IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)
e-ISSN: 2278-1684,p-ISSN: 2320-334X, Volume 19, Issue 4 Ser. II (Jul. – Aug. 2022), PP 49-64
www.iosrjournals.org

Flexural Behavior of Reinforced Concrete Beams Contained Nano Silica with Internally Injected by Epoxy

D.M. Alaa[1],A. Abd-Alazeem[2], A.Abd El-Zaher[3]
[1]*Post Graduate Student, Faculty of Engineering, Fayoum University, Fayoum, Egypt*
[2]*Associated professor, Faculty of Engineering, Fayoum University, Fayoum, Egypt*
[3]*Associated professor, Faculty of Engineering, Assuit University, Assuit, Egypt*

Abstract:
Nanotechnology is both a science and a technology that has been around for a long time. Instead, it is an extension of the sciences and technologies that have been developing for many years. It is the logical advancement of the work that has been done to investigate the nature of our world at an ever-smaller scale. Nanotechnology uses very small particles of material either by themselves or by their manipulation to create new large scale materials. This research aimed to investigate the effects of using Nano-silica and internal injection by epoxy on the flexural behavior of reinforced concrete beams. The results show that the combined use of Nano-silica with silica fume can improve the mechanical properties of concrete. In this research, the tests were applied on fourteen reinforced concrete beams specimens of dimensions (150×100×1800 mm), and divided into four main groups, based on the percentage of Nano-silica as a function in Portland cement weight by (0%, 2%, 4% and 6%), compressive strength (Fcu= 300, 450, 600kg/cm²), and repairing by internally injected epoxy. All the specimens of the experimental work were casted and strengthened at concrete research and Material Properties Laboratory, "Faculty of Engineering, Nahda University - Egypt". Casting and curing were done according to the Egyptian Code of Practice (2007). From the hardened concrete tests, the best compressive, tensile, and flexural strength came out when using Nano-silica at (4%) of cement weight with all the aforementioned concrete mixes. We also found that the Repair of reinforced concrete beams using the technique of internal injection by epoxy effectively controls the cracks and respectively increases the load carrying capacity.

Key Word:*Nano-Silica; Internally Injected by Epoxy;flexural behavior.*

Date of Submission: 06-08-2022 Date of Acceptance: 21-08-2022

I. Introduction

Nowadays, many reinforced concrete structural elements requires repair, strengthening, or replacement for various reasons, such as construction errors, environmental effects, chemical reactions, increases in applied load due to changes in structure purpose, repetitive seismic loads, etc. repair process became so common these days Because demolishing and rebuilding the entire structure is much more expensive than repairing and strengthening the reinforced concrete elements. Repaired and strengthened of damaged or vulnerable reinforced concrete structures are important to guarantee the safety of residents and users, especially Beams, as they are important structural elements for withstanding loads, so efficient repairing and strengthening methods are required to keep the structures safe.

Many studies have been conducted over the years, employing a variety of materials and methods developed with modern technology from basic techniques such as repair using internal injection by epoxy. Nowadays, the internal injection method in the present time has become a very important method, especially for the treatment of not invisible cracks of reinforced concrete beams in structures. The nano-silica is the most widely used nanomaterial in cement and concrete to enhance the properties of concrete due to its pozzolanic reactivity along with the pore-filling effect. Nano Silica is a mineral admixture, fine material with spherical particles size 60 micrometer in diameter; this makes it 50 times smaller than the average volume of cement particle. It helps in enhancing the compressive strength, bond strength, and abrasion resistance. When pozzolanic materials are incorporated into concrete, the added Nano silica reacts with the calcium hydroxide released during the hydration of cement. It forms an additional calcium silicate hydrate (C- S- H), which improves concrete's durability and mechanical properties [1].

Nano-silica mainly composed of silicon dioxide (SiO2) which can be present both in crystalline and amorphous forms. The most commonly amorphous type of Nano-silica is used in the formation of Nano-concrete [2]. Nano-silica particle size varied in the range of 5–658 nm for different types of nano silica-based products [3]. Nano-particles of SiO2 increase the densification of the concrete matrix, thus improving the strength and durability of the material. Generally, a slurry form of nano-silica is preferred in comparison to powder form due to health problems associated with the inhaling of powder [4],[5]. There are various methods for producing nano-silica. Nano-silica produced by vaporization of silica between 1500 and 2000 0C by reducing quartz (SiO2) in an electric arc furnace provides a higher fineness consisting of spherical particles or microspheres with a main diameter of 150 nm with the high specific surface area (15 to 25 m2/g) [6].

Mukharjee et al. [7] found that the slump value decreased as the amount of nano-silica increased in the concrete. Due to the high surface area of the nano-silica particles and the unsaturated bonds in nano-silica, a portion of the mixing water (water molecules) attracts toward the surface of nano-silica particles and thus produces silanol (Si-OH) groups. Consequently, the water needed for the fluidity of the concrete mixture becomes insufficient. Givi et al. [8], nano-silica particles enhanced the flexural strength at all curing stages up to 90 days without much variations in the rate of strength development. The study further identified that at 90 days, concrete containing nano-silica with 80 nm diameter exhibited a higher flexural strength compared to concrete with 15 nm dia. nanoparticles.

Another development in the repair and rehabilitation of RC systems is the epoxy injection. It is also considered as one of the most common methods used for crack repair for the last two decades. Cracks as narrow as 0.002 in. (0.05 mm) can be bonded by the injection of epoxy. The technique generally consists of establishing entry and venting ports at close intervals along the cracks, sealing the crack on exposed surfaces, and injecting the epoxy under pressure. Epoxy injection has been successfully used in the repair of cracks in buildings, bridges, dams, and other types of concrete structures. However, unless the cause of the cracking has been corrected, it will probably recur near the original crack. If the cause of the cracks cannot be removed, then two options are available [9]. One is to rout and seal the crack, thus treating it as a joint, or, establish a joint that will accommodate the movement and then inject the crack with epoxy or other suitable material. With the exception of certain moisture tolerant epoxies, this technique is not applicable if the cracks are actively leaking and cannot be dried out. Wet cracks can be injected using moisture tolerant materials, but contaminants in the cracks (including silt and water) can reduce the effectiveness of the epoxy to structurally repair the cracks [10].

Reinforced concrete structures are designed to work under compression as well as tension when subjected to bending stresses. It is been proven that concrete can only resist tension between 1/10 and 1/14 of its compressive strength; hence, the cracking of concrete is inevitable. Apart from tensile cracks, concrete may crack because of drying shrinkage. Excessive cracking in concrete members due to either physical attack (e.g., corrosion, ASR, etc.), which can be caused by ingression of detrimental chemical gases or liquids, or overload can result in serviceability problems. Cracks can be categorized in three groups: cracks due to inadequate structural performance, cracks due to inadequate material performance, and acceptable cracks [11]. Structural cracks are caused primarily by overloading; material related cracks are due to shrinkage and chemical reaction; and acceptable cracks are those that develop due to service level loading for tensile stresses to be distributed properly along the length of the material. Cracks in structural elements can also be classified as dormant or active. Active cracks, such as cracks caused by foundation settlement, cannot be fully repaired, whereas dormant cracks can be successfully repaired. Crack repair systems have been used for many years [12].

