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Strengthening of Reinforced Concrete Beams using Self-consolodating Concrete Jacket Consisting of Glass Fiber and Fiber-silica Fume Composite Gel

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ABSTRACT

In this paper, strengthening of RC beams with self-consolodating concrete (SCC) jacket containing glass fiber (GF) and fiber-silica fume composite gel (FSCG) were investigated. FSCG can use as a substitute for a part of the cement that contains silica fume powder, polypropylene fibers, superplasticizer, concrete waterproof, and some other admixtures. In order to evaluate the performance of the proposed jacket, twelve beams were strengthened and a control beam was made. The variables included the amount of glass fibers consumed in the jacket (0, 0.25, 0.5, 0.75, 1 and 1.25% by volume) and the amount of FSCG gel (0 and 7%), respectively. Fresh and hardened concrete properties and flexural capacity of RC beams were investigated. The use of FSCG in RC jackets can compensate well for the deficiency in strength due to the GF entry into the concrete matrix. High affinity of these materials improve the cohesion between cement and GFs. RC jackets containing GF and FSCG increased the beams' energy absorption capacity by about 89 to 463%, depending on the percentages of GFs. RC jacket containing GF and FSCG delays the growth of the primary crack and it can significantly increase the maximum load. Also, Glass Fiber Reinforced Polymer (GFRP) sheets have poor performance compared to the proposed method due to separation from the surface of the strengthened beams, and their load-bearing capacity and energy absorption are lower.

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1. INTRODUCTION

In recent years, strengthening of existing structures and repair of damaged buildings has increased widely. Changes in structure occupancy require strengthening with increasing bearing capacity of their members [1-3]. The strengthening method's choice depends on strength, amount of damage, type of members and connections, access to materials, and economic aspects [4, 5]. These methods can include methods such as changing the lateral-resisting system (brace or shear wall), adding steel plates (steel jacket), using concrete jackets, using reinforced polymer fiber, using fiber concrete, shotcrete, and using near-surface mounted composite rebars, etc. [6-9]. Nowadays, strengthening and rehabilitation of beams, which are essential members of structural frames, have been investigated. Increasing flexural or shear capacity, control of deformation, and cracking are the main goals of strengthening these members [10-12].

Monir et al. [13] analyzed RC beams using concrete jackets. The slip in the analysis was ignored and the jacket overall behavior was examined, which results in higher estimates of stiffness or capacity. Aldhafairi et al. [14] used steel jackets to retrofitting normal concrete beams, high strength and self-compacting. For this purpose, steel plates and angles were used and it was shown that steel angles have better performance compared to steel plates [14]. Tayeh et al. [15] investigated the flexural performance of RC beams retrofitted with self-compacting concrete jackets containing welded steel wire mesh. The results showed that the proposed method significantly increased the beams bearing capacity [15]. Yuan et al. [16] evaluated the strengthened beams using basalt sheets and a new epoxy was used. They showed that baslat fiber sheets

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with the proposed epoxy can improve the behaviour of the RC beams and delay the debonding of the fiber [16]. Shadmand et al. [10] showed that the combined use of steel plate and steel reinforced fiber can improve the flexural thoughtness of RC beams by about 89 to 119%. Rahmani et al.[11] conducted a laboratory study on strengtheneing of RC with RC jackets containg steel fibers. They showed that steel fiber can decrease the cracks and improve the performance of the RC jacket [11]. Faez et al. [12] examined the strengthened beams with RC jacket. They used aluminum oxide nanoparticles and silica fume in jacket. The proposed method enhanced the bearing load about 155 to 447% [12]. Maraq et al. [17] investigated the flexural behavior of reinforced concrete beams with steel wire mesh and self-compacting concrete jacket. The proposed method increased the bearing capacity of the beam by about 110 to 163% [17]. Ghalehnovi et al. [18] investigated the retrofitting of concrete beams made from recycled materials using reinforced concrete jackets made of steel fibers. The results showed that the use of 2% steel fibers can play an effective role in improving the bearing capacity of beams made with recycled materials [18]. According to studies, tensile, compressive, and flexural concrete strengths can be significantly increased using fiber [6, 19, 20]. In a number of mentioned studies, it has been observed that steel fibers have been used in concrete jackets. One of the problems with steel fibers is that they rust in the long run, which can affect its performance. To overcome this weakness, in the proposed method, glass fibers are used in jackets, which in addition to not having the problem of corrosion, its weight is less compared to steel fiber. The use of FSCG is also expected to improve the adhesion between the fibers and the cement. In this paper, strengthening of the beams was investigated using SCC jackets containing glass fiber (GF) and fiber-silica fume composite gel (FSCG). FSCG and GF can compensate for tensile weakness of concrete. It should be noted that the concrete used in the concrete jacket is SCC, so that there will be no problem with vibration for obtaining the required compacting. In this method, RC beams' peripheral surface is first reinforced with longitudinal and transverse reinforcement rebars. The distance between steel reinforced rebars and the peripheral surface of beams is filled with SCC containing GF in which FSCG is used. Considering the use of GFRP plates is being developed as a conventional strengthening method, comparing the newly presented method with strengthening of RC beams using GFRP sheets in new aspects. Using a concrete jacket reinforced with GF and FSCG is more effective in strengthening irregular outer beams that do not have suitable concrete covering than GFRP sheets. Morever, in many cases, tensile forces of concrete are not precisely known. Since reinforcement rebar forms a small part of the section, the concrete section's assumption is a homogenous and isotropic section is incorrect. Therefore, GF and FSCG in the concrete jacket can create isotropic conditions and reduce fragility weakness and concrete brittle.

