IJE TRANSACTIONS B: Applications Vol. 35, No. 11, (November 2022) 2164-2175

International Journal of Engineering

Journal Homepage: www.ije.ir

Retrofitting of Reinforced Concrete Beams using Lightweight RC Jacket Containing Silica Nano Particles and Glass Fiber

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PAPER INFO

Paper history:
Received 23 June 2022
Received in revised form 10 August 2022
Accepted 13 August 2022

Keywords:
Laboratory Study Beam
Lightweight Concrete Jacket
Silica Nano Particles
Glass Fiber
Retrofitting

ABSTRACT

The concrete jacket method is a common method used in retrofitting buildings. Although this method has many advantages, engineers criticize it due to an increase in the structure's weight. In the present study, lightweight concretes containing silica nanoparticles (SNPs) and glass fibers (GF) have been used in concrete jackets to strengthen concrete beams. Several reinforced concrete (RC) beams were constructed and retrofitted using the proposed lightweight concrete jackets and their response to four-point loading was evaluated. The SNPs amount in the lightweight concrete jackets was 0, 2, 4, and 6% by weight of cement and the amount of GF was 1.5% by volume of concrete. Load-deflection curves were extracted and the response of the beams was examined by parameters such as crack load, yield load, maximum load, energy absorption capacity, and ductility. The proposed lightweight concrete jacket containing 1.5% of GFs in which 0, 2, 4, and 6% of SNPs were used, increased the energy absorption capacity by 33%, 54%, 61%, and 62%, respectively. The presence of SNPs in lightweight concrete reinforced by GFs leads to the filling of small cavities in the concrete. Also, the bearing capacity of the retrofitted RC beams increased with an increase in SNPs in the concrete jacket. A portion of this increase can be attributed to an increase in tensile and compressive strength of the proposed concrete, and the other part can be attributed to the effect of SNPs on the surrounding surfaces of the main beam and jacket.

doi: *10.5829/ije.2022.35.11b.11*

1. INTRODUCTION

One of the major issues in the building's design is the materials' self-weight. Many engineers have always focused on reducing the building dead load using concretes with lower specific gravity and higher compressive strength. This issue is important since the seismic loads on the structure are proportional to the structural mass, and the mass structure reduction is the most important factor in reducing the earthquake impact [1-3].

The lightweight materials reduce the dead load and the weight, ultimately leading to economical design. The concrete's relatively high specific gravity (about 2400 kg/m^3 for unreinforced concrete) in RC buildings increases the concrete structure building weight and, as a result, increases the dead weight of the building, causing increases in the gravitational forces and seismic forces. This ultimately requires large elements that require a larger concrete volume with more reinforcement bars. Increasing the dimensions of the structural elements is one of the important disadvantages of RC buildings, which creates architectural problems and reduces useful infrastructure.

On the other hand, RC jackets and increasing cross-sections are more accessible and economical than other techniques in retrofitting of RC beams. This technique effectively improves bearing capacity and stiffness; however, adding concrete and steel to repair the beams increases the beam's weight, which is not desirable. For this purpose, lightweight concrete for retrofitting may be desired.

Numerous manuscripts have been published about retrofitting RC beams. Narayanan et al. [4] investigated the seismic retrofitting of beams using concrete jackets. A number of experiments were performed to investigate

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Please cite this article as: M. Ghanbari, O. Kohnehpooshi, M. Tohidi, Retrofitting of RC Beams using Lightweight RC Jacket Containing Silica Nano Particles and Glass Fiber, ***International Journal of Engineering, Transactions B: Applications,*** Vol. 35, No. 11, (2022) 2164-2175

the interaction between new and old concrete. Then several beams were retrofitted using the concrete jacket. In the next step, several beam-column connection specimens were retrofitted using concrete jackets. Finally, analytical studies were performed. The results showed that self-compacting concrete or shotcrete could be used to make the concrete jacket. Because the self-compacting concrete flowability causes the concrete to be completely in the space between the formwork and the old concrete, and no space remains. Rayal and Dave [5] investigated the different methods of retrofitting RC beams using RC jackets. For this purpose, ten RC beams were made. The four beam surfaces were perfectly smooth, and the other four roughened. Eight beams were retrofitted using RC jackets with a thickness of 60 mm, and two beams were examined as control samples. In beams with rough surfaces, concrete jackets had a more significant effect on improving the bending behavior of beams.

Pandian and Karthick [6] compared the shear strength of concrete beams retrofitted by polymer and concrete jackets. The retrofitted beams with RC jackets have excellent flexural strength, and the bending strength of the beams has increased using the proposed strengthening method. RC jackets can increase the RC beam's ductility, while the CFRP method cannot provide sufficient ductility. Shadmand et al. [7] evaluated the efficiency of a new retrofitting method in improving the bearing capacity of reinforced concrete beams. They investigated a type of composite steel-concrete jacket in RC beams and found that the proposed method can increase the bearing capacity of RC beams by about 2.25 times. Hassan et al. [8] retrofitted damaged beams using strain-hardening cementitious composites. They showed that the proposed method could increase the shear capacity of the damaged beam by about 27%. Mohsenzadeh et al. [9] evaluated the behavior of RC beams with RC jackets containing glass fibers and micro silica gel. The results of the tests indicated that the proposed jackets could increase the energy absorption capacity by about four times. Song and Eun [10] investigated the beams retrofitted with glass fiber-reinforced polyuria. The proposed method increased flexural ductility about 8.52 to 13.9 times.

Vulnerability and an increase in age of concrete buildings have caused new solutions for retrofitting. The lightweight of the proposed method is one of the factors that should be considered. The concrete jacket method is a common method used in retrofitting buildings. Although this method has many advantages, engineers criticize it due to an increase in the structure's weight. In the present study, lightweight concretes containing silica nanoparticles (SNPs) and glass fibers have been used in concrete jackets to strengthen concrete beams. According to the literature review, SNPs can replace a part of cement and improve concrete's mechanical characteristics and durability. Also, glass fibers can be considered a desirable reinforcing option and improve the tensile strength of concrete. In fact, in this research, an attempt has been made to introduce a lightweight concrete jacket that, in addition to increase in the load-bearing capacity of concrete beams, decreases the structure's weight compared to ordinary concrete jackets.