This study analyzed the usage of the epoxy injection to repair an acutely damaged RC beam using acoustic emission technique. Following the study’s completion:

1. It is concluded that the repaired RC beam can sustain a higher maximum load in contrast to the reference beam. The damaged RC beam repaired with epoxy injection increased the strength up to 15% compared with reference beam. It indicates the strength of the repaired RC beam can be increased using this repairing technique [13].
2. Crack mode classifications of the beam subjected to four-point loading were performed on the basis of AE signal strength and load with respect to time. Then, five crack modes were identified namely nucleation of crack, first crack, flexural crack localisued, flexural shear crack and failure. In general, it is found that the results for the AE signal strength of the reference beam are higher than the repaired beam. It is because the reference beam emits more AE energy than repaired beam. Since the repaired beam is more ductile and more substantial than reference beam, it absorbs more energy compared to the reference beam. Hence, the damaged RC beam repaired with epoxy injection significantly improve its integrity and performance [13].

According to ACI 546R-96 [14], epoxy resins generally have excellent bonding and durability characteristics. Calder and Thompson [16] reported that the overall structural performance of RC slabs retrofitted with epoxy resin injection performed the best compared to some other materials. The bond between concrete and the injection material is very critical. A good bond may restore the original stiffness of the repaired material and prevent further penetration of chloride ions and water [15]. Therefore, the crack should also be clean and dry prior to injection. Hence, epoxy injection is not applicable if the cracks are actively leaking or cannot be dried out. French et al. [17] confirmed the effectiveness of epoxy techniques to repair damaged specimens in restoring over 85 % of the original specimens' stiffness, strength, and energy dissipation characteristics. Filiatrault and Lebrun [18] reported on the performance of damaged exterior joints, which were repaired by epoxy pressure injection and concluded that the repair procedure was particularly effective in improving the strength, stiffness and energy dissipation capacity.

Karayannis et al. [19] repaired eleven damaged one-way exterior joint specimens by epoxy injection only and then retested. However, out of all the specimens, one with one joint stirrup exhibited the same failure mode before and after repair. The variations in performance were partially attributed to the variations in being able to inject epoxy successfully into the joint cracks. Nikoupour and Nehdi [20] investigated the behaviour of RC beams after repaired with low viscosity epoxy injection. They concluded that an increase of stiffness was observed in the linear region of the load– displacement curves of all the repaired RC beams.

II. Material And Methods

1. Material properties

The used concrete constituents were in accordance with Egyptian Standard Specifications (ESS). All used materials were obtained from local Egyptian sources which are commonly used in Egyptian construction field. The used materials were as follows:

- Ordinary Portland cement (CEM I 42.5N)
- Silica fume (SIKA FUME) contains extremely fine (0.1 µm) latently reactive silicon dioxide with 2.2 specific gravity, increases compressive strength, flexural strength of the concrete and decreases permeability.
- Mineral admixtures [super plasticizers (ADDICRETE BVF)]. Manufactured to conform to ASTM C 494 type A and F, EN 934-2 and ES 1899.
- Normal drinking tap water.
- Coarse aggregates (crushed gravels) with maximum nominal size of 10mm, 2.64 specific gravity and 1.567 t/m^3 volume weight.
- High grade tensile steel and mild steel have been used for longitudinal and transversal reinforcement, respectively.
- Nano-silica mainly composed of silicon dioxide (SiO2). Nano-silica produced by vaporization of silica between 1500 and 2000 C by reducing quartz (SiO2) in an electric arc furnace provides a higher fineness consisting of spherical particles or microspheres with a main diameter of 50 nanometer. Properties of nano-silica, as shown in Table 1.

Table 1: Properties of Nano Silica

Physical state	**Powder form**
Specific gravity	2.1
Nano pore rate (ml/g)	0.6
Density (g/m^3)	2.4
Molar mass (g/mol)	59.96
Tamped bulk density (g/l)	40
Sio2 (%)	99.8
Surface area (m^2/g)	80

2. Concrete mix

In this research, the required compressive strength of concrete was 30, 45, 60 MPa. This study also uses commercial, regular silica fume combined with the locally produced nano-silica. Concrete mixes were produced by nano-silica at 0%, 2%, 4%, and 6% from cement content. Mix proportion used in preparing concrete for one cubic meter by weight (kg/m^3) of fresh concrete is given in Table 2. In order to evaluate the properties of hardened concrete, compressive strength, splitting strength, and flexural strength tests.

Table 2: Mix Proportion by Weight (kg/m^3)

Mix	**Gravel**	**Sand**	**Cement**	**Water**	**Silica Fume**	**Super plasticizer**	**Nano Silica**
B-300-0	1312	656	275	140	20.63	8.25	0
B-300-2	1309	655	275	140	20.63	8.25	5.5
B-300-4	1306	653	275	140	20.63	8.25	11
B-300-6	1304	652	275	140	20.63	8.25	16.5
B-450-0	1241	621	370	145	27.75	11.1	0
B-450-4	1234	617	370	145	27.75	11.1	14.8

B-600-0	1150	575	470	160	35.25	14.1	0
B-600-4	1141	571	470	160	35.25	14.1	18.8

3. Test specimens

The experimental program consists of fourteen RC beams with a length of 1800 mm, a clear span of 1500 mm, and a typical rectangular cross section of 150 mm height and 100 mm width. The unstrengthened beams have been designed with a/d= 1.5 using insufficient flexural reinforcement to ensure flexural failure. The bottom longitudinal reinforcement of the beams are three bars with a nominal diameter of 12 mm laid into one layer, while the top longitudinal reinforcement are two bars with a nominal diameter of 10 mm laid into one layer. The clear cover over both the top and the bottom reinforcement is 10 mm. The beam has been reinforced with double legged deformed steel stirrups with a nominal diameter of 8 mm uniformly spaced at 125 mm along the beam length. The beam layout, dimension, and reinforcement details are shown in Fig. 1.

The parameters considered in this research work are the different cement content to obtain a concrete compressive strength 300, 450, 600 kg/cm², the different ratio of nano-silica (0%, 2%, 4% and 6%), and repairing by epoxy internally injected technique. The effect of the different ratio of nano-silica (0%, 2%, 4% and 6%) with the different cement content to obtain a concrete compressive strength 300, 450, and 600 kg/cm² is presented by the specimens (B-300-2, B-300-4, B-300-6, B-450-4, B-600-4). In addition, specimens (B-300-0-I, B-450-0-I, B-600-0-I) present the effect of the repairing by epoxy internally injected technique with the different compressive strength 300, 450, 600 kg/cm². Furthermore, specimens (B-300-4-I, B-450-4-I, B-600-4-I) present the effect of nano-silica with repairing by epoxy internally injected technique and different compressive strength 300, 450, 600 kg/cm². Description of Specimens, as shown in Table 3.