2. EXPERIMENTAL PROGRAM

2. 1. The Variables

The studied variables are strengthening method type (strengthening by SCC jacket containing GF, strengthening by SCC jacket containing GF and FSCG, strengthening by GFRP sheets, without strengthening), the content of the used GF in RC jacket (0, 0.25, 0.5, 0.75, 1, and 1.25 % by total volume of concrete), presence or absence of FSCG in RC jacket (0 and 7% by weight of cement) and the number of GFRP layers (1, 2 and 3 layers). Thus, according to the study variables, 16 RC beams were constructed in different modes and were evaluated using a four-point bending test. The considered beams were introduced in Table 1.

TABLE 1. Introducing the investigated beams

Name	Strengthening method	AR-GF used in jacket (%)	FSCG	Number of GFRP layers
CB	Without strengthening	-	-	-
F0	RC Jacket	0	0	-
F-0.25	RC Jacket	0.25	0	-
F-0.5	RC Jacket	0.5	0	-
F-0.75	RC Jacket	0.75	0	-
F-1	RC Jacket	1	0	-
F-1.25	RC Jacket	1.25	0	-
F0-FS	RC Jacket	0	7	-
F-0.25-FS	RC Jacket	0.25	7	-
F-0.5-FS	RC Jacket	0.5	7	-
F-0.75-FS	RC Jacket	0.75	7	-
F-1-FS	RC Jacket	1	7	-
F-1.25-FS	RC Jacket	1.25	7	-
GFRP-1L	GFRP wrapping	-	-	1 Layer
GFRP-2L	GFRP wrapping	-	-	2 Layers
GFRP-3L	GFRP wrapping	-	-	3 Layers

CB: Control beam F: Glass fiber, FSCG: Fiber silica fume composite gel

RC Jacket: Reinforced concrete jacket

GFRP-1L: Glass-fiber reinforced polymer - 1 Layer

GFRP-2L: Glass-fiber reinforced polymer - 2 Layers

GFRP-3L : Glass-fiber reinforced polymer - 3 Layers

2. 2. Material Mixture details of the original beams and RC Jacket are presented in Table 2. Materials for constructing the 13 beams were gravel, sand, cement, water, GF, FSCG, and reinforcement rebars (Figure 1).

FSCG can be used as a substitute for a part of the cement that contains silica fume powder, polypropylene fibers, superplasticizer, concrete waterproof, and some other admixtures. According to the manufacturer's

TABLE 2. Mixture details of the original beams and RC Jacket

Member	Mix code	$\frac{W}{C}$	C (kg/m^3)	G (kg/m^3)	S (kg/m^3)	GF (kg/m^3)	FSFGe (kg/m^3)	SP (%)
Original Beam	S-OB	0.625	320	900	850	-	-	-
RC Jacket	S-0-0	0.27	760	480	414	0	0	1.52
	S-0.25-0	0.27	760	478	412	6.75	0	1.52
	S-0.50-0	0.27	760	475	410	13.5	0	1.52
	S-0.75-0	0.27	760	474	408	20.25	0	1.52
	S-1.00-0	0.27	760	471	406	27	0	1.52
	S-1.25-0	0.27	760	480	414	33.75	0	1.52
	S-0-0	0.27	703	478	412	0	57	1.49
	S-0.25-7	0.27	703	475	410	6.75	57	1.50
	S-0.50-7	0.27	703	474	408	13.5	57	1.51
	S-0.75-7	0.27	703	471	406	20.25	57	1.51
	S-1.00-7	0.27	703	480	414	27	57	1.52
	S-1.25-7	0.27	703	478	412	33.75	57	1.53

Figure 1. Used material a: Coarse aggregates b: Fine aggregates c: Cement d: GF e: Superplasticizer f: FSCG g: GFRP plates h: Paste

information, this product is following ASTM C1240 [21]. Properties of this gel are presented in Table 3. The consumption amount of this product in this study is considered 7% by the weight of cement. This product should be thoroughly mixed with about 200 g of water, and after mixing, it should be added to all concrete components, and then the mixing process should be continued for 5 minutes. The density of FSCG is 1.6 g/cm^3. These materials are pasty and dissolve in water, and their color is gray.

