

## **Flexural Performance of RC Beams Repaired with Commercial Repair Materials**

**Yousef A. Al-Salloum**

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

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**Abstract.** Different types of cementitious repair materials are commercially available in the local market. Almost all repair material suppliers claim that their products are most suitable for concrete repair under different environmental and loading conditions. This necessitates the need to check all aspects of the repair materials which include their behavior when used in structural elements. The objective of this research was to investigate the performance of the most commonly used cementitious repair materials when used to repair structural elements. This was achieved through the evaluation of the flexural performance of 24 RC beams repaired using nine selected types of the most commonly used repair materials (supplied by three leading suppliers in the country). The results were compared with two identical beams repaired with concrete and also with two identical beams cast with concrete monolithically (no repair). The results showed that the repair materials subjected to tensile stresses had no significant contribution (to beam response) compared to normal concrete. However, the influence of the repair materials was much better when used to repair structural parts subjected to compressive stresses.

**Keywords:** RC beams, Repair materials, Flexural performance.

### **Notation**

$a$	=	depth of stress block for beam repaired with concrete
$a_r$	=	depth of stress block for beam repaired with repair material
$A_s$	=	reinforcement area
$b$	=	width of beam
$c$	=	depth of neutral axis for beam repaired with concrete
$C$	=	total force of compression
$c_r$	=	depth of neutral axis for beam repaired with repair material
$d$	=	effective depth of beam
$h$	=	height (thickness) of beam
N.A.	=	neutral axis

$T$	=	total force of tension
$Z_{con}$	=	lever arm for beam section repaired with concrete
$Z_{rep}$	=	lever arm for beam section repaired with repair material
$\varepsilon_y$	=	yield strain of steel bars
$\varepsilon_s$	=	strain in steel bars
$\varepsilon_{cu}$	=	ultimate strain in concrete
$f'_c$	=	compressive strength of concrete
$f'_{c(rep)}$	=	compressive strength of repair material
$f_y$	=	yield strength of steel bars

### Introduction

In recent years, concrete deterioration due to the corrosion of the steel reinforcement has become a major problem worldwide. Undoubtedly, the prevention of deterioration is the best cure for the problem, but a large number of structures, which are already contaminated with chlorides and carbonation, require urgent repair. The most common form of rehabilitation for a deteriorated structure is through patching (removing the deteriorated concrete and replacing it with a new material), thus increasing the design life of the structure.

Although patching is widely used in the rehabilitation of structures, there is a little differentiation shown between the repair materials used in structural or non-structural elements. Concrete patching materials are usually used in two different ways: structural repairs, which restore the design load-bearing capacity of a damaged member, or improve the load-bearing capacity of an under-designed member; and non-structural repairs, which improve surface appearance, reduce permeability, protect reinforcement, or improve abrasion resistance.

Repairing a concrete beam should result in a composite concrete beam whose strength is at least as high as the original monolithic beam. The strength of the composite beam depends on the bond between the old concrete and the new concrete or the new repair material. Repairing process consists of the removal of unsound concrete, cleaning of exposed concrete surface and reinforcement, replacement of corroded reinforcing steel, replacement of removed concrete with repair material, and finally curing of the repaired part [1-3]. Regardless of the type of repair, ensuring that the repair is compatible with the substrate concrete is crucial, as the repaired member must behave monolithically and carry all stresses in the region of the repair without distress or deterioration [4].

The proper selection of materials for a repair program is normally more involved and important than it is for new construction. The range of materials used is usually broader than just reinforcing steel and Portland cement concrete. Thus, the rehabilitation engineer has to be concerned with the compatibility of the various materials with each

other and with the original concrete, and frequently, the speed at which they can be applied and the serviceability conditions of the structure under consideration [5].

Over the years, the number of researches investigating the properties of repair materials has increased considerably. Some of the engineering properties of repair materials can be found in the literature [6-9] 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 technique must be evaluated in the light of field conditions [6]. Therefore, under given conditions, in order to arrive at appropriate repair material and method of application, systematic rules and guidelines are needed. Extensive lab and field tests are required to prepare these rules and guidelines.

Concrete repair industry has witnessed an enormous growth in the Kingdom of Saudi Arabia. The difficulty arises from the lack of generally accepted performance criteria guidelines for the repair technology and the advanced engineering concepts. Different types of repair materials are commercially available in the local market. Although there are wide conflicts in the material characteristics as indicated in the literature [10-11], the producers of these materials claim that their materials are the most suitable for concrete repair under different environmental and loading conditions. However, limited research has been carried out to investigate the actual performance of the cementitious materials and their compatibility with the substrate concrete under flexural tensile or compressive stresses (bending).

The objective of this research was to investigate the flexural performance of some of the major commercially available repair materials (under ambient laboratory conditions) to strengthen or repair structural elements. Nine cementitious repair materials from three main local suppliers of repair materials (three materials from each supplier) were used to repair identical specimens of RC beams, which were then subjected to flexural stresses. The performance of each repair material was assessed through the flexural behavior of the different specimens. The results of this investigation are expected to provide a certain confidence level in using these commercially available materials to repair structural elements.

### **Experimental Program**

In addition to concrete, which was used as a reference repair material, three of the widely used repair materials from each of the three leading repair material suppliers were used in the investigation. The three materials from each supplier were equivalent to the three materials from each of the other two suppliers (according to the material supplier representative and the data sheets of the materials).

