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REVIEW ARTICLE

Evaluating the Efficiency of Epoxy Injection Technique for Repairing Normal and High Strength Concrete Beams - A Critical Review

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ABSTRACT – Concrete deficiency is a very common issue and has several forms, including cracks in a plastic or hardened state. Various materials and methods are used nowadays for repairing because repairing is cost-effective, can rehabilitate deteriorated structures, and increases the overall structural life cycle. Epoxy injection is one technique used for repairing cracks with 0.05mm width. The main objective of this review is to evaluate the efficiency of this technique for normal and high-strength concrete beams and investigate the factors that affect the improvement ratio of repaired samples, such as; the depth of the beam, the number of drilled holes for injection, reinforcement distribution, the viscosity of the epoxy and width of the crack. The results proved that epoxy injection is an effective method for restoring the original structure and stiffness if sufficient repairing procedures are followed. A low viscosity epoxy is preferred as it can penetrate easily into the crack depth and restore strength. On the other hand, beams with smaller depth had a higher percentage of improvement, and the number of drilled holes for injection directly affects the results, fewer holes better the strength improvement.

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BACKGROUND

The actual tendency in civil engineering is to extend the life cycle of large-scale structures [1]. Due to reduced or lack of raw materials and resources for constructing new buildings, it is essential to repair the existing structures using modern techniques since these techniques are just as important as constructing and designing new structures [2]. The most common causes of Failures and defects in concrete structures are; Structural deficiency, Fire damage, deterioration due to low-quality concrete and the presence of chlorides in the concrete, chemical attack, and Physical damage [2, 3]. One type of deterioration in concrete is crack, which can appear in plastics and hardened concrete. In the plastic state, there are two types of cracks; plastic shrinkage and settlement cracking. Meanwhile, the main causes for cracking in a hardened state are dry shrinkage, thermal expansion, chemical attacks, temperature, and R.C. corrosion [4]; they are not only damaging the aesthetic of the structure but lead to reinforcement corrosion, decrease durability, and strength [5- 9].

The proper crack repair depends on knowing the causes and selecting the repair procedures to take these causes into account; otherwise, the repair may only be temporary [14]. Successful long-term repair procedures must attack the causes of the cracks as well as the cracks themselves [10-12]. Many methods are used to upgrade the structural members, such as routing and sealing, gravity filling, ferrocement, dry packing, polymer impregnation, overlay and surface treatment, and Epoxy injection [13]. The epoxy injection technique is considered for investigation and review in this literature. It has been one of the most common techniques for repairing cracks for the last two decades [14]. This paper highlights the efficiency of the epoxy injection method for repairing normal and high-strength reinforced concrete beams. In addition, to explain how this technique affects the load carry capacity of repair normal and high-strength reinforced concrete beams.

GENERAL OVERVIEW OF EPOXY INJECTION METHOD

This technique is used to repair structural cracks having 0.05mm in width to increase the bond and strength of cracked concrete [14]. In this technique, several holes are drilled at close intervals along the length of the cracks. In the case of huge structures, several holes (2cm in diameter and 2cm deep spaced at 15 to 30cm intervals) are drilled along the crack direction. Moreover, the epoxy is injected under pressure in each hole until it starts to flow out of the adjacent hole. Later the injection starts at the next hole and so on until the full length of the crack has been treated. Before injecting the sealant, it is necessary to seal the crack at the surface between the holes with rapid curing resin [15]. This technique requires a special technician for execution, having two major components; low viscosity epoxy with compressive strength more than the cracked concrete and a high strength epoxy for sealing the surface cracks between drilled holes [14]. The implementation steps are: [14,15].

1. **Surface Preparation:** Clean and dry the surface with a brush and remove any dirt or fine particle using compression air. The last holes are routed with epoxy at a depth of about 12mm and 20mm in width, having a V- shape.

