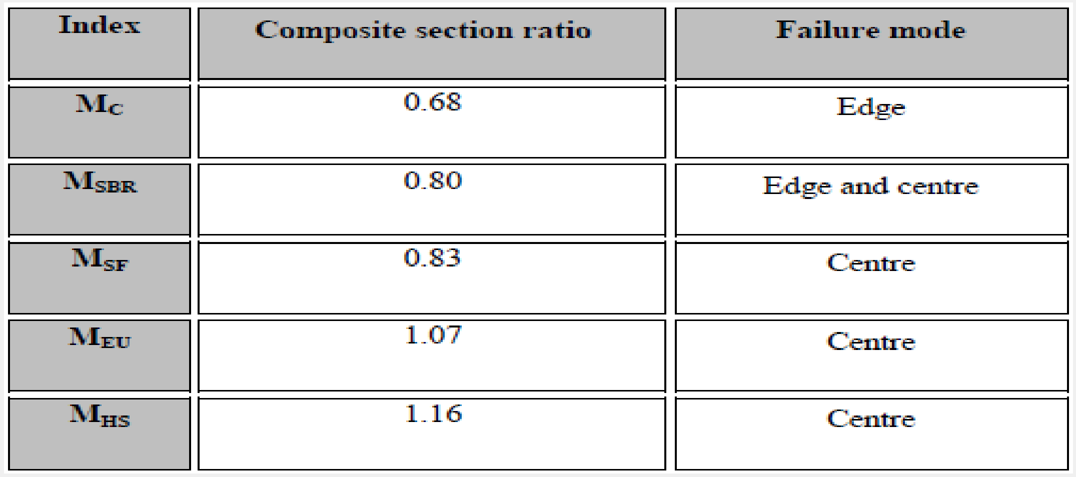
The bending test results of composite section beam for both types of substrate concrete (C_{25} and C_{50}) using three different shapes for repaired area edge are shown in Tables (7) through (12).

Fig.6 shows the three failures modes that observed through conducting the bending tests on the composite section beam.

It can be observed from Tables (7) through table (12) that failure modes for repair materials that have FCR less than 1.0 are either at the edge or de-bonding. For instance repair material M_C in the Table (7) and repairing material M_{SBR} in the Table (8), have the FCR 0.68 and 0.76 and the failure occur at the edge and de-laminated, respectively. This indicates that these materials are not compatible with the substrate concrete. While the M_{EU} or M_{HS} in Tables (7) through 10, M_{HS} in Tables (11 and 12), have composite section ratios greater than 1.0, which indicate that these section beams have greater flexural strength than a substrate concrete beam. Therefore, these materials are considered to be compatible with the substrate concrete, whether failure occurs at the centre, or at the edge.

Also it can be observed from Tables (7) through 12, that even though FCR of repair materials M_{SF}, M_{EU}, and M_{HS} in Tables (7) through 9; M_C, M_{SBR}, and M_{SF} in Tables (10) through table(12) ; M_{EU} in Tables (11) and (12) are greater than 1.0, have composite section ratios less than 1.0. The repair materials that have composite section ratios less than 1.0, and have FCR greater than 1.0, are considered incompatible with the substrate concrete.

Table(7) Compatibility test results of repair materials and concrete using C_{50} + acute angle.



Index	Composite section ratio	Failure mode
M_C	0.68	Edge
M_{SBR}	0.80	Edge and centre
M_{SF}	0.83	Centre
M_{EU}	1.07	Centre
M_{HS}	1.16	Centre

Table(8) Compatibility test results of repairing materials and concrete using C_{50} + square angle.

Index	Composite section ratio	Failure mode
M_{C}	0.68	De-lamination
M_{SBR}	0.76	De-lamination
M_{SF}	0.80	Edge
M_{EU}	1.01	Centre
M_{HS}	1.10	Centre

Table (9) Compatibility test results of repairing materials and concrete using C_{50} + obtuse angle.

Index	Composite section ratio	Failure mode
M_{C}	0.65	De-lamination
M_{SBR}	0.76	De-lamination
M_{SF}	0.78	De-lamination and edge
M_{EU}	1.02	Centre
M_{HS}	1.10	Centre

Table(10) Compatibility test results of repairing materials and concrete using C_{25} + square angle

Index	Composite section ratio	Failure mode
M_{C}	0.99	Centre
M_{SBR}	0.98	Centre
M_{SF}	0.99	Centre
M_{EU}	1.01	Centre
M_{HS}	1.07	Centre

Table(11) Compatibility test results of repairing materials and concrete using C_{25} + acute angle

Index	Composite section ratio	Failure mode
M_C	0.95	Edge
M_{SBR}	0.94	Edge
M_{SF}	0.96	Centre
M_{EU}	0.99	Centre and edge
M_{HS}	1.04	Centre

Table(12) Compatibility test results of repairing materials and concrete using C_{25} + obtuse angle.

Index	Composite section ratio	Failure mode
M_C	0.96	Centre
M_{SBR}	0.93	Edge
M_{SF}	0.94	Edge
M_{EU}	0.99	Centre
M_{HS}	1.05	Centre

(a) (b) (c)

Figure (6) Failure modes of composite section beam, (a) the failure at the centre, (b) the failure at edge of the notch section, and (c) the failure as de-lamination notch section.

CONCLUSIONS

Based on the results from the experimental program it can be concluded the following:

a) The M_{EU}, M_{HS}, M_{SF}, and M_{SBR} repair materials show considerable improvement in compressive strength**,** modulus of rupture, drying shrinkage, and bond strength as compared with the reference repair material. M_{EU} and M_{HS} are the better among them.

b) Using silica fume, high range water reducing agent and styrene butadiene latex were improve the mechanical and durability properties of the repair material compared with conventional mortar Mc

c) 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**.**

d) The compressive and flexural strengths are not the crucial factors in the success of repairing systems. It is the dry shrinkage and bond strength between repair and substrate concrete which is greatly influence the compatibility of concrete repairing systems, and therefore determine its successful use.

e) The compatibility results explain that using M_{SF}, M_{SBR}, and M_C with C_{25} showed better compatibility results than it's using with C_{50}, while using M_{HSX}, and M_{EU} with C_{50} showed better compatibility results than it's using with C_{25}.

f) The compatibility between the repair materials and the substrate concrete was significantly influence by edge shape of the area being repaired. Acute angle edge shapes seem to be more efficient than square and obtuse angle shape.

Further investigations need to be done to recognize the effect of curing conditions, surface texture and roughness on bond strength

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