### Beam details and set-up

The test program consisted of 28 beams divided into 6 groups as shown in Table 1. The first group (2 beams) was cast with concrete monolithically (no repair) and was used as the control (reference) group. The second group (2 beams) was repaired using normal concrete mix as that of the reference beams.

The third group (6 beams) was divided into 3 subgroups (2 beams each) that were repaired in the tension side (bottom of the beam) with 3 equivalent repair materials, namely M1, M2 and M3 from the 3 different material suppliers.

**Table 1. The beam groups**

Repair Material Group	Material Designation	Repair Supplier	No. of Beam Specimens	Repaired in Tension (T) or in Compression (C)
Reference	Control	No Repair	2	-
R-NC	N	Normal Concrete	2	T
R-G1	M1	1	2	T
	M2	2	2	T
	M3	3	2	T
R-G2	M4	1	2	T
	M5	2	2	T
	M6	3	2	T
R-G3	M7	1	2	T
	M8	2	2	T
	M9	3	2	T
R-G3C	M7-C	1	2	C
	M8-C	2	2	C
	M9-C	3	2	C
<b>Total</b>			<b>28</b>	

The fourth group (6 beams) was also divided into 3 subgroups (2 beams each) that were repaired in the tension side with another 3 equivalent repair materials, namely M4, M5 and M6 from the 3 material suppliers. The fifth group (6 beams) was also divided into 3 subgroups (2 beams each) that were repaired in the tension side with another 3 equivalent repair materials, namely M7, M8 and M9 from the same 3 material suppliers. The last group (sixth group) was similar to the fifth group but the repair was applied on the compression side (top of the beam).

The test span of all beams was 1200 mm with a cross section of 150 mm x 150 mm. All beams were reinforced with 2  $\phi$ 10 mm steel bars (main reinforcement) in tension side (bottom) of the beam, and 2 $\phi$  6 mm in the compression side (top) of the beam, and provided with  $\phi$ 6 mm steel stirrups @75 mm center to center. Details are shown in Fig. 1. All beams were tested simply supported subjected to two-point loads symmetrically placed at equal distances 75 mm from the centerline of the beam.

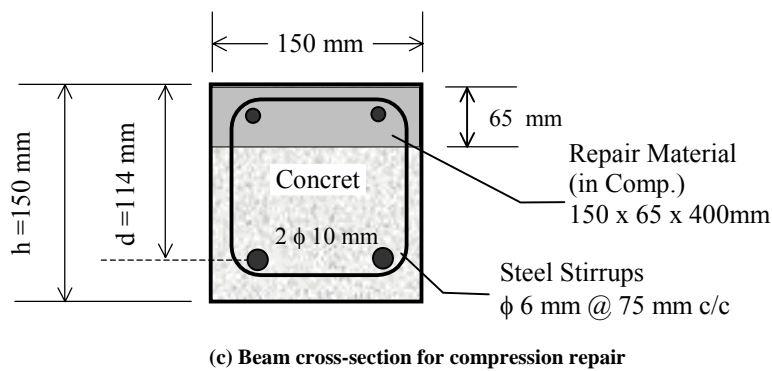
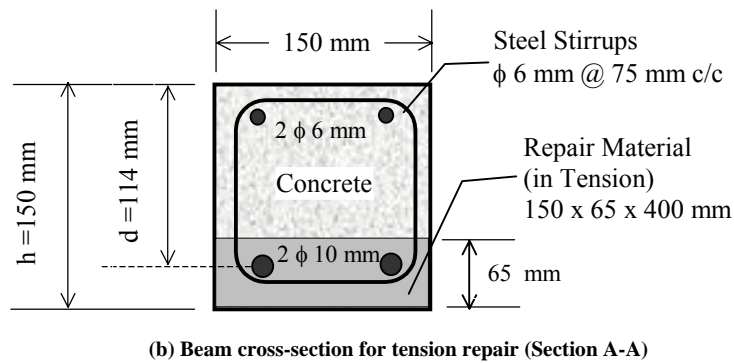
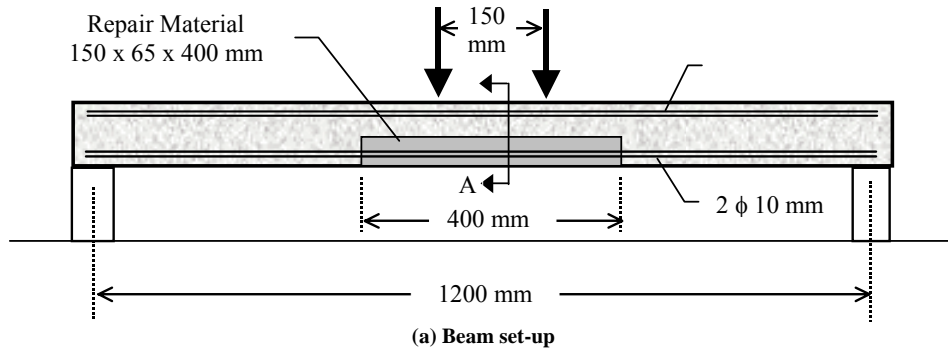


Fig. 1. The beam set-up and cross-sections for tension and compression repair.

The beams were cast as shown in Fig. 1 in which a hole of 400 mm (length) by 65 mm (height) and 150 mm (width) was left open in each beam which represents the

damaged or deteriorated area that needs to be repaired using the repair materials. This hole was placed at the middle third region of the beam, having the highest moment. Similar dimensions of this opening were also used in the compression side (top) for the beams repaired in compression side.