The size range of the aggregates and their comparison with the values of the ASTM-C33 [22] are presented in Figure 2. The used cement was produced following ASTM C150 [23] (Table 4). Drinking water was used following ASTM C190 [24]. The plasticizer was liquid, and the density was 1.1 g/cm^3. AR-GFs were used in this study (Length: 30 mm, Diameter: 5 to 20 mm). The reason for using this size is their better results in experiments conducted by other researchers. Although fibers whose size is smaller than optimum have better

TABLE 3. The attributes of FSCG

Physical state	**Colour**	**Density (gr/cm^3)**
Elastic paste	Gray	1.6
PH	Percent elongation	Tensile strength (MPa)
Neutral	4.8	3300

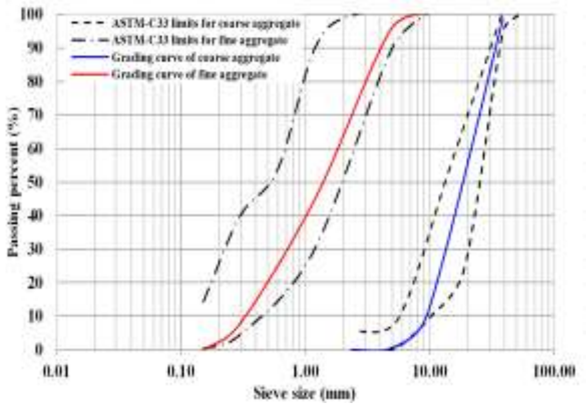


Figure 2. The size range of the aggregates and their comparison with the values of the ASTM-C33

TABLE 4. Chemical attributes of the used cement

Components	Cement type II%
SiO_2	21.27
Al_2O_3	4.95
Fe_2O_3	4.03
CaO	62.95
MgO	1.55
SO_3	2.26
K_2O	0.65
Na_2O	0.49

composition ability, they reduce strength; Larger fibers also have composition ability [25]. The properties of GF are presented in Table 5.

GFRP plates were cut into rectangles with 12 cm width and required length. And after smearing with the paste, the beams were carefully installed. Properties of the GFRP plates are presented in Table 6. The paste used for sticking GFRP plates on the beam is obtained from a mixture of resin and hardener in the ratio of 100 to 15. The mix of these two materials was performed concurring to the method suggested by the FRP producer. All resin components were mixed at a sufficient temperature until the mixing and stirring of materials reached a uniform and complete mix. Resin composite materials usually have different colors and must be mixed enough to achieve a uniform color (Table 7) [26].

TABLE 5. The attributes of the used GF

Type	Length (mm)	Density(g/cm^3)
A-Glass	30	2.44
Fiber diameter (mm)	Percent elongation	Tensile strength (MPa)
5-20	4.8	3300

TABLE 6. Properties of GFRP sheets

GFRP Type	Thickness (mm)	Tensile strength (MPa)
E-Glass	0.16	2200
Tensile modulus (GPa)	Young,s Modulus (MPa)	Density (kg/m^3)
70	72000	2550

TABLE 7. Properties of resin and hardener

Properties	Amount	Unit
Type	EPL1012	-
Compressive Strength	97.4	MPa
Flexural Strength	96	MPa
Tensile Strength	76.1	MPa
Impact resistance	7.850	kJ/m^2

According to the mentioned proportion, the two resin and hardener materials were mixed in the laboratory when the GFRP sheet was being pasted to the beam. After a short time, GFRP plates were installed on the beam.

2. 4. Preparation of the Beams before Strengthening Geometric properties of the original beams are shown in Figure 3. Four reinforcement rebars are used in the beams (Diameter: 12 mm). Rebars with diameters and intervals of 10 and 100 mm were used as stirrups. Wooden molds were built acording to the beams' measurements. The beams samples were expelled from molds 24 hours after concrete pouring and put away in a water tank for 28 days. After curing, the beams were arranged for strengthening by SCC jackets and GFRP sheets. The preparation steps of the original beams is shown in Figure 4.

2. 4. Preparation of RC Jackets Three types of RC jackets were constructed in the present study. GF and FSCG weren't used in the first group. GF was used in the second group, and GF and FSCG were used in the third group. The beams' strengthening was conducted on three sides of the beams (bottom and lateral sides of the beam up to 2/3 height of beam). The distances and diameters of the reinforcement rebars were 50 mm and 10 mm, respectively. The beam surface preparation process is one

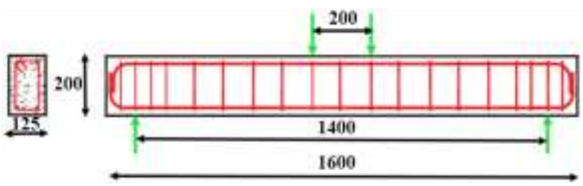


Figure 3. Geometric properties of original beams

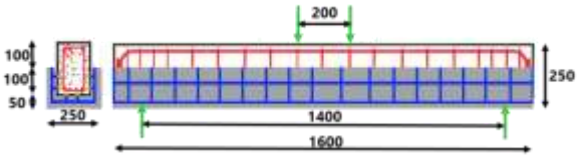
Figure 4. Preparation of original beams

of the important parts of the experiment. For occurring no debonding during the test, a full bond must be made between the surface of the prior concrete, concrete jacket, and GFRP. The steps of preparing concrete jackets are shown in Figure 5.