The study flowchart is presented in Figure 1. Rheological, durability, and mechanical properties were investigated in a study conducted by Ghanbari et al. [11], and the experiment results are summarized in Table 1. The samples in which 1.5% of GFs were used have higher tensile and flexural strengths than other samples; therefore, this amount of fibers was selected as the most optimal and was used to make the proposed concrete jackets. In general, five RC beams were made. One beam was not retrofitted, and the other four beams were retrofitted using lightweight concrete jackets containing GF, SNPs, and zeolite. The variable studied is the SNPs amount used in the jacket, which was considered 0, 2, 4, and 6% by weight of cement, respectively.

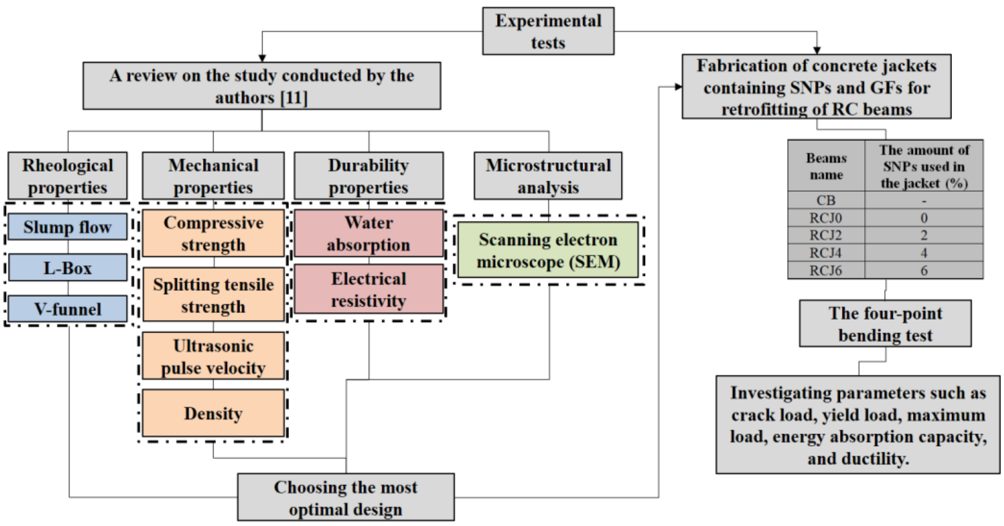


Figure 1. The study flowchart

TABLE 1. The properties of specimens containing SNPs and GF [11]

Mix ID	Slump flow		V-funnel time (s)	L-box (H_2/H_1)	Density (kg/m^3)	Compressive strength (MPa)	Ultrasonic pulse velocity (UPV)	Spilitingtensile strength (MPa)	Electrical resistivity	Water absorption percentage
	D (mm)	T_{50} (s)								
NS0F0	747	3	8.1	0.93	1886	27.2	3891	2.19	55	4.50
NS0F0.25	733	3.2	8.7	0.92	1885	27.1	3887	2.25	53	4.89
NS0F0.50	721	3.3	8.9	0.89	1887	26.9	3881	2.28	52	4.95
NS0F0.75	716	3.3	9.3	0.88	1888	26.5	3878	2.38	51	4.99
NS0F1	691	3.5	9.5	0.86	1888	26.4	3868	2.45	50	5.01
NS0F1.5	683	3.5	9.9	0.84	1890	26.3	3858	2.49	45	5.03
NS2F0	717	3.1	9.1	0.9	1888	35.1	3923	2.48	130	2.85
NS2F0.25	713	3.3	9.6	0.89	1890	35.1	3921	2.58	128	2.87
NS2F0.50	677	3.4	9.6	0.88	1890	34.9	3920	2.63	127	2.91
NS2F0.75	656	3.4	9.9	0.87	1891	34.6	3911	2.76	126	2.95
NS2F1	645	3.6	10.1	0.85	1892	34.5	3895	2.83	125	2.96
NS2F1.5	635	3.7	10.6	0.84	1891	34.3	3893	2.91	124	2.98
NS4F0	692	3.3	9.9	0.88	1890	40	4001	3.23	151	2.66
NS4F0.25	684	3.5	10.2	0.87	1890	39.9	3995	3.27	150	2.69
NS4F0.50	665	3.8	10.6	0.86	1892	39.8	3991	3.31	149	2.75
NS4F0.75	642	3.9	10.6	0.85	1891	39.7	3990	3.35	149	2.81
NS4F1	614	4	10.9	0.83	1893	39.5	3990	3.38	148	2.85
NS4F1.5	609	4.2	11.3	0.82	1894	39.6	3989	3.41	148	2.87
NS6F0	677	3.7	10.6	0.81	1893	39.7	3999	2.95	162	2.89
NS6F0.25	667	3.9	10.9	0.79	1893	39.1	3992	2.98	161	2.91
NS6F0.50	642	4	11.2	0.77	1894	38.9	3991	3.1	160	2.93
NS6F0.75	619	4.3	11.5	0.76	1895	38.8	3990	3.15	159	2.95
NS6F1	608	4.6	11.7	0.74	1896	38.7	3990	3.21	158	2.98
NS6F1.5	601	4.8	11.9	0.72	1897	38.4	3988	3.25	157	2.99
EFNARC recommendatis [12]										
Min.	550	2	6	0.8	NS: Nani silica particles					
Max.	850	5	12	1	F: Glass Fiber					

2. LABORATORY PROGRAM

2. 1. Geometric Characteristics of the Beams

The jacket thickness on each side (left, right, and bottom sides) was 40 mm. The total length of the beams is 1200 mm. The beam cross-section is a rectangle with dimensions of 150×200 mm (Figure 2). The examined beams were slender because the shear span to effective depth ratio was more than 2.5. Shear span means the distance from the support to the loading point. The characteristic of the investigated beams is presented in Table 2.