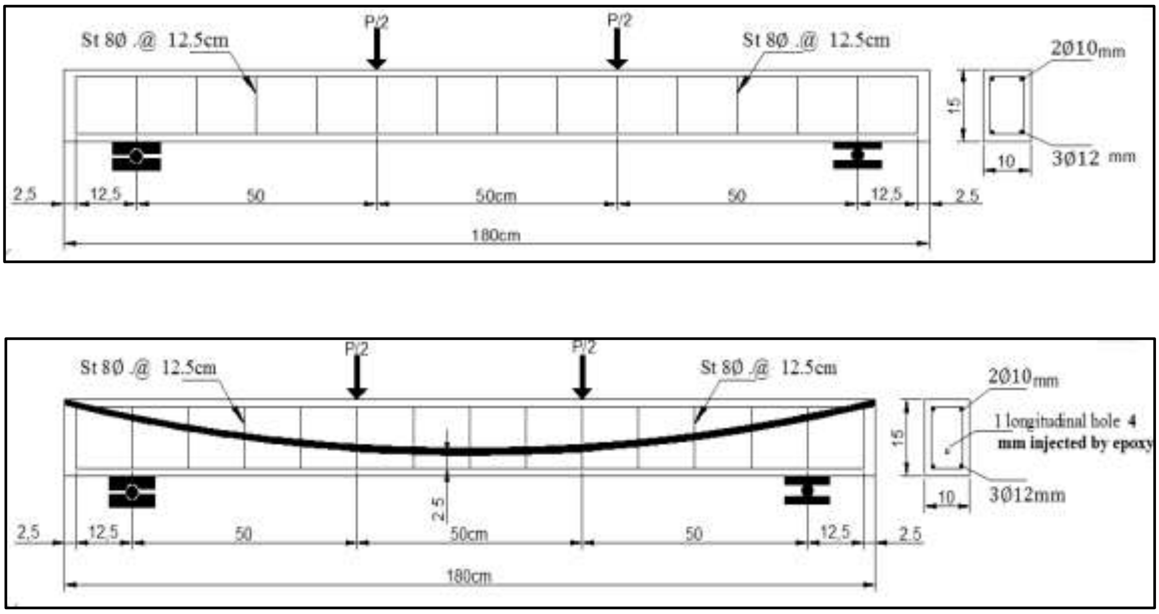


Fig. 1. Reinforcement Details for Control Beam and Beam with Internally Injected by Epoxy

Table 3: Description of Specimens

Group no.	Beam no.	L (cm)	L$_0$ (cm)	a (cm)	d (cm)	a/d	Nano silica (%) SiO_2	Silica Fume (%)	Super plasticizer (%)	Fcu (kg/cm^2)	Repair (epoxy) V(cm^3)
G1	**B/300/0**	180	150	50	12.5	4	0	7.5	2	300	—
	B/300/2						2	7.5	2		
	B/300/4						4	7.5	2		
	B/300/6						6	7.5	2		
G2	**B/450/0**	180	150	50	12.5	4	0	7.5	2	450	—
	B/450/4						4	7.5	2		
	B/600/0						0	7.5	2	600	
	B/600/4						4	7.5	2		
G3	**B/300/0-I**	180	150	50	12.5	4	0	7.5	2	300	30
	B/450/0-I						0	7.5	2	450	30
	B/600/0-I						0	7.5	2	600	30
G4	**B/300/4-I**	180	150	50	12.5	4	4	7.5	2	300	30
	B/450/4-I						4	7.5	2	450	30
	B/600/4-I						4	7.5	2	600	30

4. Epoxy injection technique

The normal and nano-silica concrete mixture has been casted in the formwork and the required boreholes have been kept open during casting. Boreholes of a suitable diameter were drilled along the entire length of the reinforced concrete beams to allow the internal injection mixing to pass through the cracks and fissures. The bore hole diameter that are used are (5 mms.). Butting a pipe inside the concrete works by using a soft rubber pipe with a diameter of 5 mm is the most commonly used piping work operation.

The injection operation is performed by pressing the injection mixture through the concrete Specimens special boreholes to fill the voids, cracks, and joints in the concrete Specimens body. To withstand abrasion and the maximum grouting pressures, the hose pipe used to transport the injected materials was made of a pliable soft rubber. Then, the required holes have been cleaned with an air blower to remove all dirt and other impurities before injection beams by epoxy. The rubber hose is used to connect the supply line to the manifold (header) at the hole to facilitate shifting of the grout line from one hole to another. The Specimens were subjected to a sustained loading level at which small cracks started to appear with a width of about 1 mm; it was observed to be about (70%) of the ultimate load of the previously tested specimens under the same conditions. And then inject them with epoxy through a small 5mm longitudinal hole using a rubber pipe with the same diameter; after being sure that the epoxy filled all cracks, specimens were left to achieve full hardness after 7 days of epoxy injection before finalizing the test. The epoxy injection technique as shown in Fig. 2.

(a) Boreholes have been kept open during casting

(b) Epoxy injection

Fig. 2. Stages of repairing RC beams using epoxy injection technique

(c) Filling cracks with epoxy

Fig. 2. Stages of repairing RC beams using epoxy injection technique (continued)

5. Test setup

The beam specimens have been subjected to a four point loading up to failure using a hydraulic machine of deflection control at a rate of 0.25 mm/min as shown in Fig. 3. Vertical deflections have been measured using one linear variable differential transducer (LVDT) at the mid-span of the beam specimens. The tested beams have been tested after 28 days of casting concrete mixture.

Fig. 3. Test setup

III. Result

1. Fresh and Hardened Concrete Properties

The slump decreases when using high dosages of nano-silica in concrete, such as 2%, 4%, and 6% ratio of nano-silica. Properties of hardened concrete, as shown in Table 4. The slump of nano-silica concrete (B/300/2, B/300/4, B/300/6, B/450/4 and B/600/4) decreases to 0.25%, 0.31%, 0.44%, 0.29% and 0.33% for Fcu= 300, 450, 600 kg/cm², compared to conventional concrete (B/300/0, B/450/0 and B/600/0), respectively.

The increase of compressive strength at 28 days concerning the control concrete specimen (B/300/0) was found to be 48.43%, 60.97 % and 26.28 % for (B/300/2), (B/300/4), and (B/300/6) for nano silica dosages of 2%, 4% and 6%, respectively. While, The increase of compressive strength at 28 days concerning (B/450/4) and (B/600/4) was found to be 31.84% and 24.68% for nano silica dosage of 4%, respectively, when compared to (B/450/0) and (B/600/0).The increase of splitting-tensile strength at 28 days concerning the control concrete specimen (B/300/0) was found to be 48.74%, 61.37% and 26.35% for (B/300/2), (B/300/4), and (B/300/6) for nano silica dosages of 2%, 4% and 6%, respectively. While, The increase of splitting-tensile strength at 28 days concerning (B/450/4) and (B/600/4) was found to be 31.70% and 24.82% for nano silica dosage of 4%, respectively, when compared to (B/450/0) and (B/600/0). The increase of modulus of rupture at 28 days concerning the control concrete specimen (B/300/0) was found to be 48.46%, 60.96 % and 26.35% for (B/300/2), (B/300/4), and (B/300/6) for nano silica dosages of 2%, 4% and 6%, respectively. While, The increase of modulus of rupture at 28 days concerning (B/450/4) and (B/600/4) was found to be 31.91% and 24.67% for nano silica dosage of 4%, respectively, when compared to (B/450/0) and (B/600/0).

Table 4: Properties of hardened concrete

Type of mix	**% Nano Silica**	**Slump (mm)**	**Compressive Strength (N/mm²)**		**Splitting Tensile Strength (N/mm²)**	**Mean of The Modulus of Rupture Strength (N/mm²)**
			7 days	**28 days**	**28 days**	**28 days**
B/300/0	0	80	26.85	34.67	2.77	5.20
B/300/2	2	60	38.60	51.46	4.12	7.72
B/300/4	4	55	41.86	55.81	4.47	8.37
B/300/6	6	45	32.84	43.78	3.50	6.57
B/450/0	0	70	36.37	48.49	3.88	7.27
B/450/4	4	50	47.95	63.93	5.11	9.59
B/600/0	0	60	53.30	71.07	5.68	10.66
B/600/4	4	40	66.45	88.61	7.09	13.29

2. Load versus deflection curves

The load versus mid-span deflection curves for the beam specimens are presented from Fig. 5 to Fig. 8. In addition, the load-deflection properties of tested beam specimens have been summarized in Table 5, which shows the peak load (Pu), first crack load (Pcr), failure load (Pf), ultimate shear force (Vu), ultimate shear stress (τ), crack moment (Mcr), ultimate moment (Mu) and ultimate flexural stress for each beam. The toughness is defined as the energy absorption capability of a material or structure under a load-deflection curve up to its failure. The toughness index was calculated for each beam in this study by calculating the area under the load deformation curve. The peak load (Pu), crack toughness (AEcr), ultimate toughness (AEu), failure toughness (AEf), % Increase in Pu, % Increase in AEu, crack deflection (Δcr), ultimate deflection (Δu) and failure deflection (Δf) of all tested concrete beams is presented in Table 6.