2. 5. Installation of GFRP Plates Pollution, dust, oil, and anything else that may interfere with the FRP system's cohesion and concrete should be eliminated [27]. One of the significant failures of retrofitted RC beams with FRP plate is deboning from the beam surface, known as deboning. Much work has recently been done to prevent this phenomenon. Mostofinejad and Shameli [28] proposed a groove method to avoid this phenomenon. In this experiment, the beams considered for strengthening were reinforced with GFRP after preparing the concrete surface and making longitudinal grooves. It should be noted that these grooves were filled with paste. The GFRP plate was cut into the desired size, and the resin was scattered evenly to the surface using a brush. Fibers were put on the surface using rolling brushes that rotate and move in the direction of the fibers, the fibers were pasted to the resin, and air bubbles which were a detrimental factor for bonding, were removed. The time required for setting and curing the resin at temperatures above 7 ° C is 72 hours. The steps of pasting the GFRP plate onto the beam surfaces are shown in Figure 6.

2. 6. Experimental Tests Table 8 provides a list of tests performed to determine the attributes of fresh concrete and hardened concrete. Compressive strength and splitting tensile strength tests were performed in accordance with ASTM-C39 [29] and ASTM-C496, respectively. Slump flow, T50, V-funnel and L-box tests were also performed in accordance with EFNARC Standards. The beams supports were simple and the loads were applied to the center of the beam. Since four beam points (two support points and two loading points) are subjected to load, this method is called four-point loading. In many studies [30-34] that have been done in the field of beam retrofitting, this method is used for loading and is similar to ASTM-C293 [35] except that it has more load points.

The bending test machine used has an increasing bearing capacity of 200 tons. Loading was continued until the beam fails. The center distance to the support center is 140 cm, and the load span is 20 cm. Loading device and schematic image of loading is shown in Figure 7. Mid-span deflection were measured using a displacement gauge located just below the load site.



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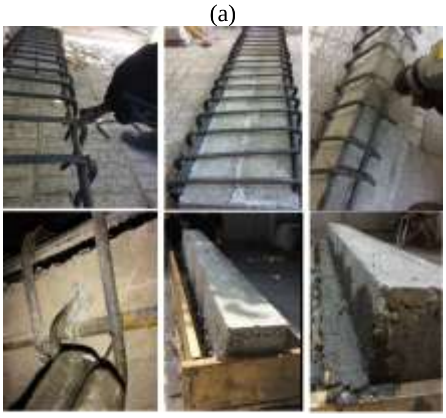


(b)

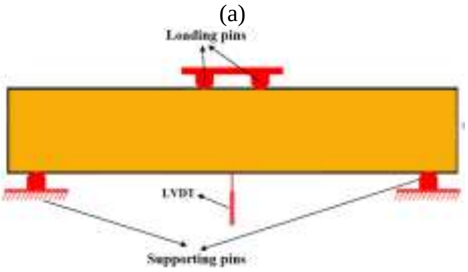
Figure 5. Preparation of RC jackets a: Geometric properties and steel reinforcement arrangement b: Preparation

Figure 6. Installation of GFRP plates

TABLE 8. A list of tests performed to determine the attributes of fresh concrete and hardened concrete

Test	Standard	Properties type	Specimen dimension (cm)
Slump flow	EFNARC	Fresh properties	--
T50			
V-funnel			
L-box			
Compressive strength	ASTM-C39 [29]	Hardened properties	15×15×5
Splitting tensile strength	ASTM-C496 [37]		30×15

(a)



(b)

Figure 7. Details of loading a: Loading device b: Schematic image of loading

4. RESULTS AND DISCUSSION

4. 1. Fresh Concrete Results Table 9 presents controlling fresh properties of SCC according to EFNARC Standards and ASTM C293 [35, 36]. The results show that all specimens meet SCC requirements and fall within the EFNARC standard range.

TABLE 9. Fresh concrete properties

Mix code	Slump flow		V-funnel flow time (s)	L-box (H_2/H_1)
	D (mm)	T_{50} (s)		
S-0-0	669	3.78	8.6	0.99
S-0.25-0	668	4.24	10.2	0.99
S-0.50-0	667	4.83	10.9	0.97
S-0.75-0	653	4.91	11.5	0.95
S-1.00-0	651	4.95	11.8	0.95
S-1.25-0	650	4.98	11.9	0.92
S-0-0	781	2.98	6.7	0.94
S-0.25-7	773	3.15	7.9	0.93
S-0.50-7	761	3.45	8.3	0.93
S-0.75-7	751	3.65	9.1	0.92
S-1.00-7	743	3.98	9.5	0.89
S-1.25-7	738	4.21	10.1	0.89
EFNARC recommended values				
Min.	650	2	6	0.8
Max.	800	5	12	1

The slump flow diameter decreases slightly by adding GF to concrete (Figure 8). The slump flow diameter of specimens containing 0, 0.25, 0.5, 0.75, 1 and% GF were decreased 0.14, 0.29, 2.4, and 2.7 %. Fibers prevent the flowability of cement paste [38, 39]. Güneyisi et al. [40] showed that using 1% GF reduces the slump flow diameter by about 6% [40]. Decreasing slum flow and T50 in fiber concrete was detailed in the study of Faraj et al. [41]. On the other hand, the slump flow diameter of specimens containing FSCG with GF was significantly higher than specimens containing GF. So, the slump flow diameter of specimens containing 0.25, 0.5, 0.75, 1 and 1.25% GF and 7% FSCG were 16.7, 15.5, 13.8, 12.3, 11.1 and 10.3% more than control specimen. The reason for this is that FSCG increases the viscosity and flowability of the concrete. In other words, the addition of FSCG increases the plastic viscosity of cement paste due to higher inter-particle friction. Studies by Hosseinpoor et al. [42] also showed that increasing the paste's plastic viscosity increases with increasing the volume ratio of the binder.