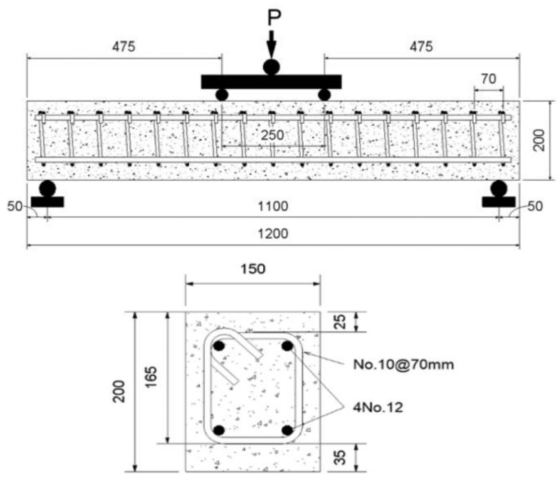


Figure 2. Geometric characteristics of the main beams and cross section (without retrofitting)

2. 2. Material

The materials used in this work are shown in Figure 3. The coarse aggregates used in this research are lightweight Scoria prepared from Qorveh city (Kordestan Iran). The 24-hour water absorption

TABLE 2. The investigated beams

Beams name	Diameter of jacket reinforcement bars (mm)	Jacket thickness (mm)	GF used in the jacket (%)	SNPs used in the jacket
CB	-	-	-	-
RCJ0	8	40	1.5	0
RCJ2				2
RCJ4				4
RCJ6				6

CB: Control beam (beam without retrofitting)
RCJ: Reinforcement concrete jacket

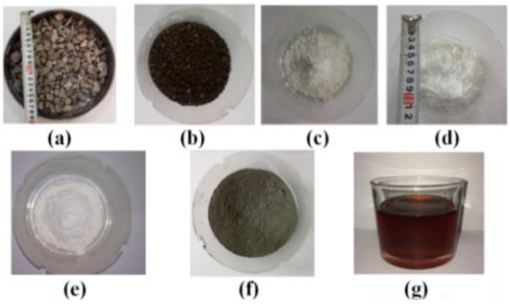


Figure 3. Materials a: Scoria aggregates b: Sand c: Zeolite d: GFs e: SNPs and f: Cement: g: Super-plasticizier

percentage, elastic modulus, and specific weight of scoria were 16%, 12.8 GPa, and 680 kg/m^3, respectively. The mineral chemical and physical characteristics of scoria aggregates are presented in Table 3. ASTM C136 [13] was used for grading coarse aggregates. The grading characteristics are presented in Table 4. The used cement is Portland type II with a specific weight of 3150 kg/m^3 (Table 3). The chemical analysis of SNPs and zeolite are presented in Table 3. GFs are very thin filaments of glass. The fibers used in this study type A with a size of 12 mm.

2. 3. Mix Design The mixed design specifications of the RC jacket are presented in Table 5. The desired mixing design was obtained using past experimental studies and according to ACI-211 [14]. The main purpose was to investigate the changes in SNPs. The water in all samples was considered constant. Also, the amount of water relative to the binder (cement and SNPs) was investigated. Variables includes SNPs (0, 2, 4 and 6% by weight of cement) and GF (0, 0.25, 0.50, 0.75 and 1 and 1.5% by weight of cement).

3. STEPS OF MAKING THE BEAMS AND CONCRETE JACKET

The materials included Portland cement type II, coarse aggregates, fine aggregates, deformed steel bars with 12 mm diameter for longitudinal reinforcement, deformed steel bars with 10 mm diameter for transverse reinforcement, wire, wooden boards for making molds, nails, superplasticizers, and burnt oil.

1. Squared timbers were used to make the molds. Vertical backs were used to create resistance to lateral pressure of concrete and to prevent mold distortion. These struts were made using four 50×50 mm lathes. The wooden molds picture is shown in Figure 4a.
2. Longitudinal and transverse reinforcement bars were cut to the desired dimensions using guillotine.
3. The mold's inner surfaces were impregnated with an oil to prevent the concrete from sticking to the mold. The reinforcement mesh bar was placed inside the mold by creating a cover (Figures 4b and 4c).
4. The main concrete beam compressive strength was considered to be 32 MPa. Coarse and fine aggregates, water, and cement were poured into the mixer according to the mix design and placed into the molds. The beams are shown in Figure 4d.

TABLE 3. Properties of Portland cement, Scoria, zeolite and SNPs

Description	Scoria	Portland cement	Zeolite	SNPs
SiO_2 (%)	58.8	21.54	67.79	99.98 ≥
Al_2O_3 (%)	32.16	4.95	13.66	-
Fe_2O_3 (%)	3.98	3.82	1.44	-
CaO (%)	3.28	63.24	1.68	-
MgO (%)	1.5	1.55	1.20	-
SO_3 (%)	0.75	2.43	0.5	-
K_2O (%)	-	0.54	1.42	-
Na_2O (%)	-	0.26	2.04	-
Loss on ignition	3.02	-	10.23	1.00 ≤
Specific gravity (kg/m^3)	680	3.15	1.1	0.5
Specific surface area (m^2/g)	–	326	1.1	200