### Materials properties

#### Concrete

The compressive strength of concrete was determined by testing concrete cylinders on the day of testing of beams. The average compressive strength of the tested cylinders was 34 MPa.

#### Steel

The yield strength of steel bars used in this experimental program was determined by performing the tensile test on specimens of each bar diameter. The yield strengths of  $\phi$  10 mm (main reinforcement) and  $\phi$  6 mm (transverse reinforcement) were 424 MPa and 316 MPa, respectively.

#### Repair materials

Nine repair materials available in the local market were used for repairing the RC beam specimens. As per the details provided by respective manufacturers, these repair materials are durable and possess sufficient bonding ability. Some key features of these materials, significant for present study, are listed in Table 2. The values shown in these tables are obtained from the manufacturers' datasheets.

**Table 2. Mix details and salient features of repair materials**

Mix No.	w/cp Ratio	Wt. of Powder, kg	$f'_c$ at 28 days, MPa (company data)	Curing (company data)
M1	0.1610	57.50	70	Required (time is not mentioned)
M2	0.1577	56.25	55-60	Light fogging for 48-hour curing compound
M3	0.1566	55.00	64	Required (time is not mentioned)
M4	0.1900	40.00	35	Required (time is not mentioned)
M5	0.1735	54.00	45-50	Light fogging for 48-hour curing compound
M6	0.1200	61.25	55	Required (time is not mentioned)
M7	0.1306	61.25	65	Required (time is not mentioned)
M8	0.1050	66.00	65	Light fogging for 48-hour curing compound
M9	0.1060	64.50	60	Required (time is not mentioned)

#### Surface preparation

Regardless of the repair materials to be bonded, surface preparation is the first step in the process of achieving a successful bond between two materials. In this study,

'sand blasting' was employed to prepare the surface of all the test specimens. The purpose of surface preparation was to remove the weak surface layer of the concrete, expose the concrete aggregate to improve the bond with the new material, and provide an even surface.

## **Methodology**

### **Mixing procedure**

The water-cementitious powder ratios (w/cp) used with each mix are described in Table 2 as recommended by the manufacturers.

Mixing procedure for all the materials was carried out as follows: the mixing drum was cleaned properly by means of the jet of water. Then the drum was properly dried. Almost half of the calculated water was then introduced inside the drum and the repair material was then added. The mixer was operated for 1-2 minutes and then the remaining water was added into the mixer. The mixing was carried out until a homogenized mix was achieved (usually takes 6-8 minutes).

It is worth mentioning that in order to repair the tension side of the beam, the beam was kept upside down and the repair material was applied on the prepared surface. This procedure was adopted for easy and effective application of repair material on the tension side. However, to repair the tension side of the beam (bottom) in real field conditions, the repair material can be conveyed through a hose and pneumatically projected at high velocity onto the prepared surface. This procedure will place and compact the repair material simultaneously due to the force with which it is projected from the nozzle.

The beams to be repaired were first coated with the primers of the corresponding repair material. The mix was then poured into the properly enclosed pouring gap of the beam to be repaired by means of a scoop and the material was then tampered uniformly as shown in Fig. 2. After achieving the required filling, the repair material was smoothed-off on the surface by a trowel. Wet-burlap and plastic sheets were used to cover the beams to avoid any kind of moisture loss. The wooden enclosures of the repair section were demolded after 24 hours and the spray curing was started. The moist curing was continued for 28 days, and later the beams were tested.

## **Test Results**

The 28 beams (presented in Table 1) were tested simply supported subjected to two-point loads as shown in Fig. 1. The load-deflection relationships for the control (reference beam with no repair) specimens and for beams repaired with normal concrete are shown in Figs. 3 and 4, respectively. Three repair materials (M7, M8 and M9) were selected to present the load-deflection relationships for repaired specimens. Figures 5-7 show the load-deflection relationships for tension side repaired beams, whereas Figs. 8-10 show load-deflection relationships for compression side repaired beams. A summary

of test results, however, is presented in Table 3. The average load capacity of the control (reference) specimens (no repair) was 35.2 kN.



Fig. 2. Application of primer and repair material.

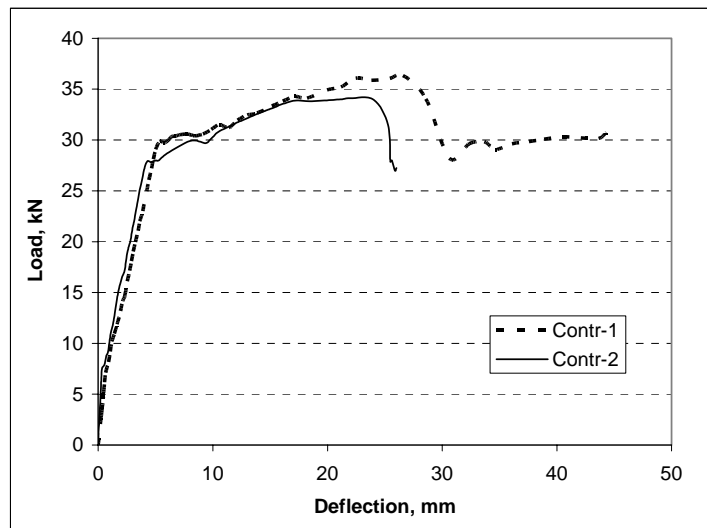


Fig. 3. Load versus deflection for the control (reference) specimens.