As shown in Figure 8 and Table 9, the T50 range in specimens containing GF is between 4.24 to 4.98 seconds, and the T50 range in specimens containing GF and FSCG is between 2.98 to 4.21 seconds. Accordingly, the T50 slump flow time in all mixtures is between 2 and 5 seconds. In this range, the mixture viscosity is high enough to increase strength against segregation and limit excessive pressure to mold [43]. Figure 8 also shows that increasing GF can increase T50 slump flow time. Increasing T50 time in concrete specimens containing GF has also been reported in Güneyisi et al. [40] and Faraj et al. [41] studies.

The effect of GF and FSCG on the V-funnel flow time and blocking ratio (L-box test) is shown in Figure 9 and Table 8. The results show that fibers' presence in SCC increases the plastic viscosity of the concrete and the V-funnel flow time increases with increasing fiber percentage. Moreover, all obtained times from the V-funnel test correspond to EFNARC considerations (6 to 12 seconds). The V-funnel flow time for each specimen

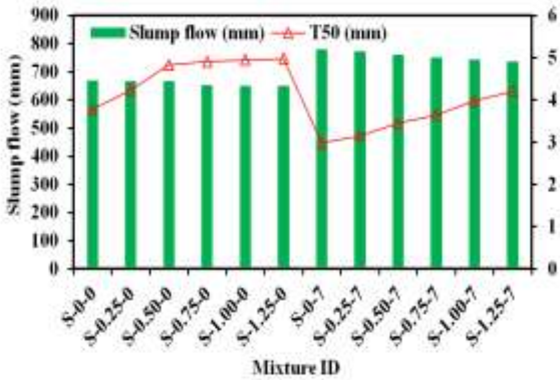


Figure 8. Slump flow and T50 results

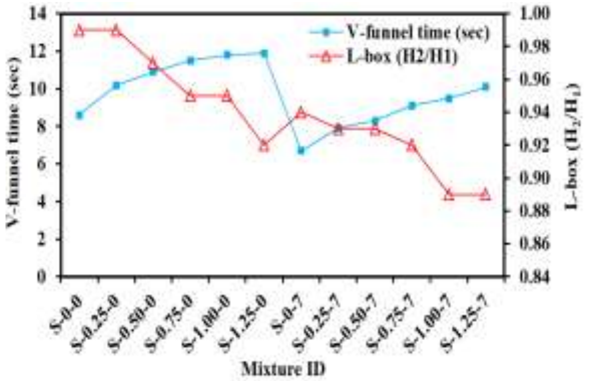


Figure 9. Fresh concrete results (V-funnel and L-box tests)

containing 0.25, 0.5, 0.75, 1, and 1.25% GF and 7% FSCG was 34, 27, 27, 22, 20, and 50% lower than corresponding specimens without FSCG, respectively.

L-box test results indicate that all mixtures have a good filling ability. But observations suggest that an increase in GF percentage has decreased the H1/H2 ratio. In other words, fibers' presence reduces the passing ability between rebars, and the passing ability is more reduced by increasing fiber percentage. According to the results obtained by Liu et al. [43], Chen et al. [44], and Kina et al. [45] fibers decrease the flowability. Fiber had adverse effects on the rheological properties of SCC. The studies above can confirm the fresh concrete results of the present study.

ACI has divided the viscosity of the SCC based on T50 and V-funnel flow time into two groups VS1/VF1 and VS2/VF2. Acording to the Figure 10 most of the specimens in the present study are classified into VS2/VF2 group. A good relationship is estimated by Equations (1) and (2) between the V-funnel flow time (V_f) and the T50 slump flow time (T50) for concrete containing GF without FSCG and concrete containing GF and FSCG.