Table 5: Experimental results.

Group	ID	Pcr (KN)	Pu (KN)	Pf (KN)	Vu (KN)	Ʈ (Mpa)	Mcr (KN.m)	Mu (KN.m)	Fru (Mpa)
Group 1	**B/300/0**	32.16	63.81	44.20	31.90	5.10	8.04	15.95	42.54
	B/300/2	40.25	74.41	47.70	37.20	5.95	10.06	18.60	49.60
	B/300/4	42.74	79.15	50.88	39.58	6.33	10.69	19.79	52.77
	B/300/6	34.26	73.64	49.46	36.82	5.89	8.57	18.41	49.10
Group 2	**B/450/0**	44.05	79.05	59.53	39.52	6.32	11.01	19.76	52.70
	B/450/4	46.64	92.11	65.23	46.05	7.37	11.66	23.03	61.40
	B/600/0	48.71	110.56	80.91	55.28	8.84	12.18	27.64	73.71
	B/600/4	57.89	111.83	80.75	55.91	8.95	14.47	27.96	74.55
Group 3	**B/300/0-I**	34.45	67.97	50.01	33.99	5.44	8.61	16.99	45.31
	B/450/0-I	53.19	93.96	66.38	46.98	7.52	13.30	23.49	62.64
	B/600/0-I	57.15	117.45	85.83	58.72	9.40	14.29	29.36	78.30
Group 4	**B/300/4-I**	45.46	85.52	60.03	42.76	6.84	11.37	21.38	57.01
	B/450/4-I	57.88	97.92	68.84	48.96	7.83	14.47	24.48	65.28
	B/600/4-I	64.50	118.19	77.04	59.09	9.46	16.13	29.55	78.79

Table 6: Experimental results.

Group	ID	Pu (KN)	AE (crack) (KN.mm)	AE (ultimate) (KN.mm)	AE (failure) (KN.mm)	% Increase in Pu	% Increase in AE (ultimate)	Δcr (mm)	Δu (mm)	Δf (mm)
Group 1	**B/300/0**	63.81	89.89	449.57	1222.24	-	-	5.59	13.91	28.22
	B/300/2	74.41	105.25	774.33	1308.57	16.61%	72.24%	5.23	15.71	24.46
	B/300/4	79.15	41.03	896.80	1521.34	24.05%	99.48%	1.92	17.29	26.90
	B/300/6	73.64	87.71	722.96	1255.66	15.42%	60.81%	5.12	15.34	23.99
Group 2	**B/450/0**	79.05	133.69	894.21	1873.75	-	-	6.07	17.10	31.24
	B/450/4	92.11	132.92	1124.84	2377.64	16.52%	25.79%	5.70	19.16	35.08
	B/600/0	110.56	205.56	1204.55	2876.14	-	-	8.44	20.58	38.04
	B/600/4	111.83	131.41	1644.66	2980.77	1.14%	36.54%	4.54	22.36	36.24

Group 3	**B/300/0-I**	67.97	93.88	627.41	1048.40	6.53%	39.56%	5.45	15.57	22.71
	B/450/0-I	93.96	236.43	1073.47	1947.84	18.86%	20.05%	8.89	18.92	29.83
	B/600/0-I	117.45	56.86	1325.27	2743.75	6.23%	10.02%	1.99	21.68	35.64
Group 4	**B/300/4-I**	85.52	199.11	1125.60	2550.93	8.05%	25.51%	8.76	17.68	37.27
	B/450/4-I	97.92	109.39	1514.13	2383.76	6.31%	34.61%	3.78	19.58	30.01
	B/600/4-I	118.19	249.29	1805.92	3017.90	5.69%	9.81%	7.73	22.67	35.09

3. Effect of the nano-silica ratio in concrete mixture

In order to evaluate the influence of the nano-silica in a concrete mixture, the load versus deflection curves for the beam specimens B/300/2 (2% nano-silica), B/300/4 (4% nano-silica) and B/300/6 (6% nano-silica), are presented in Fig. 4 as well as B/450/4 (4% nano-silica) and B/600/4 (4% nano-silica), are presented in Fig. 5 along with B/300/0, B/450/0 and B/600/0 respectively. From the figures, it is obvious that nano-silica dosage up to 2 to 4% could improve mechanical, durability properties, and behavior of the strengthened beams. This could be due to pozzolanic action, filling effect, and pore structure refinement. However, the strength may reduce if the dosage of nano-silica exceeds 4% or more.

For the beam B/300/2, where a nano-silica ratio of 2% has been used, cracking and ultimate loads are approximately 1.25 and 1.17 times those of beam B/300/0, respectively. Moreover, as compared to beam B/300/0 the increase in ductility, and toughness of the beam by 1.13, and 1.72 times, respectively. The ultimate load of B/300/4 is just around 1.06 times greater than that of B/300/2. In addition, its toughness and ductility is higher than B/300/0′ s one by 2.00 and 1.24 times. Furthermore, B/300/4′ s cracking and the ultimate loads are greater than B/300/0′ s ones by around 1.32 and 1.24 times, respectively. On the contrary, the ultimate load of B/300/6 is lower than that of B/300/2 and B/300/4. In addition, its toughness and ductility is higher than B/300/0′ s by 1.61 and 1.10 times. Furthermore, B/300/6′ s cracking and the ultimate loads are greater than B/300/0′ s ones by around 1.07 and 1.15 times, respectively.

The same results have been obtained for beams B/450/4 and B/600/4. when using a 4% nano-silica ratio, the ductility, toughness, cracking, and ultimate load values have increased. The ductility of the beams is around 1.12 and 1.09 times that of B/450/0 and B/600/0 for B/450/4 and B/600/4, respectively. In addition, the beams’ toughness is increased by 1.26 and 1.36 times, respectively. Furthermore, the beams’ cracking loads are higher than the B/450/0 and B/600/0 ′s one by around 1.06 and 1.19 times, respectively. On the other hand, the ultimate load of the beams is 1.17 and 1.01 times that of B/450/0 and B/600/0, respectively.