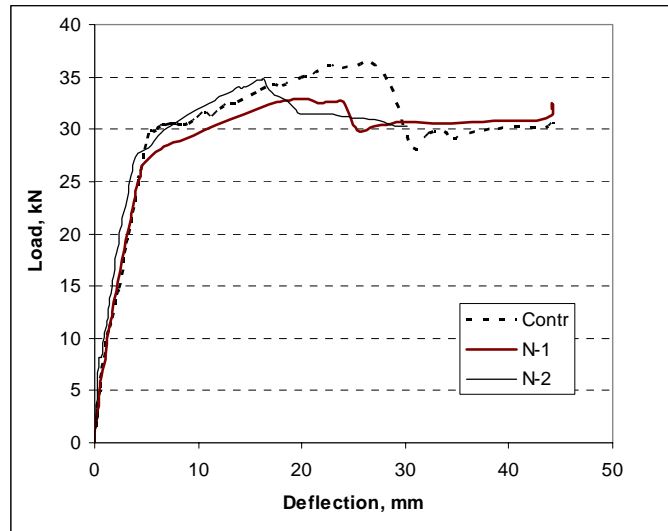


Fig. 4. Load versus deflection for control specimen (Contr) and specimens repaired with normal concrete (N).

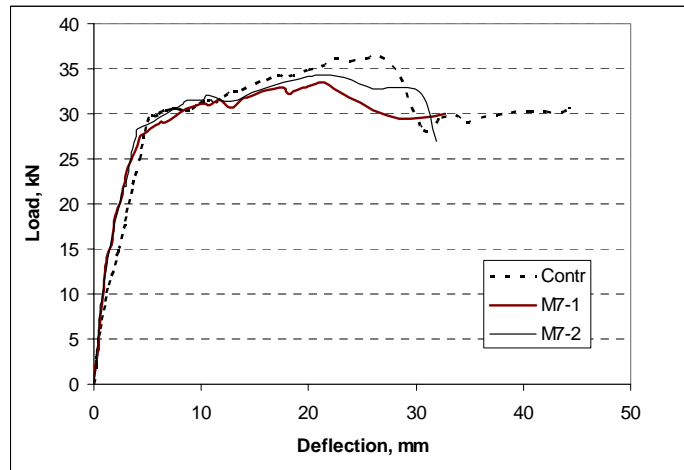


Fig. 5. Load versus deflection for the specimens repaired with material (M7) compared with the control specimen (Contr).

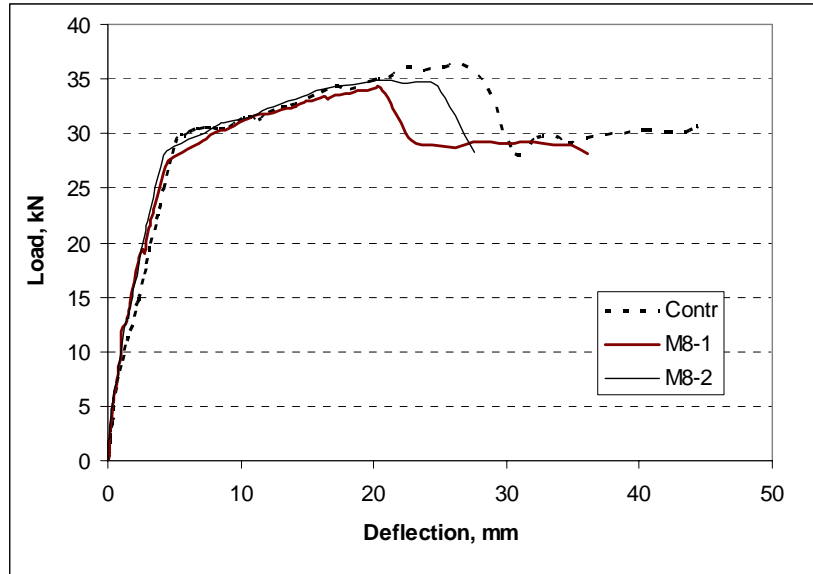


Fig. 6. Load versus deflection for the specimens repaired with material (M8) compared with the control specimen (Contr).

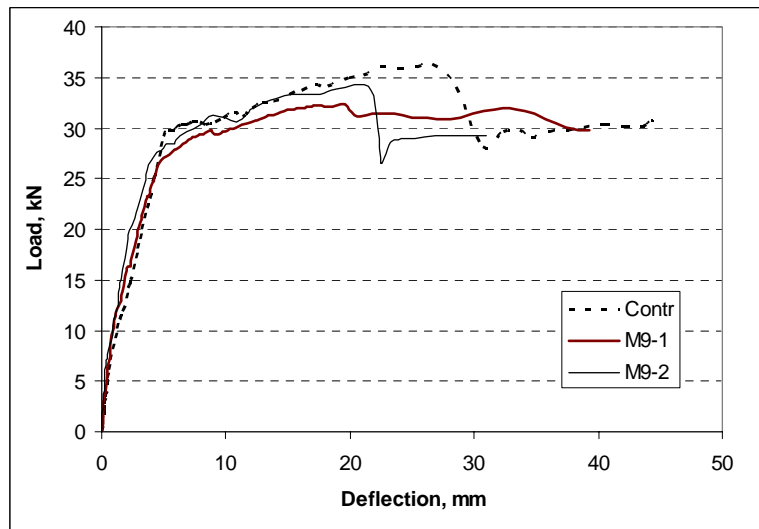


Fig. 7. Load versus deflection for control specimen (Contr) and specimens repaired with material (M9).