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2. **Installation of Entry Ports**: The entry port or nipple allows epoxy injection directly into the crack without leaking. In the V-grooving of the cracks, a hole of 20mm in diameter and 12 to25mm below the apex of the V-grooved section is drilled into the crack.
3. **Mixing process**: The mixing can be done by batch or continuous methods. In batch mixing, the adhesive components are premixed in specified proportions with a mechanical stirrer in amounts that can be used before the commencement of the curing of the material.
4. **The epoxy injection step:** In its simplest form, the injection equipment consists of a small reservoir or funnel attached to a length of flexible tubing to provide a gravity head. For small quantities of repair material, small hand-held guns are usually the most economical. They can maintain a steady pressure, reducing the chances of surface seal damage. For big jobs, power-driven pumps are often used for injection. The injection pressures are governed by the width and depth of cracks and the resin's viscosity and seldom exceed 0.10Mpa. The low pressure for fine cracks is a common practice to increase the injection pressure during work to overcome the increase in resistance against the flow as the crack is filled with material.
5. **Removal of Surface Seal:** After completing the injection process, the surface seal is removed using a grinder or other tools appropriate for cleaning. Fittings and holes at the entry ports should be painted with an epoxy patching compound.

OBJECTIVES

The main objectives of this review are to evaluate the efficiency of this technique for normal and high-strength concrete beams and investigate the factors that affect the improvement ratio of repaired samples, such as; depth of the beam, number of drilled holes for injection, reinforcement distribution, the viscosity of the epoxy and width of the crack.

LITERATURE REVIEWS

Normal Strength Unreinforced Concrete Beams

Kunieda et al. [16] evaluated the flexural failure behavior and size effect on the flexural strength of concrete beams repaired by crack injection techniques. For this reason, 12 specimens with 100, 200, and 300 mm depth were prepared and coded under size 1, size 2, and size 3, respectively. Four-point bending tests tested the control beams at age 35 until fractures happened at full depth. After that, both halves joined together with a 3 mm width crack. The bottom of the cracks was sealed to prevent the epoxy's leakage, and after five days of curing, a zero shrinkage epoxy having 7.5 MPa bond strength was used to fill cracks and cured for another seven days. The same procedure and machine were used to load the repaired beams; the results of strength and energy absorption were (1.27, 1.21, and 1.12 %) and (1.41, 1.34, and 1.14 %) for (size 1, size 2, and size 3) respectively compared to their control beams as shown in Figure 1. which means that the epoxy injection is a suitable repairing technique for beams having cracks of 3mm width or restoring concrete loaded until fractured.

Nevertheless, when comparing beams depending on their depth, it is clear that small beams had a higher percentage of improvement in load carry capacity of reinforced concrete beams (strength) and fracture energy ratio compared to the larger size, as illustrated in Figure 1. This is due to complex cracking behavior in larger sizes, which affects the strength of repairing results. Griffin et al. [17] studied the effectiveness of three different epoxies in repairing cracked concrete beams. For this reason, multiple unreinforced concrete beams were constructed with dimensions of 50.5cm long by 10.5cm high. The width of the beams was 10cm at the bottom, and 10.5cm at the top—the slight difference in width allowed for the concrete beams to be removed easily from the molds.

The Avery Universal Testing Machine is used for testing using the third point loading method, as shown in Figure 2. Where a constant bending moment is applied to the middle 100mm of the beam span length, after preparing all samples on the machine, a constant rate of loading was used till caused the beam breakage; then, the fractured beams were repaired by three different epoxy materials, the detail of three epoxies are illustrated in Table 1. Type 1 and Type 2 beams were repaired by epoxy injection method through two injection ports 100 mm apart; the beams were left for at least seven days to allow the epoxy to gain the required strength. Meanwhile, beams in Type 3 were repaired by the gravity filling method. Lastly, all repaired beams were transported and tested under flexural loading. The result was that all beams failed at 2/3 of the span, and the average failure load ratio is 0.71 for Type 1, which means this type of epoxy failed to resist the flexural tensile stresses. Meanwhile, the average failure load ratio was 0.81 and 0.84 for Type 2 and Type 3, respectively.