TABLE 4. Granulation characteristics of coarse and fine aggregates

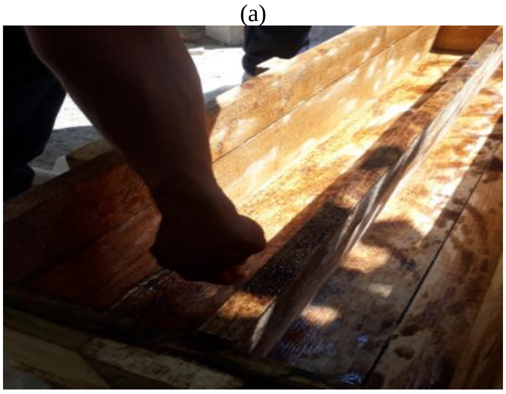
Sieve size (mm)	ASTM-C33 for coarse aggregates	Percent passing (Scoria)	ASTM-C33 for fine aggregates	Percent passing (sand)
12.5	90-100	91	-	-
9.5	40-80	63	-	-
4.75	0-20	10	-	-
2.36	0-10	6	95-100	95
1.18	-	-	40-80	60
0.30	-	-	10-35	25
0.15	-	-	5-25	17

5. The molds were opened twenty-four hours after concreting. The beams were cured inside the laboratory (18ºC) by spraying water every twenty-four hours until 28 days. The images of the main beams after opening the molds are shown in Figure 4e.
6. In order to make lightweight RC jackets containing SNPs and GF, wooden molds were made again according to the mold dimensions. The jacket's thickness on each side was considered to be 40 mm. In other words, the main beams' wooden molds dimensions were increased (Figure 5a).
7. In order to make lightweight self-compacting concrete jackets containing SNPs and GF, several holes were performed in the main beam surfaces using a drill. The hole depth was considered to be about 40 mm. Dust in the holes was cleaned with a brush. Then 8 mm L-shaped bars were placed inside the holes. The epoxy adhesive firmly connected these L-shaped reinforcement bars to the beam body. The epoxy adhesive brand is injection epoxy adhesive (IEA). This adhesive is a two-component paste or reinforcement bar implant adhesive with high mechanical strength (Table 6). This product has a high viscosity, and in addition to planting reinforcement bars and reinforcement, it is suitable for installing various strips and sheets such as FRP laminate on horizontal and vertical surfaces. This adhesive can also be used to plant steel rods and install steel sheets (Figures 5b and 5c).
8. The jacket's steel reinforcement bars' distances from each other were approximately 50 mm.
9. In order to make concrete jackets, the most optimal mixing design obtained from the technology study section (mentioned in the previous sections) was selected, and its manufacturing steps were performed. Scoria aggregates, sand, cement, zeolite, superplasticizer, GF, and SNPs (0, 2, 4, and 6%) were used to make the desired lightweight concrete in the jacket.

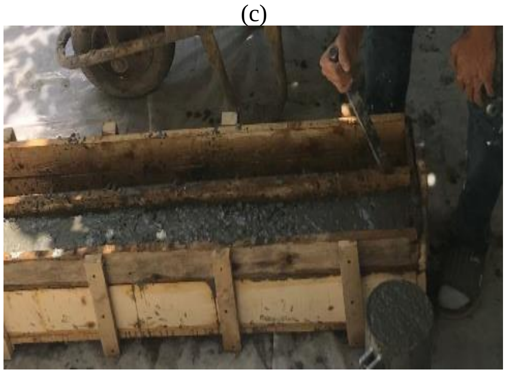
TABLE 5. Mix properties of RC jacket containing SNPs and GFs

Mix ID	Water to binder ratio	Cement	SNPs		Zeolite		GF (%)	Water (kg)	Sand (kg)	Scoria (kg)	Superplasticizer	
			Percentage	Amount (kg)	Percentage	Amount (kg)					Percentage	Amount (kg)
NS0F0	0.4	405	0	0	10	45	0	180	950	393	1.62	7.45
NS0F1.5	0.4	405	0	0	10	45	1.5	180	950	393	1.62	7.45
NS2F1.5	0.4	396.9	2	9	10	44.1	1.5	180	950	393	1.62	7.45
NS4F1.5	0.4	388.8	4	18	10	43.2	1.5	180	950	393	1.62	7.45
NS6F1.5	0.4	380.7	6	27	10	42.3	1.5	180	950	393	1.62	7.45


(a)


(b)


(c)


(d)

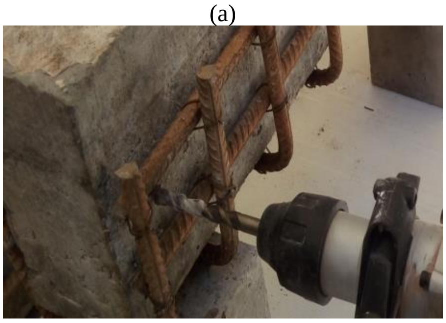
(e)

Figure 4. Steps of making main beams a: Wooden formwork used to make the main beams b: Dipping the mold using oil c: Place the reinforcement mesh bar inside the mold d: Concreting the main beams e: Main beams made after molding

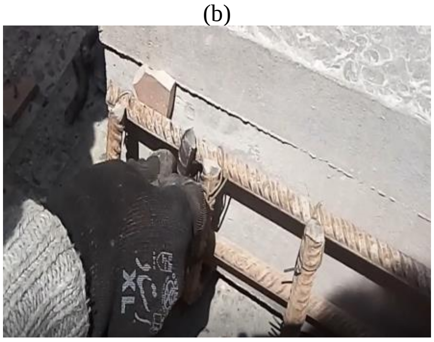
TABLE 6. Mechanical parameters of IEA

Compressive strength (MPa)	**9**
Density (kg/m^3)	1400
Bond strength (MPa)	16
Color	Gray
Substrate temperature (ºC)	5-40
Ambient temperature (ºC)	5-40

(a)



(b)



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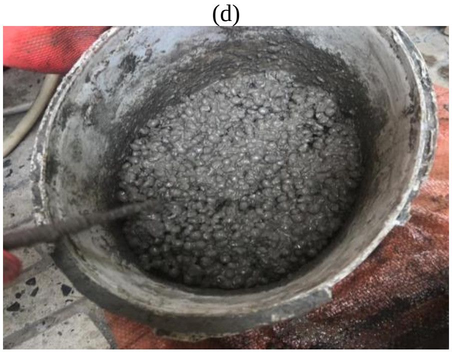
(d)