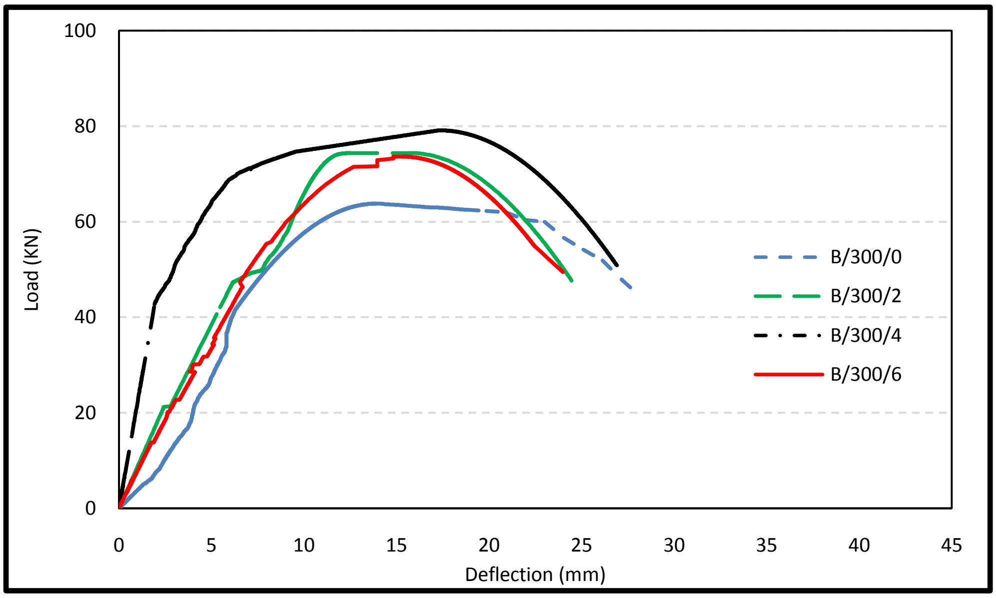


Fig. 4. Load deflection relationship for specimens B/300/0, B/300/2, B/300/4, and B/300/6.

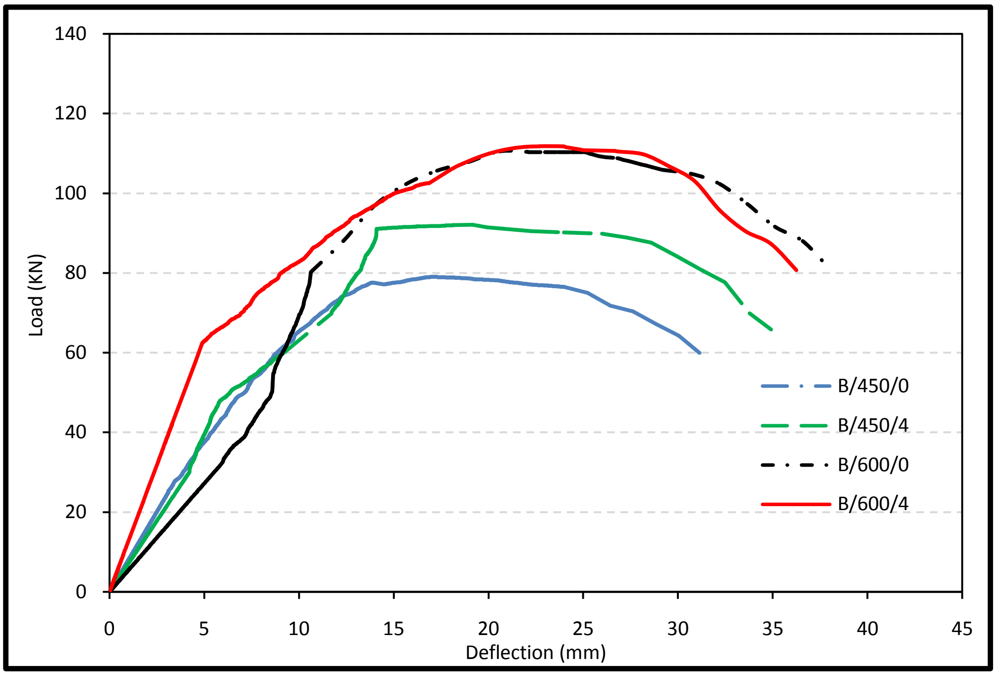


Fig. 5. Load deflection relationship for specimens B/450/0, B/450/2, B/600/0, and B/600/4.

4. Effect of the repairing technique

Repairing by epoxy internally injected procedures have been utilized in this research work. Crack injection provided an increase in stiffness in the linear region of the load–displacement curves for all of the RC beams. In order to investigate the effect of the repairing technique, the load versus deflection curves for the beam specimens B/300/0-I (compressive strength 300 kg/cm2), B/450/0-I (compressive strength 450 kg/cm2) and B/600/0-I (compressive strength 600 kg/cm2), as shown in Fig. 6, respectively. From the figure, it is observed that the epoxy injection technique has been successfully effectively used in the repair of cracks in beams. When compared to the beam B/300/0, the ductility, toughness, cracking, and ultimate load of the beam B/300/0-I are 1.12, 1.39, 1.07 and 1.06 times higher; respectively, whereas the beam B/450/0-I ′ s ones are 1.11, 1.20, 1.21, and 1.19 times greater than the control beam B/450/0. For beam B/600/0-I, the ductility, toughness, cracking, and ultimate load are 1.05, 1.10, 1.17, and 1.06 times higher than those of B/600/0; respectively.

5. Effect of the repairing technique with nano-silica

For the epoxy injection technique with nano-silica, the load versus deflection curves for beams B/300/4-I (Fcu= 300 kg/cm2 with 4% nano-silica), B/450/4-I (Fcu= 450 kg/cm2 with 4% nano-silica) and B/450/4-I (Fcu= 600 kg/cm2 with 4% nano-silica), as shown in Fig. 7. When compared to the beam B/300/4, the ductility, toughness, cracking, and ultimate load of the beam B/300/4-I are 1.02, 1.26, 1.27 and 1.08 times higher; respectively, whereas the beam B/450/4-I ′ s ones are 1.02, 1.35, 1.24, and 1.06 times greater than the beam B/450/4. For beam B/600/4-I, the ductility, toughness, cracking, and ultimate load are 1.01, 1.10, 1.11, and 1.06 times higher than those of B/600/4; respectively.

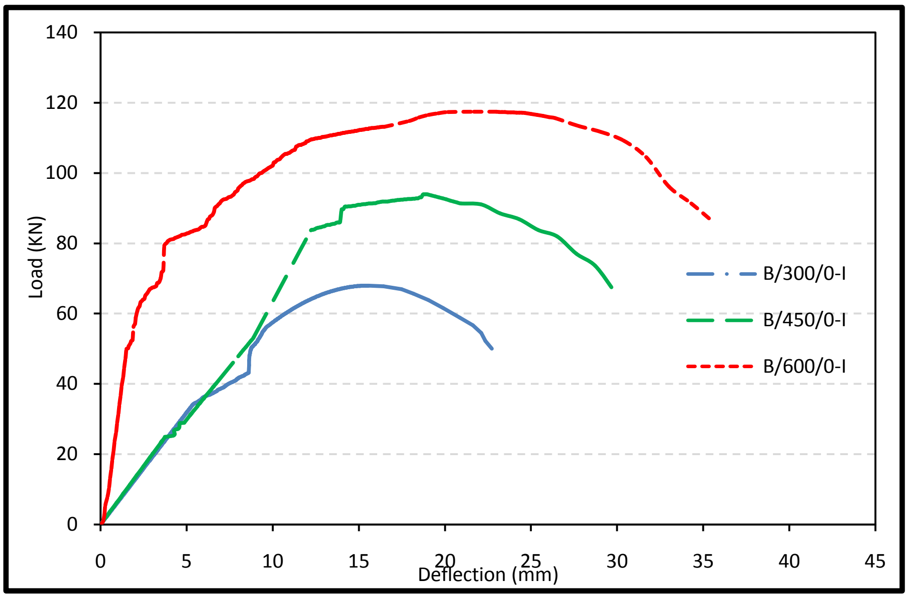


Fig. 6. Load deflection relationship for specimens B/300/0-I, B/450/0-I and B/600/0-I.