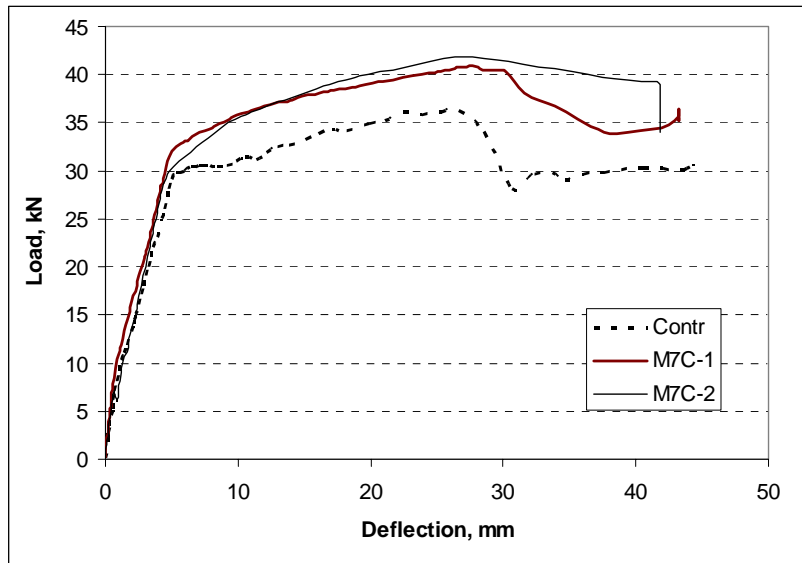


Fig. 8. Load versus deflection for control specimen (Contr) and specimens repaired (in the compression side) with material (M7).

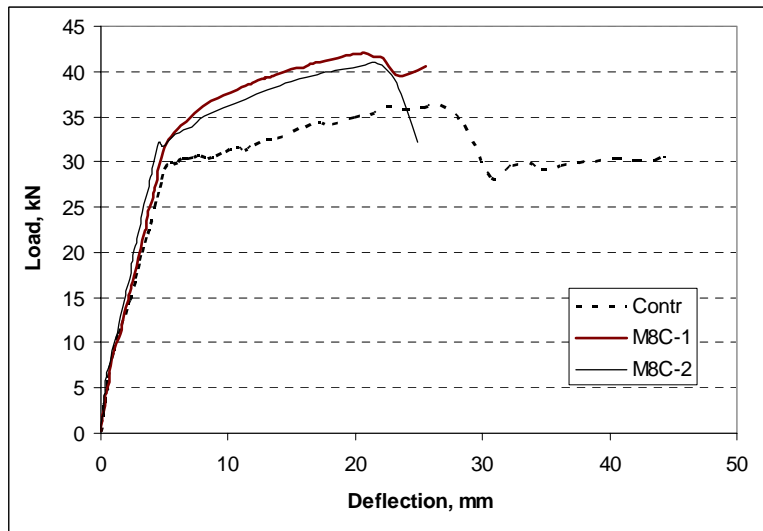


Fig. 9. Load versus deflection for control specimen (Contr) and specimens repaired (in the compression side) with material (M8).

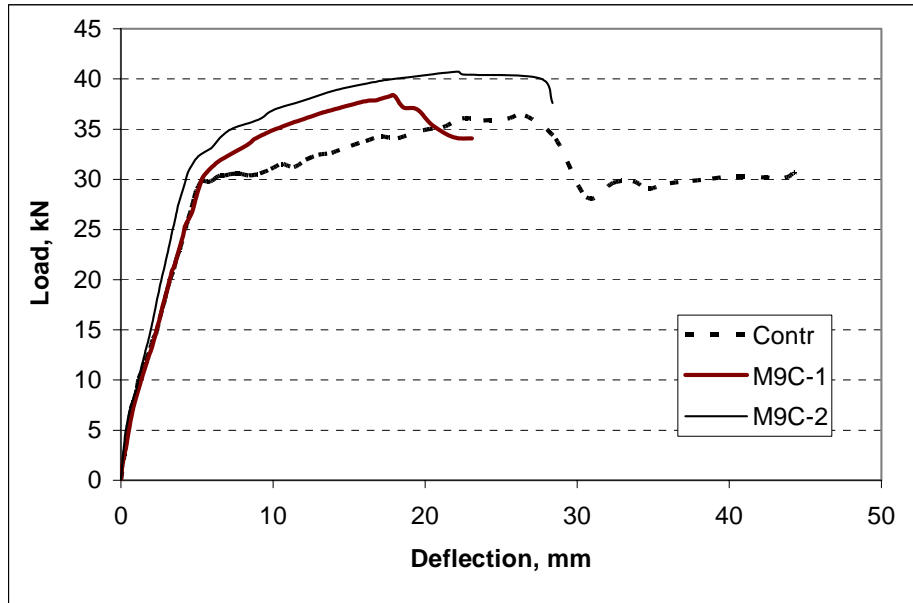


Fig. 10. Load versus deflection for control specimen (Contr) and specimens repaired (in the compression side) with material (M9).