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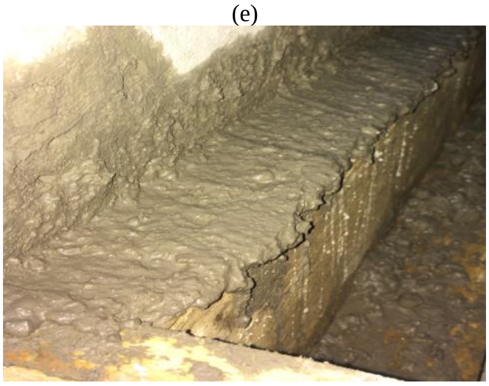

(f)

Figure 5. Steps of making concrete jackets a: Making wooden molds to install the jacket b: Making holes on the beam surfaces to install L-bars rebars c: Making holes on the beam surfaces to install L-bars reinforcement bars d: Placing the reinforcement mesh bars on the main beam body e: Making lightweight concrete samples used in the jacket and f: Concrete jacket after concreting

10. The main beams made were placed inside wooden molds, which were impregnated with oil, and light concrete was poured between the mold and the beams. Due to the self-compaction of lightweight concrete, the space between the reinforcement bars was completely filled, and the necessary compaction was created (Figure 5d).

11. Twenty-four hours after concreting, the wooden molds were carefully and gently opened, and the RCs were stored in the laboratory for 90 days.

12. As seen in Table 2, the variables in the beams laboratory reinforcement section are the amount of SNPs used in the jacket, which was considered 0, 2, 4, and 6%

by weight of cement, respectively. The half-span ratio to beam depth (a/h) was considered 1.5. According to this ratio, the value was considered to be 300 mm. A schematic picture of how the beam is loaded with an a/h ratio of 1.5 is shown in Figure 6.

13. The bending jack used in the bending load test has a capacity of 200 tons. This jack has the ability to record the deflection corresponding to the applied force in the span center. The LVDT device is located in the center of the opening and can record a deflection up to 50 mm. The Applying load method is in the force control form. Information about the force amount and the span center displacement was transmitted to the computer via a cable installed on the device and extracted from there (Figure 7).

4. LABORATORY RESULTS RELATED TO THE CONTROL AND RETROFITTED BEAMS RESPONSE

The loading was considered as four points and the corresponding load-deflection values were extracted in the form of load-deflection curves. According to research on four-point loading of concrete beams, parameters such as crack load, yield load, maximum load and ultimate load, ductility and energy absorption capacity are usually extracted and evaluated to measure the behavior of beams [14-17]. Therefore, each of the mentioned parameters is illustrated in Figure 8.

The crack distribution in the CB beam (control beam) and the load-deflection curv are shown in Figures 9 and 10, respectively. In this beam, no elements were used to

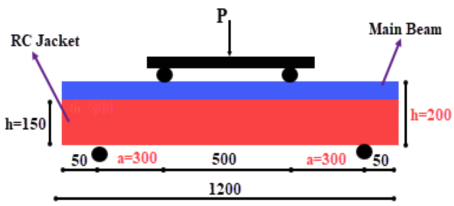

Figure 6. Schematic image of the load test set up

Figure 7. Bending jack used in the beams flexural load test

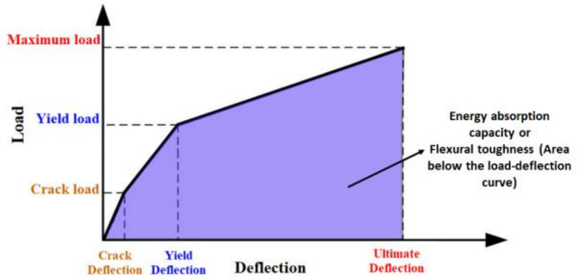

Figure 8. Introduction of the studied parameters in load-deflect curves

Figure 9. The failure mode of control beam

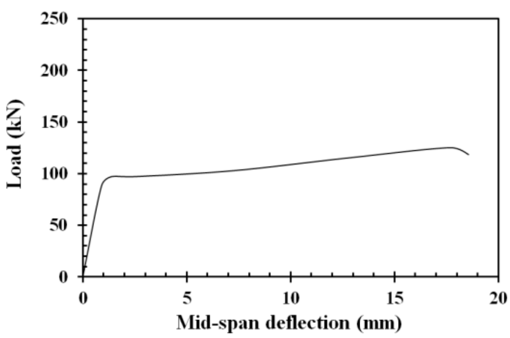

Figure 10. Load-deflection curve of control beam (without jacket)

strengthen the beam, and in fact, this beam was made with the aim of investigating the the effectiveness of the proposed retrofitting method. The crack load and deflection of CB are 88.5 kN and 0.902. The yield load and deflection of this beam is 97.2 kN and 1.38 mm, respectively. On the other hand, the maximum bearing capacity is 125 kN.

The failure mode of the beam retrofitted with lightweight concrete jackets containing 1.5% GF and 0% SNPs (RCJ0) is shown in Figure 11. In this beam, the crack load are 126 kN and 0.826 mm, respectively. The proposed concrete jackets addition has caused the crack load to increase by approximately 42%. The RCJ2 beam yield and maximum loads are 168 and 180 kN, respectively (Figure 12). The RCJ2 beam energy absorption capacity is 2633 kJ, which is an increase in about 34% compared to the control beam.