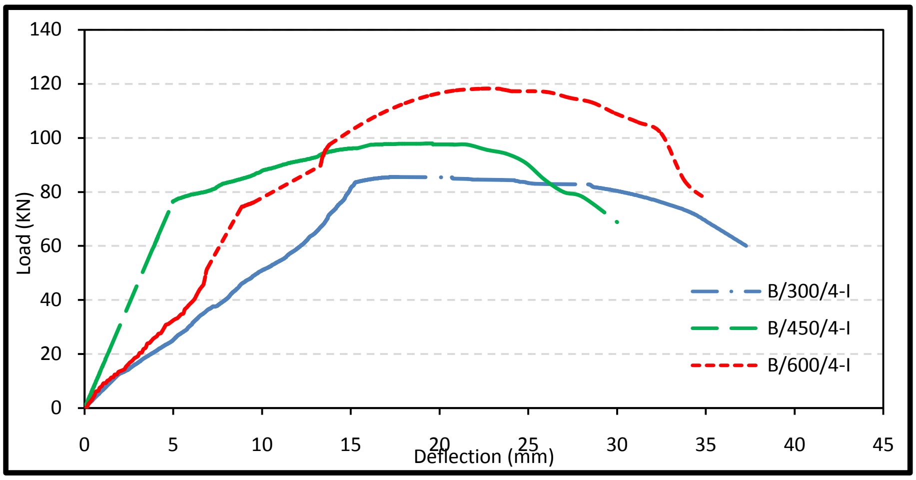


Fig. 7. Load deflection relationship for specimens B/300/4-I, B/450/4-I and B/600/4-I.

6. Crack pattern and failure modes

Fig. 8 (a–n) shows the representative failure modes of the beam specimens. The control beam (B/300/0, B/450/0, B/600/0) has exhibited the typical behavior of RC beams in compressive strength (Fcu =300, 450, 600 kg/cm²). The beam has failed in flexural by forming vertical and diagonal cracks in mid-span of the beam specimens at an ultimate load of 63.81 kN, 79.05 KN and 110.56 KN, respectively, as shown in Fig. 4(a), Fig. 4(e) and Fig. 4(g). The failure patterns of (B/300/2, B/300/4, and B/300/6) are containing a different ratio of nano-silica (NS= 2%, 4%, 6%), respectively. The beam has failed in flexural by forming vertical and diagonal cracks in moment zone at an ultimate load of 74.41 kN, 79.15 KN and 73.64 kN, respectively, as shown in Fig. 4(b), Fig. 4(c) and Fig. 4(d).

The beam specimens B/450/4 and B/600/4 contain the best ratio of nano-silica (NS= 4%) have exhibited flexural failure by forming flexural cracks within the moment zone where vertical cracks have begun and progressed as shown in Fig. 4(f) and Fig. 4(h); respectively. The ultimate loads of the beams are 92.11 KN, and 111.83 KN, and the increase in the ultimate load was 16.52% and 1.15% for (B/450/4 and B/600/4), respectively compared to the control beam (B/450/0, B/600/0).

On the other hand, beams with repairing cracks using epoxy injection and different compressive strength (Fcu =300, 450, 600 kg/cm²) have behaved in a ductile manner by failing in flexure by forming vertical cracks in the maximum moment zone, as shown in Fig. 4(i), Fig. 4(j) and Fig. 4(k) for (B/300/0-I, B/450/0-I and B/600/0-I), respectively. Their ultimate loads are 67.97 KN, 93.96 KN and 117.45 KN for beams (B/300/0-I, B/450/0-I and B/600/0-I), respectively.

The failure pattern of the beams (B/300/4-I, B/450/4-I and B/600/4-I), which repair cracks using epoxy injection contain the best ratio of nano-silica (NS= 4%) with different compressive strength (Fcu =300, 450, 600 kg/cm²), illustrates the ductile way in which the beam has failed an ultimate load of 85.52 KN, 97.92 KN and 118.19 KN, and the increase in the ultimate load was 25.82%, 4.22% and 0.63% for (B/300/4-I, B/450/4-I and B/600/4-I), respectively compared to the control beam (B/300/0-I, B/450/0-I and B/600/0-I). Flexural cracks can be seen clearly in the maximum moment region, as shown in Fig. 4(l), Fig. 4(m) and Fig. 4(n). Specimens with crack injection exhibited higher initial stiffness than their counterpart specimens without injection as the epoxy injection helped to ‘‘restore’’ their initial pre-cracked stiffness.