Table 3. The test results of all beam groups

Repair Material Group	Material Designation	Repair Supplier	$P_u$ (kN) Spec-1	$P_u$ (kN) Spec-2	$P_u$ (kN) Avg.	$P_u / P_u\text{-Contr}$
Reference	Control	No Repair	36.3	34.1	35.2	1.000
R-NC	N	-	32.9	34.8	33.8	0.961
R-G1	M1	1	35.7	35.2	35.4	1.006
	M2	2	32.4	34.2	33.3	0.945
	M3	3	32.9	33.7	33.3	0.945
R-G2	M4	1	34.2	32.7	33.4	0.949
	M5	2	34.1	32.5	33.3	0.945
	M6	3	33.5	35.0	34.3	0.973
R-G3	M7	1	33.5	34.3	33.9	0.963
	M8	2	34.2	34.9	34.5	0.981
	M9	3	32.3	33.9	33.1	0.940
R-G3C	M7-C	1	40.9	41.9	41.4	1.175
	M8-C	2	42.0	40.9	41.5	1.178
	M9-C	3	38.3	40.7	39.5	1.123

**Beams repaired in the tension side****Beams repaired with normal concrete (group R-NC)**

The beams repaired with normal concrete (R-NC) in the tension side showed an average load capacity of 33.8 kN, with a change of only -4.0% of the original capacity of the reference beam.

**Beams repaired with cementitious repair materials***Group R-G1*

The beams of group R-G1 repaired with materials M1, M2 and M3 showed load capacities of 35.4, 33.2 and 33.3 kN, respectively, with changes of +0.6%, -5.5% and -5.5% of that of the original capacity of the control (reference) beam.

*Group R-G2*

The beams of group R-G2 repaired with materials M4, M5 and M6 showed load capacities of 33.4, 33.3 and 34.2 kN, respectively, with changes of -5.1%, -5.5% and -2.7% of that of the original capacity of the control (reference) beam.

*Group R-G3*

The beams of group R-G3 repaired with materials M7, M8 and M9 showed load capacities of 33.9, 34.5 and 33.1 kN, respectively, with changes of -3.7%, -1.9% and -6.0% of that of the original capacity of the control (reference) beam.

All beams repaired in tension showed capacities between 33.1 and 35.4 kN, i.e. within +0.6% to -6.0% the capacity of the reference beam (35.2 kN). The beams repaired with normal concrete (R-NC) in the tension side performed almost as those repaired with commercial materials M1 through M9. Therefore, as the costs of repair materials are many times (10-30 times) higher than that of normal concrete, the use of normal concrete is an economical and equally effective proposition for tension side repair of beams.

It is to be noted that, in the tension side, at an early stage, concrete or repair material has to crack in order to transfer strains to steel through bond. At the ultimate strength stage, stress in tension steel exceeds its yield value and beam reaches its load capacity (i.e. failure stage) when the concrete strain in compression reaches its ultimate value, that is,  $\sim 0.003$  (Fig. 11). Therefore, depending on the strength of the repair material, crack may initiate earlier or later but the load capacity will finally be governed by the bond between the repair material and steel. It is due to this reason, with repair material, that no improvement in load capacity was observed compared to repair with concrete. Further, with repair material, the load capacity values were little less than that of the reference beam because the bond with repair material was a bit less strong than that with concrete in the reference beam.

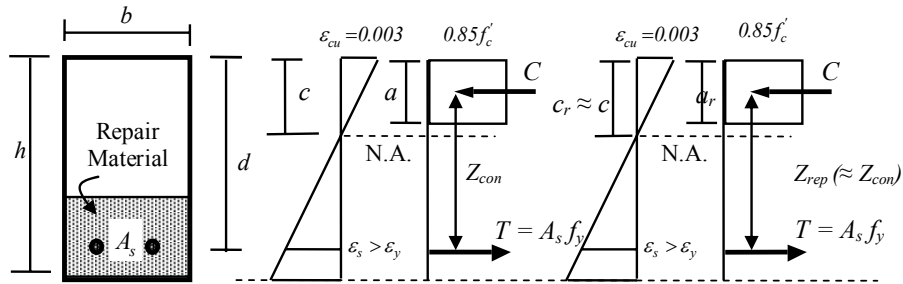


Fig. 11. Stress-strain diagrams for tension side repaired specimens.

Furthermore, the load-deflection curves of beams repaired in the tension side (Figs. 5-7) showed initial stiffness almost similar to that of the reference beam. Also, the results show that there is no gain in the deformation capacity or ductility (defined as the area under the load-deflection curve).

### Beams repaired in the compression side

#### Group R-G3C

The beams of group R-G3C repaired in compression with materials M7, M8 and M9 showed load capacities of 41.4, 41.5 and 39.5 kN, respectively, with changes of 17.5%, 17.8% and 12.3% more than that of the original capacity of the control (reference) beam.

All beams repaired in compression showed capacities between 39.5 and 41.5 kN, with gains in load capacity between 12.3% and 17.8% over that of the control beam (35.2 kN). This gain in load capacity can be attributed to the higher compressive strength of repair material. Due to the higher strength on the top side, the net compressive force shifts up, and as a result, the arm of the forces becomes larger. This increase in the lever arm ultimately increases the moment resistance of the beam (Fig. 12) which leads to a higher load capacity for the repaired beam.