$$V_f = 2.4878T_{50} + 0.6644 \text{(Without fiber-silica gel)} \quad (1)$$

$$V_f = 2.5111T_{50} + 0.3647 \text{(With fiber-silica gel)} \quad (2)$$

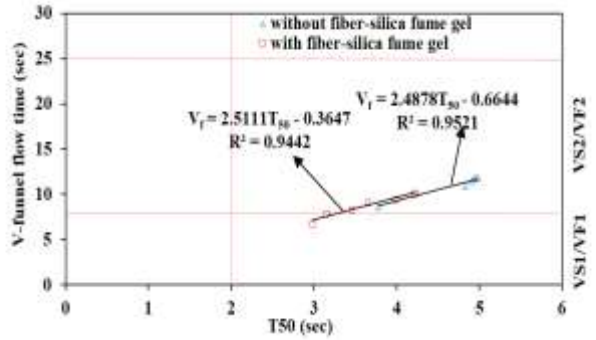


Figure 10. Variation of T50 versus V-funnel time for SCC with and without FSCG

4. 2. Hardened Concrete Results The effect of GF and FSCG at 28-day compressive strength is also presented in Figure 11 and Table 10. GF's use has no significant impact on increasing compressive strength. GFs in concrete increased the porosity and entrapped air in concrete, thereby reducing the compressive strength [46]. Changes in compressive strength of GFRC specimens are presented in Figure 12 by Swami et al. [47], Ghorpade [48] and, Hilles and Ziara [49]. The rate of change in compressive strength of specimens containing GFs is within the range of similar studies.

The compressive strength of specimens containing 7% of FSCG with 0, 0.25, 0.5, 0.75, 1, 1.25% GF increased by 13, 19, 17, 20, 24 and 20 %, respectively. FSCG increases compressive strength due to prevent cracks, reduction of cracks growth, the contact surface, and further fiber-mortar interaction. The compressive strength of specimens containing GF and FSCG is higher than specimens containing GF. Increasing GF percentage

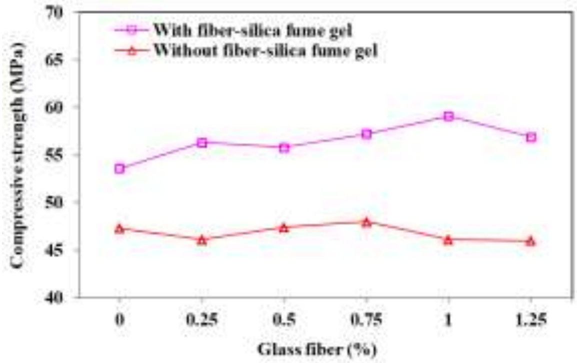
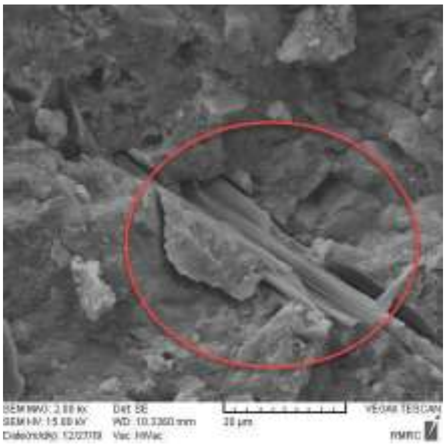


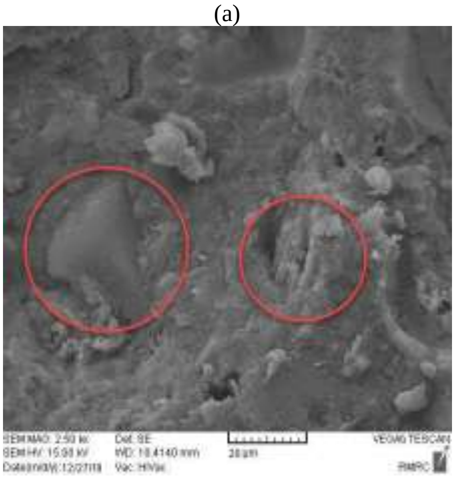
Figure 11. Compressive strength of the concrete specimens

TABLE 10. The hardened concrete results

Mix code	Compressive strength (MPa)	Splitting strength (Mpa)
S-0-0	47.3	3.11
S-0.25-0	46.1	3.26
S-0.50-0	47.4	3.39
S-0.75-0	48	3.46
S-1.00-0	46.1	3.49
S-1.25-0	46	3.53
S-0-7	53.6	3.43
S-0.25-7	56.3	3.95
S-0.50-7	55.8	4.02
S-0.75-7	57.2	4.13
S-1.00-7	59.1	4.17
S-1.25-7	56.9	4.21



(a)



(b)

Figure 12. SEM images (a) 1% GF (b) 1% GF and 7% FSCG

in concrete increases the percentage of entrapped air in concrete. The higher the percentage of entrapped air is, the higher the porosity of the concrete will be, and consequently, the strength of concrete decreases. The SEM images shown in Figure 12 exhibit that the use of FSCG, which replaces a part of the cement, can greatly improve the strength reduction caused by GF entry into the concrete matrix. Due to their high affinity, these materials improve the cohesion between cement paste and GF. On the other hand, their fine particles and high filling ability caused them to penetrate through the pores created by an increase in the percentage of entrapped air in concrete and cover them.

Adding 0.25, 0.5, 0.75 1, and 1.25% GF to the specimens without FSCG increased the splitting tensile strength by 4.8, 9, 11.3, 12.2, and 13.5%, respectively (Figure 13). Due to their high tensile resistance, the fibers prevent crack propogation by holding the cement matrix or forming a bridge between cracks. As a result, cracks do not grow in length, thickness (width). However, fibers will increase the volume of voids in concrete by forming defects at the microscale in the cement matrix.