The crack disterbution which retrofitted with lightweight concrete jackets containing 1.5% GF and 2% SNPs (RCJ2) is shown in Figure 13. The load and

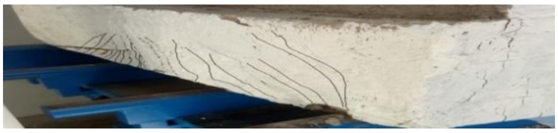

Figure 11. Beam failure and crack distribution of RCJ0 beam

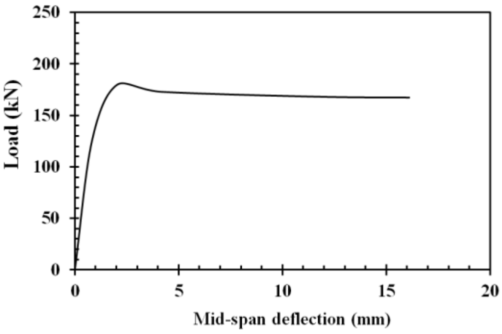

Figure 12. Load-deflection curve of RCJ0 beam

Figure 13. Beam failure and crack distribution of RCJ2 beam

deflection corresponding to the first crack are 142 kN and 0.69 mm, respectively. The proposed concrete jackets addition has increased the load corresponding to the first crack by about 60%. The yield and maximum loads of RCJ2 beam are 176 and 201 kN, respectively (Figure 14). The energy absorption capacity of the RCJ2 beam is 3044 kJ, which is an increase of about 54% compared to the control beam. Due to the high specific surface area and high reactivity, SNPs lead to calcium hydroxide, which is rapidly formed during hydration, especially at an early age, and the pores of the calcium silicate gel structure are filled, resulting in more and more dense hydrated products. It turns out that this process ultimately leads to improved bearing capacity.

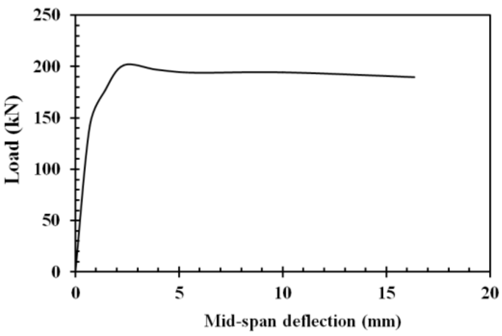

Figure 14. Load-deflection curve of RCJ2 beam

The retrofitted beams with lightweight concrete jackets containing 1.5% GF and 4% SNPs (RCJ4) and load-deflection curve are shown in Figures 15 and 16. In this beam, the first crack load and deflection are 146 kN and 0.72 mm, respectively. The proposed concrete jackets addition has caused the crack load to increase by about 65%. The yield and maximum loads of RCJ4 beam are 183 and 205 kN, respectively. The energy absorption capacity of the RCJ4 beam is 3175 kJ, which is an increase of about 61% compared to the control beam.

The retrofitted beams with lightweight concrete jackets containing 1.5% GF and 6% SNPs (RCJ6) and load-deflection curve are shown in Figures 17 and 18. In this beam, the load and deflection corresponding to the first crack are 145 kN and 0.71 mm, respectively. The proposed concrete jackets addition has increased the crack load by about 65%. The yield and maximum loads of RCJ6 beam are 500 and 600 kN, respectively. The RCJ6 beam energy absorption capacity is 3190 kJ, which is an increase of about 62% compared to the control beam.

5. RESULTS INTERPRETATION

The crack load, yield load, maximum load, deflection values, ductility, and energy absorption capacity are presented in Table 7. Also, the load-deflection curves of the beams are compared in Figure 19. The lightweight RC jackets containing SNPs and GF significantly increased energy absorption capacity. The energy absorption capacity of the retrofitted beams with jackets containing 1.5% GF in which 0, 2, 4, and 6% of SNPs were increased by 33%, 54%, 61%, and 62%, respectively (Figure 20). The presence of SNPs in

Figure 15. Beam failure and crack distribution of RCJ4 beam

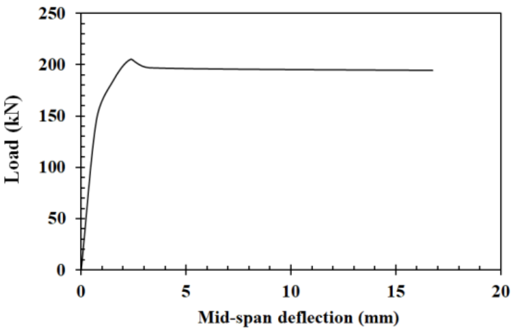

Figure 16. Load-deflection curve of RCJ4 beam

Figure 17. Beam failure and crack distribution of RCJ6 beam

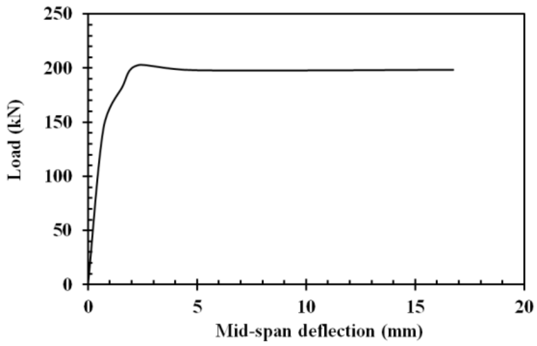

Figure 18. Load-deflection curve of RCJ6 beam

lightweight concrete reinforced by GF led to filling small holes in the concrete and significantly improved the retrofitted beams' behavior. The combined use of SNPs and zeolite effectively filled holes and reduced the concrete porosity.