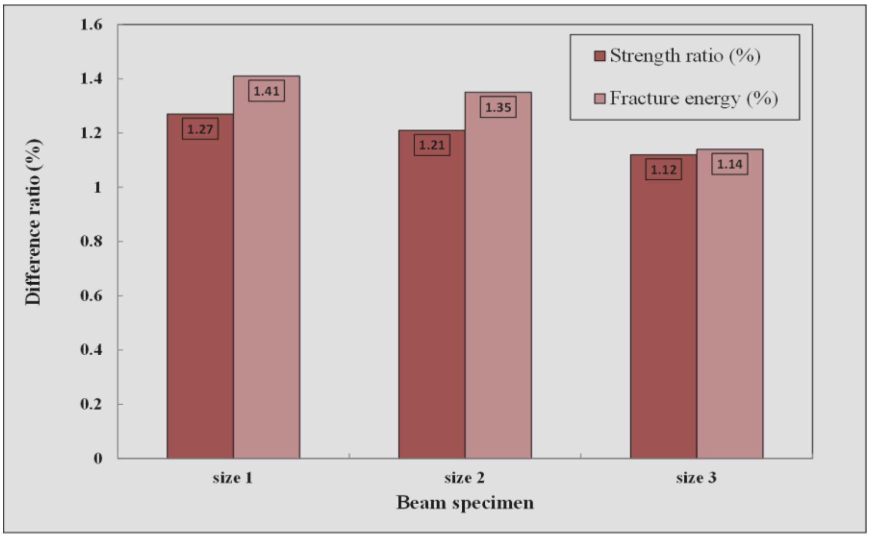

Figure 1. Comparison of strength and energy absorption ratio for different specimens [16].

In conclusion, all beams failed within the middle third due to the third point loading method, which allowed for a constant bending moment in the middle segment of the beam spans. Observation of the repaired beams after breakage shows that they performed differently depending on their epoxy type and application method. In the specimens repaired by Type1 epoxy, the failure occurred at the original crack line. On the other hand, the specimens repaired by Type2 and Type3 epoxy fractured away from the original fracture line. It means the Type2 and Type3 epoxies have performed better than Type1 in bonding the fractured section.

Figure 2. Test setup using Universal Testing Machine [17].

Table 1. Properties of epoxy resins [17].

Type of Epoxy	Flexural strength (MPa)	Compressive Strength (MPa)	Viscosity (mPas)	E modulus (MPa)
Type 1*	45	70	250- 500	3900
Type 2**	45	70	-	-
Type 3***	65	75	145	3000

*: Type1 epoxy has the highest viscosity.
**: Type2 epoxy has the same tensile and compressive strength as Type 1
***: Type3 epoxy has low viscosity and E modulus but high compressive and tensile strength.

Normal Strength Reinforced Concrete Beam

Abdel-zaherElsayedElkhateb et al. [14] investigated the effect of the number of longitudinally drilled holes on the repaired flexural and shear cracks of reinforced concrete beams, and different properties such as stiffness and flexural strength by internal injection using Epoxy103 were evaluated. The detail of all beam dimensions and their compressive strength for 28 days are explained in Table 2. All beams were loaded to failure under flexural tensile load, and the results were compared with undamaged R.C. beams. All the beams were tested to develop a 1mm crack width, three cracked beams were repaired using the epoxy injection repairing technique through different longitudinal holes at different intervals (2, 4, and 6 holes) with 0.8 cm diameter for B4, B5, and B6 respectively, and meanwhile, no repairing was done for B1 and used as a control sample. The detail of the cracked beams after the repair is shown in Figure 3.