The splitting tensile strength of the specimens containing 7% FSCG with 0.25, 0.5, 0.75, 1, and 1.25 % GF was increased by 43.1, 51.8, 58.5, 64%, and 68.8%, respectively. The use of FSCG compensates for the disadvantages of using only GF, thereby increasing the growth of concrete to a great extent and causing more tensile strength against deformation. The lack of proper cohesion and interaction between fibers and coarse aggregate reduces the tensile strength of concrete containing GF over concrete containing GF and FSCG; so the interaction between fibers and coarse aggregate can be considered a hairline crack, which accelerates concrete failure.

Lack of cohesion between cement paste, fibers, and coarse aggregates compared to cohesion between cement pastes, fibers, and fine aggregate causes this matrix not to work consistently against tensile load [50]. specimens containing FSCG increase the cohesion between fibers and coarse aggregates and increase bonding. Thus, the tensile strength of the concrete has more growth. The use of GF depending on the concrete grade in all the studies presented in Figure 14 resulted in increasing tensile strength of the concrete. As in the study of Ghorpad [48] and Swami et al. [47], the tensile strength of concrete containing 1% GF increased by 22% and 41%, respectively, compared to the control sample.

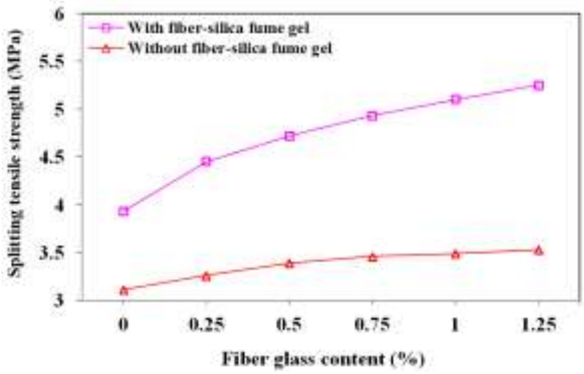


Figure 13. Splitting tensile strength

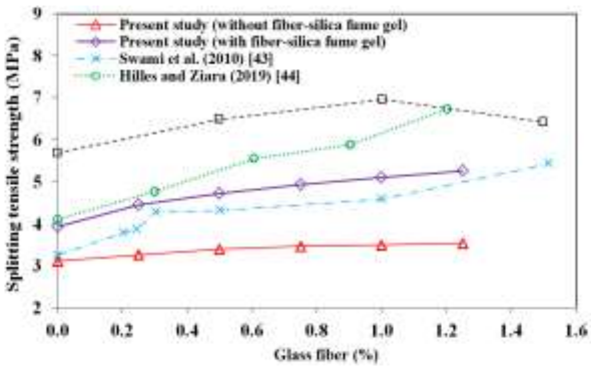


Figure 14. Comparison of 28-days tensile strength results with similar studies

Evaluating and determining the relationship predict concrete tensile strength based on its compressive strength has always been of interest to the concrete and construction industry researchers. The changes of cylindrical compressive strength versus tensile strength are shown in Figure 15. Based on this, Equations (3) and (4) for SCC containing GF and FSCG can be presented. Figure 16 shows the proposed relationship of CEB-FIP for high, low, and average tensile strength variations based on cylindrical compressive strength. As it can be seen, the results obtained in this study are within the range recommended by CEB-FIP.

However, the CEB-FIP [51] average range relationship to investigate changes in cylindrical compressive strength versus tensile strength provides a higher estimate of tensile strength at a given compressive strength.

$$f_t = 0.0015 f_c^{2.0675} \quad (3)$$

$$f_t = 25.844 f_c^{-0.562} \quad (4)$$

4. 3. Four-point Loading Results Figure 16 shows load-mid span deflection curves of retrofitted beams with RC jackets and GFRP plates. Parameters extracted from the load-displacement curve are presented in Table 11. These curves have three separate linear parts. The first part consists of the un-cracked section and the linear elastic behavior.

Load and deflection corresponding to the first crack for the control beams were 19 kN and 2.1 mm, respectively. However, jackets containing GF and FSCG increased the crack load and decreased the crack deflection. The second part of curve is the interval between the first concrete crack and yield point.

The yield deflection and yield load of the control beam were 53 kN and 13.1 mm, respectively. However,

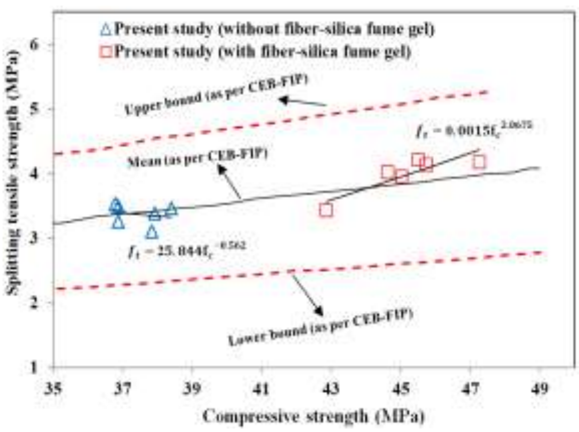


Figure 15. Comparison of the results of the relationship between compressive strength and tensile strength of SCC specimens at 28 days with the limits specified by CEB-FIP [51]