TABLE 6. Results of the flexural test

Beams name	Load (kN)			Deflection (mm)		
	P_c	P_y	P_{max}	P_c	P_y	P_{max}
CB	88.5	97.2	125	0.902	1.38	3.47
RCJ0	126	168	180	0.826	2.03	1.87
RCJ2	142	176	201	0.69	1.44	2.43
RCJ4	146	183	205	0.72	1.48	2.19
RCJ6	145	182	203	0.71	1.55	1.90

P_c: Crack load, P_y: Yield load, P_{max}: Maximum load,

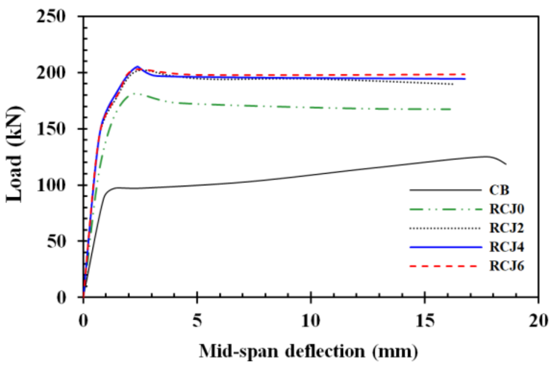

Figure 19. Comparison load-deflection curves

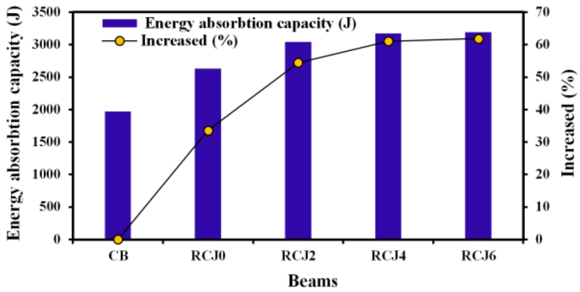

Figure 20. Energy absorption capacity

The crack, yield, and maximum loads are presented in Figure 21. The lightweight RC jackets containing GF and SNPs improved the response of the beam. The crack, yield, and maximum loads increased by 65, 88, and 64%. Among the jackets made, the jacket in which 1.5% of GF and 4% of SNPs (RCJ4) were used significantly increased beams crack, yield, and maximum loads. The use of concrete jackets containing 0, 2, 4, and 6% SNPs in which 1.5% of GF have increased the crack load by 42, 60, 65, and 63%, respectively. The yield load also increased by 72, 81, 88 and 87% and the maximum load increased (ultimate load capacity) by 44, 60, 64 and 62%, respectively.

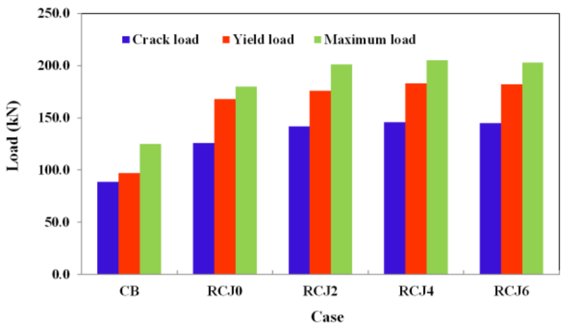

Figure 21. Comparison of the beams loads

In concrete structures retrofitting using different methods, sometimes it is possible that a decrease in ductility accompanies an increase in strength and stiffness, and the element can have a significant bearing capacity (maximum load bearing capacity); While its ductility has decreased. Ductility is one of the important features in reliable design for any structural element retrofitting [18]. In the previous sections, it was observed that the lightweight concrete jacket containing GF and SNPs could significantly increase the beam bearing capacity. In this section, the efficiency of the proposed method in ductility terms is considered. Ductility is obtained by using ultimate deformations and yielding in accordance with Equation (1):

$$\mu = \frac{\Delta_u}{\Delta_y} \quad (1)$$

In this equation, Δu and Δy are the ultimate deflection and yield deflection values, respectively. The beam's ductility and bearing capacity in different states compared simultaneously are shown in Figure 22. The deflection ductility coefficients of CB, RCJ0, RCJ2, RCJ4, and RCJ6 beams are 2.51, 0.92, 1.68, 1.47, and 1.22, respectively. Meanwhile, the maximum bearing capacity of CB, RCJ0, RCJ2, RCJ4 and RCJ6 beams is 125, 180, 201, 205, and 203 kN, respectively. As it is known, the proposed method has reduced the beam's ductility compared to the control beam but has increased the beam's ultimate bearing capacity. In strengthening concrete structures using different methods, sometimes a decrease in ductility may accompany an increase in strength and stiffness. An element can have a significant bearing capacity (maximum load); while its ductility has decreased [18]. This is true for RCJ0 and RCJ6 beams, and although these beams have a higher load-bearing capacity than the control beam, they have less ductility.

In order to compare the performance of the proposed method in this section, a comparative study of this method with similar studies has been done. Figure 23. mentions a number of studies that have been carried out in the field of retrofitting of RC beams. In the study conducted by Ying et al. [19], the method of steel plates was used to strengthen RC beams, and the highest rate of increase in bearing capacity was reported as 1.47. Jabr et al. [20] studied the jackets containing cement mortars reinforced with glass fibers and carbon fibers were used to strengthen the beams, and the bearing capacity of the beams increased by 1.33 times in the most cases. Abdullah et al. [21] investigated the strengthening of beams using the method of CFRP rebars. The maximum ratio of load capacity increase compared to the reference samples was reported as 1.59. Nanda and Behra [22] used the method of gluing GFRP sheets in strengthening beams. The results showed that this method can increase the carrying capacity by 1.34 times. Yu et al. [23] investigated the strengthening of severely damaged concrete beams using CFRP sheets. They showed that the use of CFRP sheet installation method can increase the maximum beam load by about 2.13 times. Zhang et al. [24] used concrete layers containing high-strength