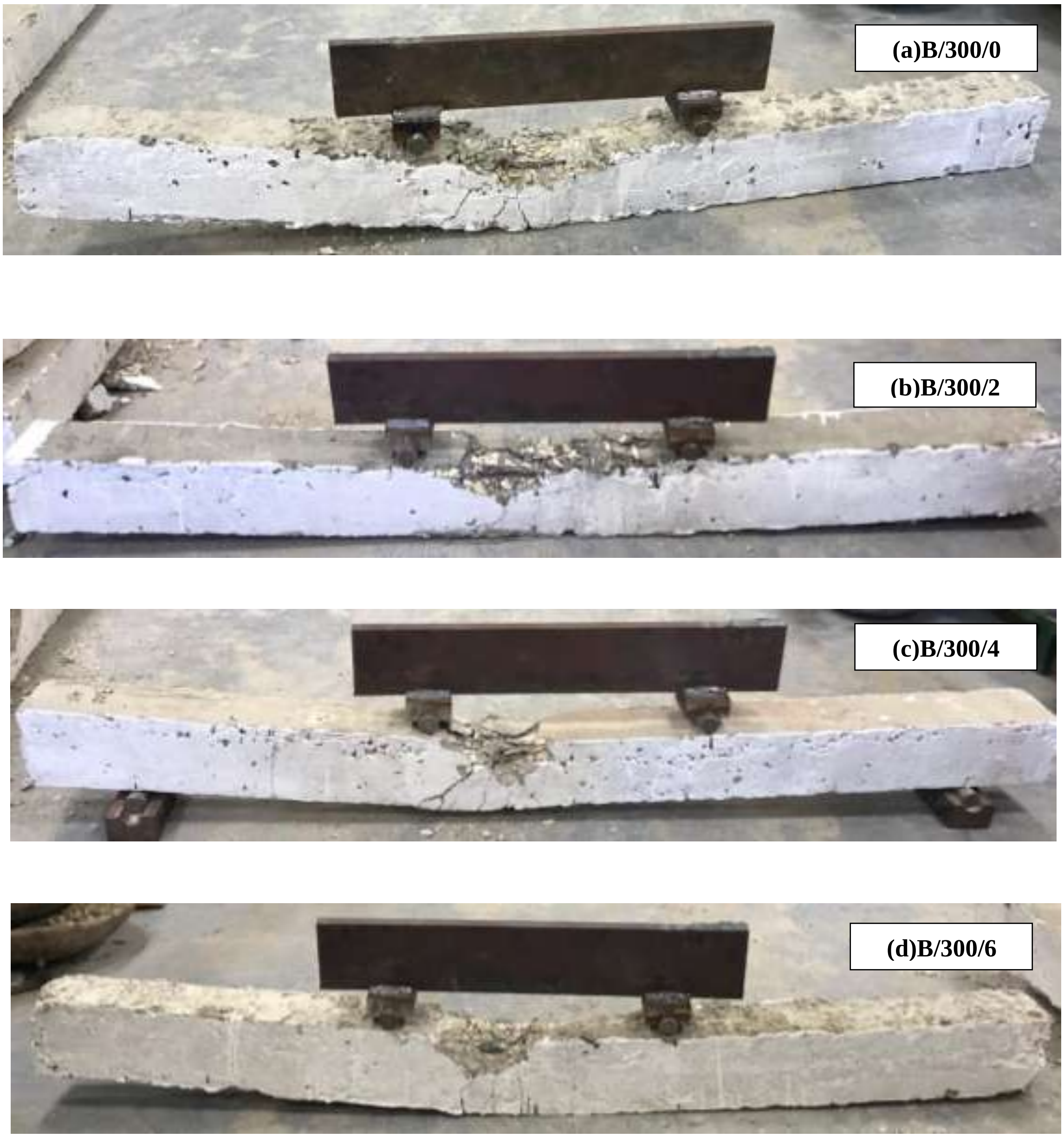


Fig. 8. Failure modes of beam specimens

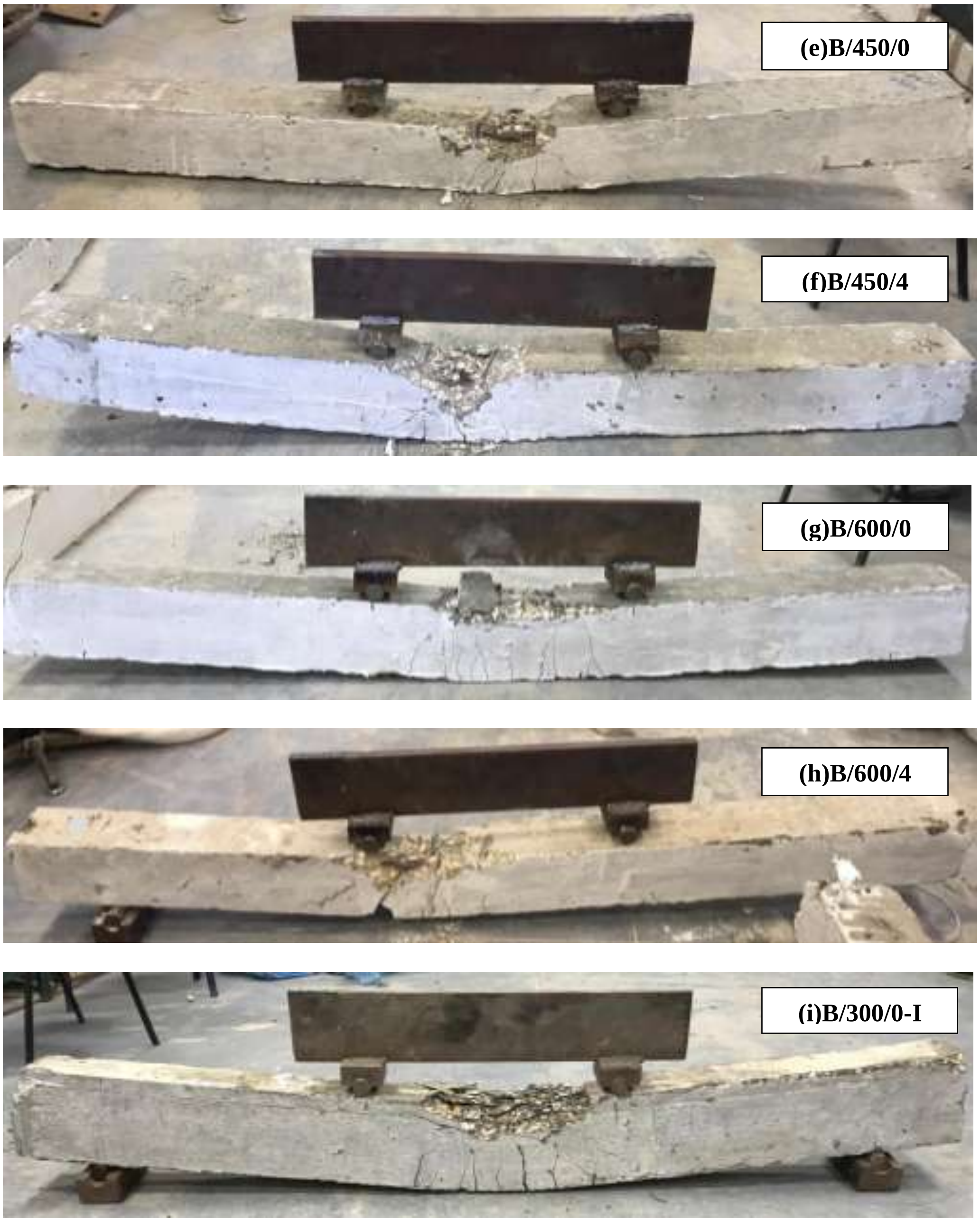
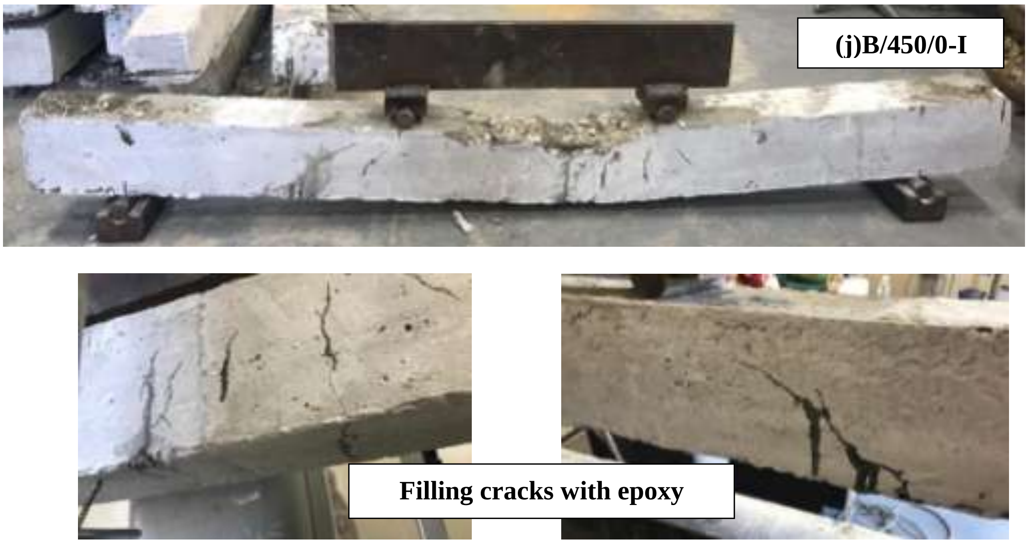


Fig. 8. Failure modes of beam specimens(continued)



Filling cracks with epoxy

Filling cracks with epoxy

Cracks under the beam

Fig. 8. Failure modes of beam specimens(continued)