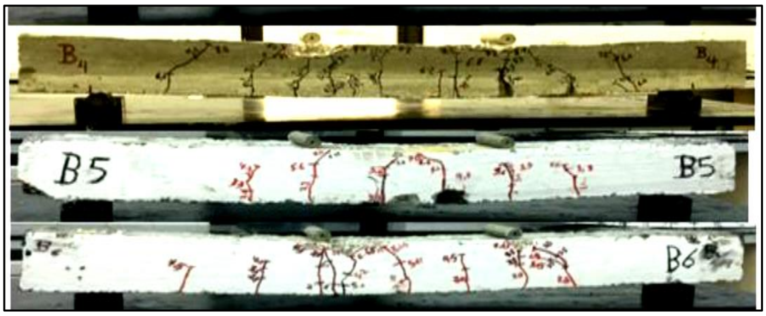

Figure 3. Crack Pattern for beams (B4, B5, and B6) [14].

The obtained test results for mid-span deflection at the crack and failure load, percentage of increase in energy absorption, and percentage of increase in ultimate load for all beams are illustrated in Figure 4. Moreover, were as following; the mid-span deflection increased for repaired beams with epoxy injection compared to the original control beam, and the ultimate deflection at crack load was 70, 96, and 138 % for B4, B5, and B6 respectively, meanwhile. The ratio of increase in ultimate deflection at failure was 53% (B4), 69.4 % (B5) and 82.2 % (B6).

However, when comparing the energy absorption and ultimate load of repaired beams with the control beam, the ratio of increase in energy absorption was 91, 97, and 83% for B4, B5, and B6, respectively, meanwhile the ultimate load increased by 24, 23 and 22% for all repaired beams (B4, B5 and, B6). From the results, it can be conclude that the evaluated properties increased in a high percentage for all repaired beams, which indicates that the internal epoxy injection technique is a suitable method to minimize and close the concrete crakes up to 1mm width and protect the reinforcement. However, the strength increased more for beams with fewer holes because drilling more holes means disturbing the internal structure of concrete, which is essential in the bond of concrete materials.

Ahmad et al. [5] studied the effect of the epoxy injection as a retrofitting technique to strengthen the existing R.C. cracked beams. A total of six full-scale R.C. beams with the same materials and water-cement ratio were prepared in two series, namely series S.B. and series F.B. Each series was composed of three beams, resulting in six full-scale beams. Series S.B. had flexural reinforcement only. Series F.B. had both the flexural and shear reinforcement shown in Table 2. The repairing process was implemented for the six beams by the epoxy injection technique using low viscosity epoxy and cured for three days; the beams were then loaded till the failure occurred to determine the load-carrying capacity of each beam, as shown in Figure 5. The beams were supported and loaded flexibly under a two points loading condition. The load increased gradually till the cracks with 1 mm width were obtained. Furthermore, the crack load, mid-span deflections, and ultimate failure load were recorded for the control samples.

It can be concluded that the beams in series S.B. and F.B. showed a high improvement in deflection, amount of load required for failure, and energy absorption. However, for series S.B., the percentage of increase in ultimate load, mid-span deflection, and energy absorption was 42, 100, and 64% more than the F.B. series. This could be due to the presence of shear reinforcement and reinforcement in the compressive zone provided in series F.B. The conclusion from the obtained results is that a beam with shear reinforcement and injected with epoxy can increase the load-bearing capacity, ductility, and energy-absorbing capacity.

Shah et al. [18] studied the performance evaluation of different materials for repairing concrete beams using the injection method. For this reason, three beams with (467.5, 30.5, and 23) cm dimensions for (length, depth, and width) respectively were prepared with concrete of grade 40, and all beams had two bars at the top, three bars at the bottom, and stirrups to connect main bars as explained in Table 2. After proper curing and hardening, each beam was loaded to a point where noticeable cracks, four to five moderate cracks having 3mm to 4mm width, running 3/4th of the beam's depth, appeared and was taken as a standard for comparison. The cracks were then repaired with epoxies (Chemdur-52, Ultra Injection Resin, and cement grout) using the injection technique. The beams were again loaded till the cracks like the previous ones appeared, and then each beam was loaded to its full capacity.