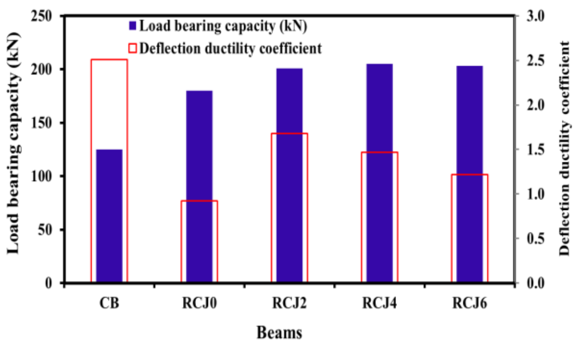

Figure 22. Comparison of deflection ductility coefficient

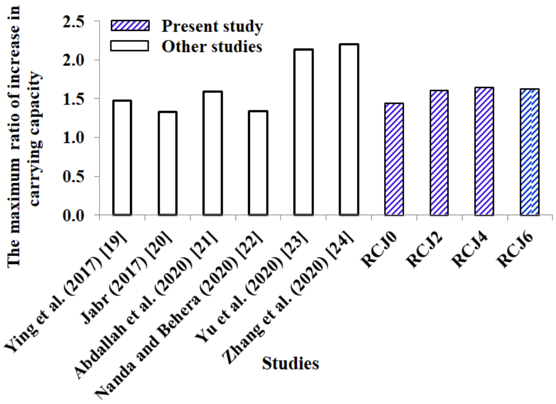

Figure 23. Comparison of the maximum ratio of increase in carrying capacity compared to reference samples

concretes to strengthen RC beams and showed that this method can increase the load-bearing capacity by about 2.2 times. The results of the present study also showed that the method of using lightweight RC Jacket containing SNPs and GFs can increase the load-bearing capacity of beams by about 1.64 times.

7. CONCLUSION

In this study, the retrofitting of RC beams was investigated using lightweight concrete jackets containing GFs and SNPs. A number of RC beams were made and retrofitted using the proposed concrete jacket and their response to four-point loading was evaluated. The variables were the amount of SNPs used in the concrete jacket, which were considered 0, 2, 4, and 6% by weight of cement, respectively. The most important results are presented in this section.

- The proposed self-compacting lightweight concrete jacket has a high capability. The RC beams bearing capacity and energy absorption capacity can increase and the beam cracking can be delayed .
- The use of the proposed self-compacting concrete jackets containing 1.5% of GF and different amounts of SNPs increased the energy absorption capacity by 33 to 64%. GFs lead to the filling of tiny cavities in concrete and have a significant effect on improving the retrofitted beams' behavior .
- The use of concrete jackets containing 0, 2, 4, and 6% SNPs in which 1.5% of GF was used, has increased the load corresponding to the first crack by 42, 60, 65, and 63%, respectively.
- SNPs can withstand higher stresses without the expansion of the unstable crack than conventional concrete, delaying the cracks spread in the beam and increasing the beam's resistance to cracking.
- The combined use of fibers and SNPs increases the beam yield capacity. The retrofitted beams yield load with the proposed self-compacting concrete jackets

containing 0, 2, 4 and 6% of SNPs increased 72, 81, 88, and 87%, respectively, compared to the control sample.

- The retrofitted beam bearing capacity increased by about 125 to 203% depending on the SNPs amount. With an increase in SNPs in the concrete jacket, the bearing capacity of the retrofitted concrete beams increased. Part of this increase can be attributed to an increase in the proposed concrete tensile and compressive strength, and the other part can be attributed to the SNPs and zeolite effect at the primary concrete and the jacket connection.

In order to develop the present study, the researcher can evaluate topics such as follows:

- Investigating the use of the proposed retrofitted method on deep RC beams
- Evaluating the use of FRP reinforcement bars in the proposed concrete jackets and comparing them with steel reinforcement bars
- Investigating the combined use of the proposed concrete jackets and FRP sheets in the retrofitting of RC beams
- Investigating the main beams' longitudinal and transverse reinforcement percentage changing effect on the present study results
- Investigating the jackets containing SNPs and GF movement effect on the old concrete surface
- Retrofitting of RC beams using lightweight RC jacket containing SNPs and GF against impact loading

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Persian Abstract

چکیده

روش ژاکت بتنی روشی رایج است که در مقاوم سازی ساختمان ها استفاده می شود. اگرچه این روش مزایای زیادی دارد اما مهندسان به دلیل افزایش وزن سازه از آن انتقاد می کنند. در تحقیق حاضر از بتن های سبک حاوی نانوذرات سیلیس و الیاف شیشه در ژاکت های بتنی برای تقویت تیرهای بتنی استفاده شده است. چندین تیر بتن مسلح با استفاده از ژاکت‌های بتنی سبک پیشنهادی ساخته و مقاوم‌سازی شدند و پاسخ آنها به بارگذاری چهار نقطه‌ای ارزیابی شد. مقدار نانوذرات سیلیس در ژاکت های بتن سبک ۰، ۲، ٤ و ٦ درصد وزنی سیمان و مقدار الیاف شیشه درصد حجمی بتن بود. منحنی‌های بار–انحراف استخراج شد و پاسخ تیرها با پارامترهایی مانند بار ترک، بار تسلیم، حداکثر بار، ظرفیت جذب انرژی و شکل‌پذیری مورد بررسی قرار گرفت. ژاکت بتنی سبک پیشنهادی حاوی ۱.۵ درصد الیاف شیشه که در آن ۰، ۲، ٤ و ٦ درصد نانوذرات سیلیس استفاده شده است، ظرفیت جذب انرژی را به ترتیب ۳۳، ٥٤، ٦١ و ٦٢ درصد افزایش داد. وجود نانوذرات سیلیس در بتن سبک تقویت شده توسط الیاف شیشه منجر به پر شدن حفره های کوچک در بتن می شود. همچنین ظرفیت باربری تیرهای بتن مسلح مقاوم سازی شده با افزایش نانوذرات سیلیس در ژاکت بتنی افزایش یافت. بخشی از این افزایش را می توان به افزایش مقاومت کششی و فشاری بتن پیشنهادی نسبت داد و بخشی دیگر را می توان به اثر نانوذرات سیلیس بر روی سطوح اطراف تیر اصلی و ژاکت نسبت داد.