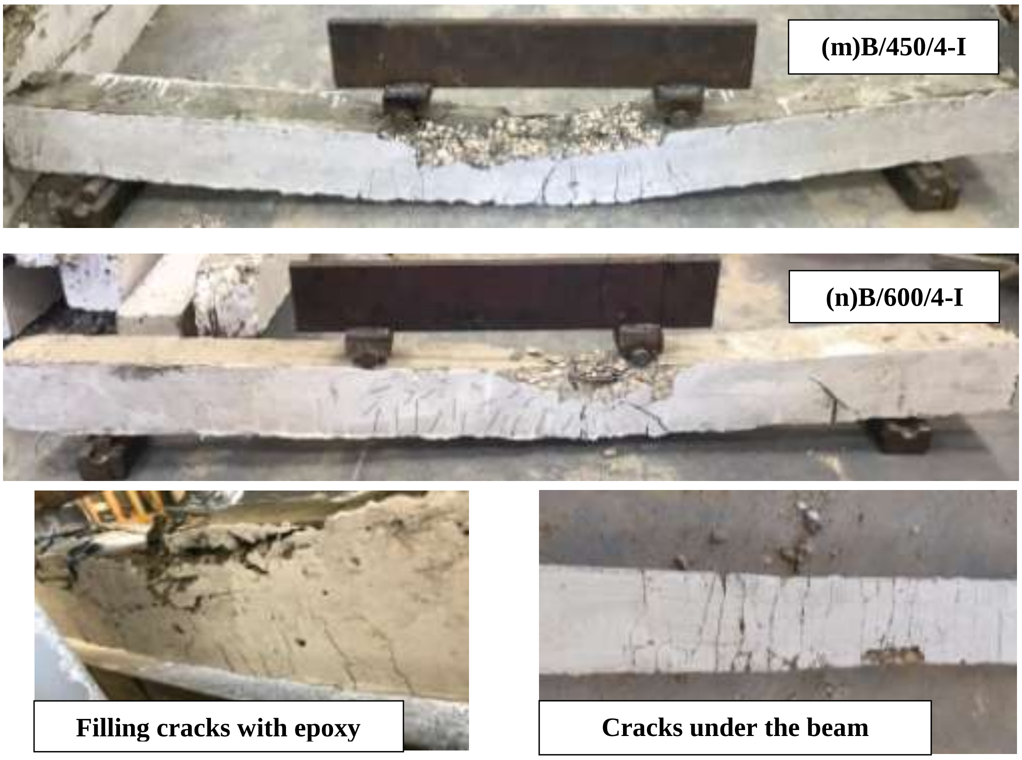


Fig. 8. Failure modes of beam specimens (continued)

IV. Conclusion

The following conclusions may be derived from the discussion of the test results collected from this research:

1- From the hardened concrete tests, using Nano-silica at 2% and 6% of cement weight can enhance the mechanical properties of concrete and increase the load carrying capacity however, the best compressive, tensile, and flexural strength came out when using Nano-silica at (4%) of cement weight.
2- The Repair of reinforced concrete beams using the technique of internal injection by epoxy effectively controls the cracks and respectively increases load-carrying capacity.
3- Crack injection provided an increase in stiffness in the linear region of the load–displacement curves for all of the RC beams.
4- The bond between concrete and the injection material is very strong. A good bond may restore the original stiffness of the repaired material and prevent further penetration of chloride ions and water.
5- Epoxy techniques to repair damaged specimens in restoring over 85 % of the original specimens' stiffness, strength, and energy dissipation characteristics.
6- Epoxy techniques are not applicable if the cracks are actively leaking and cannot be dried out. Wet cracks can be injected using moisture tolerant materials, but contaminants in the cracks (including silt and water) can reduce the effectiveness of the epoxy to structurally repair the cracks.

References

[1] M. E. B. R.Shashank, “Flexural Behavior Of Nano Silica Concrete,” pp. 799–803, 2016.
[2] M. Bastami, M. Baghbadrani, and F. Aslani, “Performance of nano-Silica modified high strength concrete at elevated temperatures,” *Constr. Build. Mater.*, vol. 68, pp. 402–408, 2014, doi: 10.1016/j.conbuildmat.2014.06.026.
[3] P. Aggarwal, R. P. Singh, and Y. Aggarwal, “Use of nano-silica in cement based materials — A review,” *Cogent Eng.*, vol. 33, no. 1, 2015, doi: 10.1080/23311916.2015.1078018.
[4] G. Quercia, G. Hüsken, and H. J. H. Brouwers, “Cement and Concrete Research Water demand of amorphous nano silica and its impact on the workability of cement paste,” *Cem. Concr. Res.*, vol. 42, no. 2, pp. 344–357, 2012, doi: 10.1016/j.cemconres.2011.10.008.
[5] A. Naji, S. Abdul, F. Nora, A. Aziz, M. Amran, and M. Salleh, “Composites : Part B Experimental investigation of the size effects of SiO 2 nano-particles on the mechanical properties of binary blended concrete,” *Compos. Part B*, vol. 41, no. 8, pp. 673–677, 2010, doi: 10.1016/j.compositesb.2010.08.003.
[6] B. Bhushan and R. Sharma, “The effect of nanomaterials on properties of geopolymers derived from industrial by-products : A state-of-the-art review,” *Constr. Build. Mater.*, vol. 252, p. 119028, 2020, doi: 10.1016/j.conbuildmat.2020.119028.
[7] B. B. Mukharjee and S. V. Barai, “Influence of Incorporation of Colloidal Nano-Silica on Behaviour of Concrete,” *Iran. J. Sci.*

Technol. - Trans. Civ. Eng., vol. 44, no. 2, pp. 657–668, 2020, doi: 10.1007/s40996-020-00382-0.
[8] A. Naji Givi, S. Abdul Rashid, F. N. A. Aziz, and M. A. M. Salleh, "Experimental investigation of the size effects of SiO2 nano-particles on the mechanical properties of binary blended concrete," *Compos. Part B Eng.*, vol. 41, no. 8, pp. 673–677, 2010, doi: 10.1016/j.compositesb.2010.08.003.
[9] ACI Committee 503, "ACI 503R-93. Use of epoxy compounds with concrete (Reapproved)," *Am. Concr. Inst.*, vol. 93, pp. 1–28, 1998.
[10] D. Darwin, "Causes , Evaluation and Repair of Cracks in Concrete Structures," pp. 1–22, 1998.
[11] G. Tsiatas and J. Robinson, "Durability evaluation of concrete crack repair systems," *Transp. Res. Rec.*, no. 1795, pp. 82–87, 2002, doi: 10.3141/1795-11.
[12] M. Ekenel and J. J. Myers, "Durability performance of RC beams strengthened with epoxy injection and CFRP fabrics," vol. 21, pp. 1182–1190, 2007, doi: 10.1016/j.conbuildmat.2006.06.020.
[13] S. Noor, M. Saliah, N. Nor, and N. Abd, "Evaluation of severely damaged reinforced concrete beam repaired with epoxy injection using acoustic emission technique," *Theor. Appl. Fract. Mech.*, vol. 112, no. December 2020, p. 102890, 2021, doi: 10.1016/j.tafmec.2020.102890.
[14] ACI-Committee 546, "ACI 546R Concrete Repair Guide," vol. 96, no. Reapproved, pp. 1–41, 2001.
[15] V. Of, A. By, K. Minoru, K. Toshiro, U. Yuichi, and R. Keitetsu, "IN," vol. 13, no. April, pp. 98–105, 2001.
[16] Calder AJJ, Thompson DM, "Repair of cracked reinforced concrete: assessment of corrosion protection. Transport and Road Research Laboratory," Department of Transport, Research Report 150, 1998.
[17] French CW, Thorp GA, Tsai WJ, "Epoxy repair techniques for moderate earthquake damage," ACI Struct J 87(4):416–424, 1990.
[18] Filiatrault A, Lebrun I, "Seismic rehabilitation of reinforced concrete joints by epoxy pressure injection technique," seismic rehabilitation of concrete structures SP-160, 1996.
[19] Karayannis C, Chalioris K, Sideris K, "Effectiveness of RC connection repair using epoxy resin injections," J Earthq Eng 2(2):217–240, 1998.
[20] Nikoupour H, Nehdi M, "Shear repair of RC beams using epoxy injection and hybrid external FRP," Mater Struct 44:1865–1877, 2011.