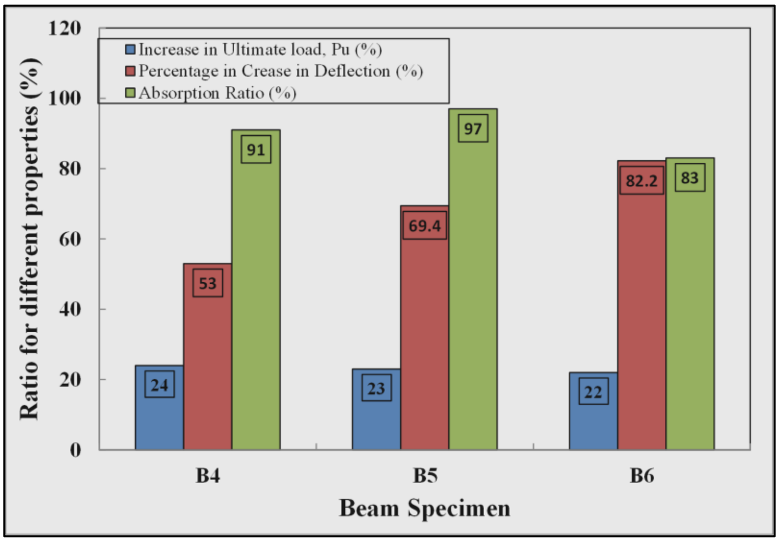

Figure 4. Comparison of strength and energy absorption ratio for different specimens [14].

Table 2. Characteristics of the Tested Beams [5,14,18].

References	Samples	Sample Dimensions, mm	Reinforcement details		Crack width, mm	Compressive Strength, MPa
Ahmed et al. [5]	SB	152.4× 304.8×3351	None	4 Ø 13 bottom	1	30
	F.B.		2 Ø 10 top			
Abdel-Zaher et al. [14]	B1	150x 150 x 1355	2Ø10 Top and Bottom	8 mm Ø stirrups @ 12.5 C/C	Control	29.42
	B4		2Ø10 Top and Bottom	8 mm Ø stirrups @ 12.5 C/C	1	29.42
	B5		2Ø10 Top and Bottom	8 mm Ø stirrups @ 12.5 C/C	1	29.42
	B6		2Ø10 Top and Bottom	8 mm Ø stirrups @ 12.5 C/C	1	29.42
Shah et al. [18]		230×300×4670	2 Ø top	stirrups No .3	3-4	50
			3 Ø bottom			

The results of the tests indicated that the ultimate load-bearing capacity of the repaired beams was more than the design load by 140, 207, and 210% for (Chemdur-52, cement grout, and Ultra Injection Resin) respectively, which is an indicator that injection was an appropriate method to partially or completely restored the strength of a beam with cracks having 3 to 4 mm depth.

Bhishma et al. [19] investigated three different epoxy resin materials (EXPACRETE SNE1, LAPOX B-47, HARDENER K-46, and CONBEXTRA EP10, 65 & 120) to be used in reinforced concrete beams for repairing and restoring good strength and for considering economic aspects. For this reason, six standard-size beams (15×23×150cm) for M50 grade of concrete were distressed in flexure by applying two points load by taking 90% of the ultimate load. After removing the distressed beams from the testing machine, v-shaped grooves were formed in the crack positions. Then loose particles were cleaned with water, and the putting process was done. The mixture of base and the hardener were mixed thoroughly and filled in the groove, and then P.V.C. nozzle pipes of 8 mm diameter were fixed in the cracks and placed at an interval of 5 cm to 10 cm. A hand-blown pressure was used to inject the epoxy mixture. After filling all pipes, they were cut down to the level of beam surface, and after curing for 24 hours, they were again retested to the ultimate failure load.