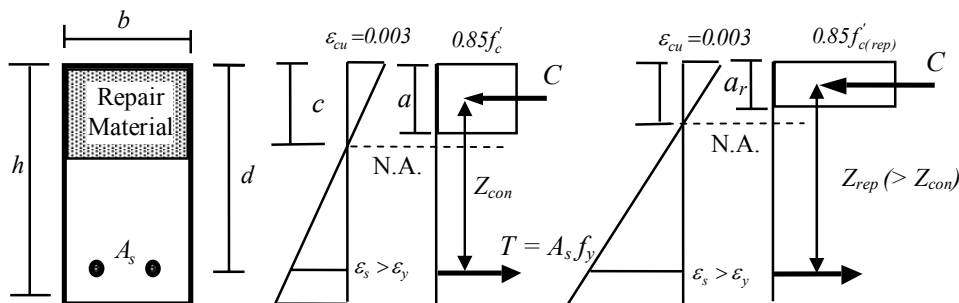


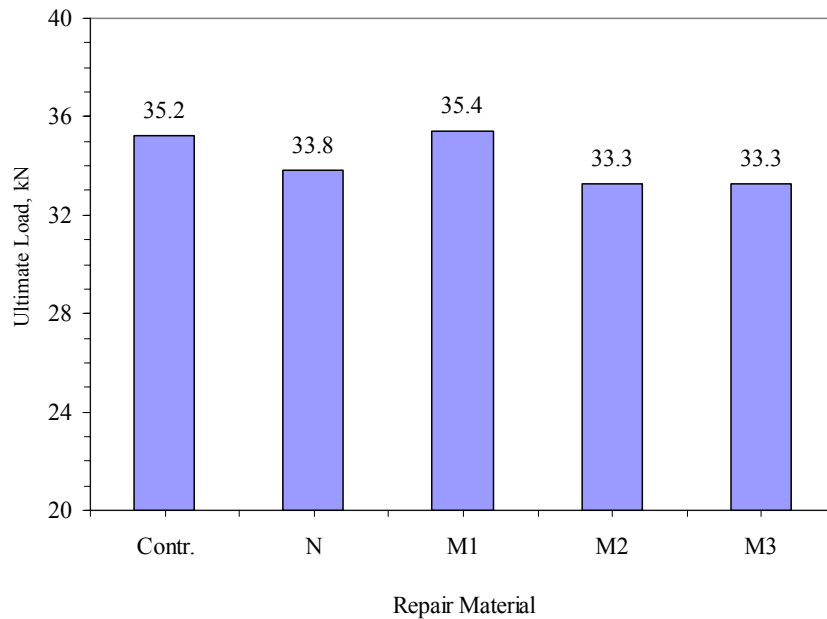
Fig. 12. Stress-strain diagrams for compression side repaired specimens.

Furthermore, the load-deflection curves of beams repaired in compression side (Figs. 8-10) showed initial stiffness almost the same as that of the control beam. However, the deformation capacity (ductility) of such repaired beams is substantially higher than that of the reference beam.

### Repair materials groups

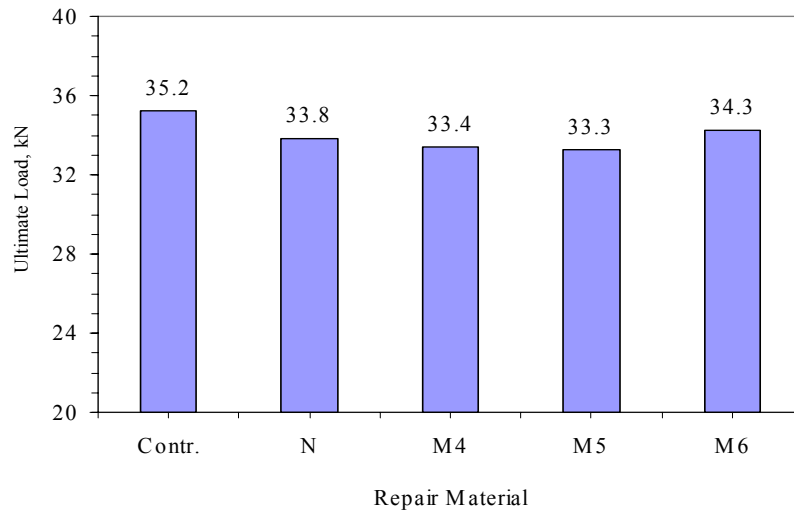
The materials M1, M2 and M3 are produced by three different companies. They are equivalent to each other in the market. Therefore, it is feasible to study the performance of each of these materials and compare the results with each other and with specimens repaired with normal concrete and with the control specimens.

Figure 13 shows this comparison of repair in tension using M1, M2 and M3 with concrete repair (N) and reference (Contr.) beams. The results show that M1, M2 and M3 produced no significant gain in performance compared to that of beam repaired with normal concrete.



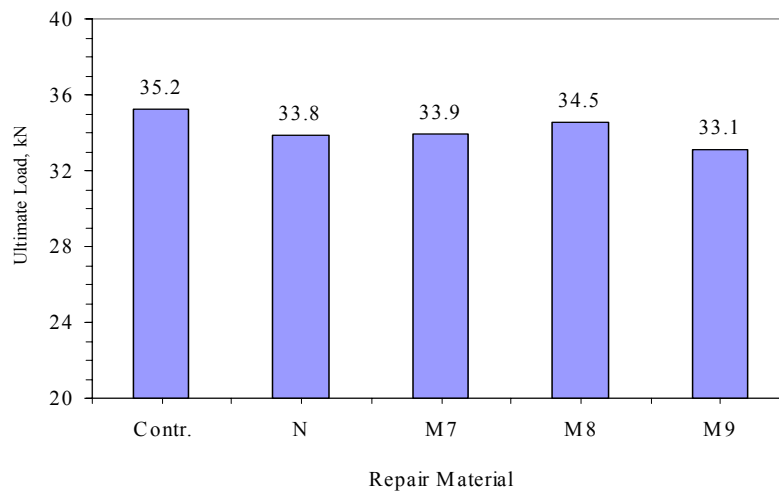
**Fig. 13. Ultimate loads of beams repaired in Tension with M1, M2, M3 and normal concrete compared to the control beam.**

Similarly, Fig. 14 shows the performance of the second group M4, M5 and M6 materials. The figure shows that M4, M5 and M6 performed in tension similar to that repaired with concrete and slightly less than the control monolithic beam.