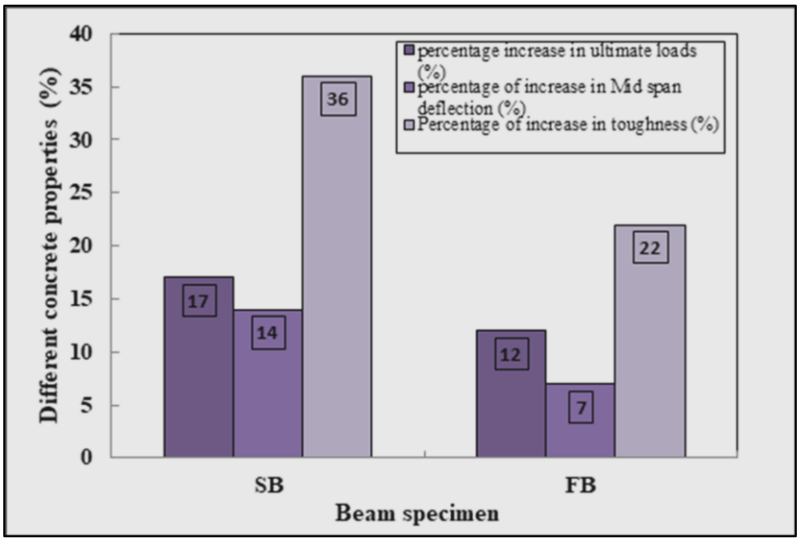

Figure 5. Comparison of strength and energy absorption ratio for different specimens [5].

When comparing the properties of repaired beams with the control beam, the results showed that the average ultimate load and strength for the repaired beams increased by 15, and 10% respectively, meanwhile Expacrete SNE1 was the cheaper epoxy and had the highest percentage of improvement in strength and ultimate load (10, and 18% respectively) as shown in Figure 6.

To sum up, the best repairing material for repairing crack width up to 4 mm in normal reinforced concrete beams is limited between cement grout and ultra-injection resin to restore the load carry capacity of beams.

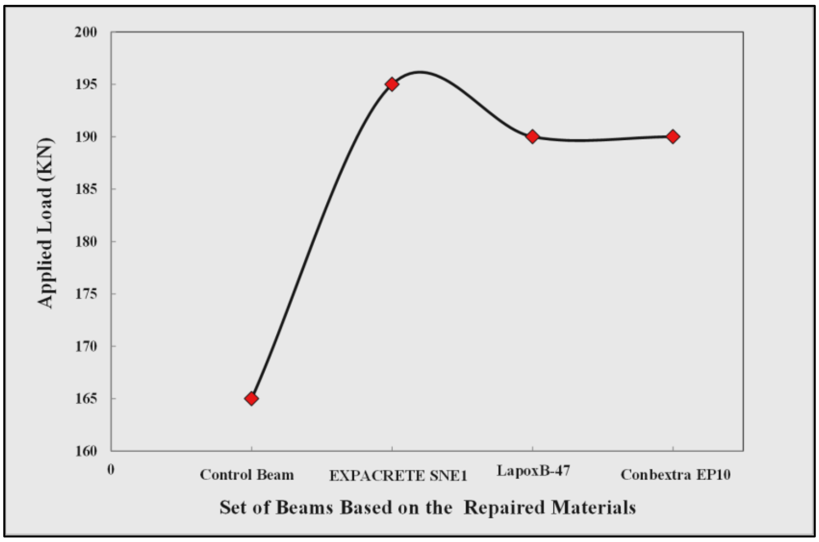

Figure 6. Comparison of Ultimate load for beams repaired by different epoxies [19].

High-Strength Reinforced Concrete Beams

Tashan [20] conducted an experimental investigation to predict the load-deformation behavior of High Strength reinforced concrete beams that failed flexibly and were repaired by epoxy injection. For this purpose, four reinforced concrete beams with dimensions of (12x23x255cm) were simply supported. Their widths were recorded at several loading levels. Two equal point loads were applied in small increments to the third points of the beams by a pair of hydraulic jacks. After each increment of loading, the deflections were recorded at the first third and second third from the support and mid-spam, and the propagation of cracks was examined and detected.

The cracked beams were then cleaned by applying compressed air using an electric blower. Surface ports having an opening at the top for the epoxy to enter and a flange at the bottom were placed 10-15cm apart and fixed along the considered crack by applying an epoxy paste to the flange portion port. After that, the surface ports and the exposed cracks were sealed with an epoxy paste extended 2-3cm on both sides of the crack with 2-3mm thickness to prevent resin seepage and left for 30-45 minutes to ensure complete curing of the paste. Later the two components of the low viscosity epoxy resin (Conbextra EP10) were mixed and injected into the cracks by a mechanical injection using low pressure, as shown in Figure 7. After completing the injection process, all beams were left at ambient temperature for 24 hours. Furthermore, the ports were removed by striking with a hammer, and the surface seal was chipped. The crushed concrete in the compression zone of the beam was repaired similarly.

Based on the study results, the behavior achieved for resin-injected high-strength reinforced concrete beams was similar to that of the original beams. However, the cracks did not re-open after retesting. Instead, new nearby cracks were developed, and the repaired beams showed greater ductility than the original beams.

Figure 7. Epoxy injection for beams.

Al-Khazraji et al. [21] investigated the behavior of high-strength reinforced concrete beams after repair with epoxy injection. For this reason, they prepared four reinforced concrete beams with dimensions of (12x23x255) cm and having different tensile steel ratios; beams 1 and 2 had a 0.0099 tensile steel ratio, while beams 3 and 4 had a 0.018tensile steel ratio. The beams under test were simply supported throughout 2550 mm. First, second, third, and mid-span deflections of the beam were measured with dial gauges. Two equal point loads were applied to the third point of the beam by a part of hydraulic jacks. The loading rate was increased gradually until the beam cracked. After each increment of loading, the deflections were recorded, and the propagation of the crack was examined.

After cleaning the surface, the damaged beams were repaired by injecting the cracks at full depth with low viscosity, fast curing, and slump-pumping liquid epoxy adhesive. The perimeter of each cracked section was sealed off with either a rapid-setting epoxy adhesive or a temporary sealer, but several small holes were left for the subsequent injection. Later the epoxy adhesive was injected into the cracks. Only the major cracks were treated in this way. The minor cracks, being less than (0.05) mm, were too fine for complete penetration of the structural epoxy. The crushed concrete in the compression zone of the beam was repaired similarly. After completing all repairing works, the repaired beams were left at ambient temperature for five days and then tested for failure as before.

The results indicated that the behavior of the repaired beams was similar to that of the control beams, and the repaired cracks did not re-open; instead, new cracks were formed adjacent to the old ones. While at failure, crushing occurred away from the epoxy-repaired region, which means that the epoxy injection was an effective method for restoring the original structure and stiffness. The epoxy injection method for repairing cracks in high-strength reinforced concrete beams shows that their load carry capacity has been recovered as an original beam.

CONCLUSIONS

This paper reviewed several types of research to understand and investigate the suitability of injection as a technique for repairing and upgrading normal and high-strength concrete beams and evaluating factors that affect the expected and final results. The main conclusions are;

1) Epoxy injection is an effective method for restoring the original structure and stiffness of normal and high-strength concrete beams.
2) The beam's depth affects the percentage of strength and fractures energy improvement, and a smaller depth has a higher percentage of improvement.
3) The fewer drilled holes for injection, the higher the percentage of increase in strength because drilling more holes disturbs the internal structure of concrete, which is essential to destroy the bond between materials in the concrete matrix.
4) Beam with only shear reinforcement injected by epoxy can increase the load-bearing capacity, ductility, and energy-absorption capacity.
5) Lower the viscosity, better distribution in epoxy impregnation into the crack depth, and thus better strength improvement.

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