**Fig. 14.** Ultimate loads of beams repaired in *Tension* with M4, M5, M6 and normal concrete compared to the control beam.

Figure 15 shows the performance of the third group M7, M8 and M9 materials in tension. The figure shows that M8 is better than M7 and M9 but less than the control. Also, M7 and M9 have performance almost similar to that of repaired with concrete.



**Fig. 15.** Ultimate loads of beams repaired in *Tension* with M7, M8, M9 and normal concrete compared to the control beam.

Figure 16 shows the performance of the third group M7, M8 and M9 materials in compression. Actually all the three materials performed well in compression. The material M8 produced the highest capacity (41.5 kN) compared to 35.2 kN of the control, i.e. an increase by 17.8%.

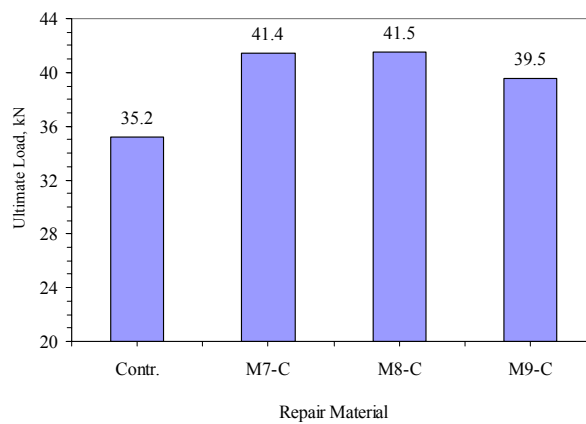


Fig. 16. Ultimate loads of beams repaired in *Compression* with M7, M8, M9 and compared to the control beam.

#### Failure pattern

All beams failed by flexure without debonding of the repair materials. Photos of the beams after testing showing typical failures of control and repaired specimens are shown in Figs. 17-19.



Fig. 17. Control and tension side concrete (N) repaired specimens.



Fig. 18. Beams repaired in *Tension* with M1, M2 and M3 materials.



Fig. 19. Beams repaired in *Compression* with M7, M8 and M9 materials.

### Conclusions

Beams repaired in the tension side:

- For materials of the same group M1, M2 and M3, the material M1 produced the best performance. Materials M2 and M3 performed similar to that of beams repaired with normal concrete.
- For materials of the same group M4, M5 and M6, all the three materials are similar to each other in their performance. They are slightly better than those repaired with normal concrete.
- For materials of the same group M7, M8 and M9, the M7 and M8 produced the best performance. The material M9 performed similar to that of beams repaired with normal concrete.

In general, the capacity of beams can be retained within 4% using normal concrete to repair damaged parts subjected to tension stresses. The results clearly indicate that under the testing conditions considered in this study, there is no sound justification for using highly expensive cementitious repair materials in replacing normal concrete for repairing RC elements subjected to tensile flexural stresses.

Beams repaired in the compression side:

- For materials of the same group M7, M8 and M9, all the three materials are similar to each other in their performance and produced capacity higher than that of the control specimen.

In conclusion, if the part needed to repair is subjected to compressive flexural stresses, the use of repair materials is highly justified since it efficiently retains the capacity of the beam.

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ص.ب. ٨٠٠، الرياض ١١٤٢١، المملكة العربية السعودية

(قدّم للنشر في ١٠/٠٥/٢٠٠٥ م؛ وقبل للنشر في ١١/٠١/٢٠٠٦ م)

**ملخص البحث.** تتوفر الآن في الأسواق المحلية أنواع مختلفة من المواد الإسمنتية المستخدمة في إصلاح الخرسانة. معظم الشركات المصنعة لتلك المواد تدعي بأن موادها هي الأفضل لعمليات إصلاح الخرسانة تحت الظروف البيئية والتشغيلية المختلفة، لذلك فإن هناك حاجة كبيرة لمعرفة مدى فعالية تلك المواد لإصلاح المنشآت الخرسانية وسلوكها عند استخدامها في العناصر الإنشائية. تم في هذا البحث دراسة سلوك بعض المواد الإسمنتية المستخدمة في إصلاح الخرسانة المتوفرة في الأسواق المحلية لترميم العناصر الإنشائية، حيث تم اختيار تسعة أنواع من تلك المواد الشائعة الاستخدام لإصلاح ٢٤ عينة من العوارض الخرسانية المسلحة تم صبها وإعدادها لهذه الدراسة، بالإضافة إلى عينتين تم إصلاحهما باستخدام الخرسانة العادية وعتين تم صبهما من الخرسانة الكاملة وذلك لاستخدامها كمراجع للمقارنة. تم اختبار جميع العينات تحت تأثير قوى الشد. أوضحت نتائج هذه الاختبارات بأن أداء تلك المواد - عند استخدامها لإصلاح الأجزاء المعرضة لإجهادات الشد - لا يختلف كثيراً عن أداء الخرسانة العادية، بينما كان أداؤها أفضل عندما استخدمت لإصلاح الأجزاء المعرضة لإجهادات الضغط.