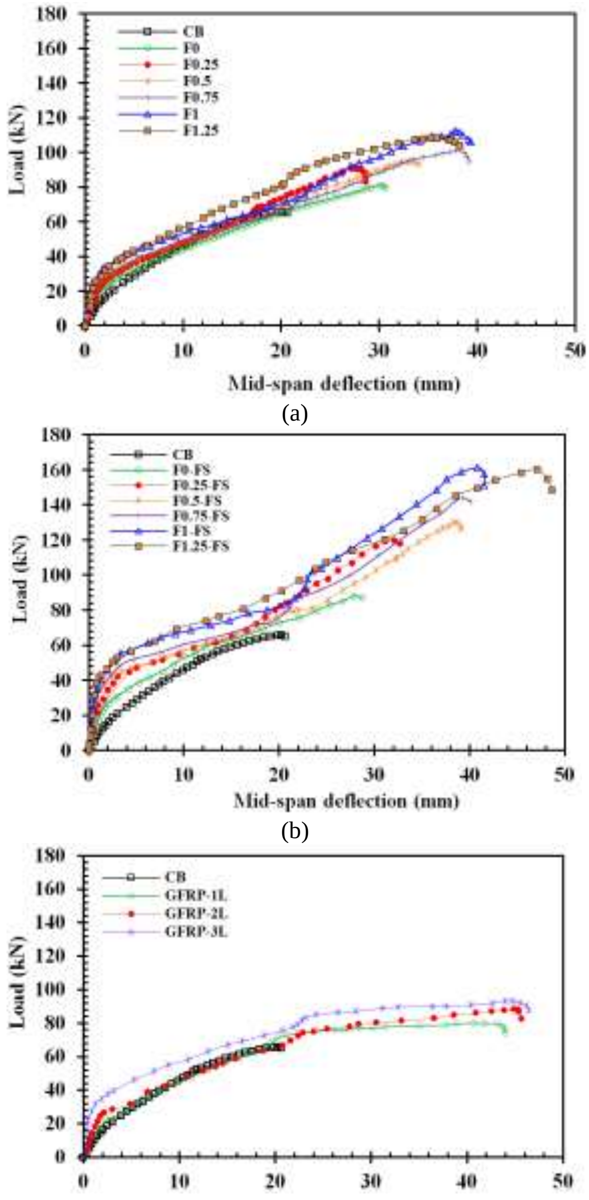


Figure 16. Load-deflection curves a: Strengthening of the beam with concrete jackets containing GF b: Strengthening of the beam with concrete jackets containing GF and FSCG c: Strengthening of the beam with GERP plates

concrete jackets containing 1.25% GF and 7% FSCG increased the yield load by approximately 102%. The third part of the load-deflection curve is the interval between yield point and ultimate failure. In this part, the deflection of beams decreased rapidly due to the decrease in stiffness. The performance of the proposed concrete jackets caused cracks to grow at a slower speed and significantly increased the bearing capacity of beams compared to the control specimen. The three different phases mentioned in the load-deflection diagrams are illustrated in the hypothetical diagram in Figure 17.

TABLE 11. Parameters extracted from the load-displacement curve

Beam	Crack Load (kN)	Yield Load (kN)	Ultimate Load (kN)	Crack deflection (mm)	Yield deflection (mm)	Ultimate Deflection (mm)	Deflection Ductility	Stiffness (kN/mm)	Energy absorbtion (J)
CB	19.0	53.0	64.0	2.10	13.10	20.0	1.53	7.5	896
F0	25.0	69.0	81.0	2.25	20.10	34.0	1.69	10.6	1636
F-0.25	28.0	63.0	91.0	2.61	16.00	28.6	1.79	10.2	1656
F-0.5	28.0	68.0	91.0	2.24	19.00	34.0	1.79	10.7	2106
F-0.75	29.0	69.0	101.0	2.37	21.00	39.0	1.86	10.8	2582
F-1	34.0	75.0	112.0	2.41	22.00	39.0	1.77	12.3	2859
F-1.25	34.0	82.0	108.0	2.51	20.00	38.0	1.90	12.0	2922
F-0-FS	29.0	61.0	88.0	2.52	13.00	28.7	2.21	10.8	1689
F-0.25-FS	40.0	71.0	117.0	2.58	17.00	33.0	1.94	13.9	2370
F-0.5-FS	42.0	78.0	128.0	2.45	20.40	39.0	1.91	14.8	2677
F-0.75-FS	45.0	85.0	144.0	2.60	21.00	40.0	1.90	16.0	3400
F-1-FS	46.4	101.0	160.0	1.78	23.00	41.6	1.81	16.3	4006
F-1.25-FS	47.0	107.0	157.0	2.00	24.80	48.6	1.96	16.6	5036
GFRP-1L	22.4	72.0	79.0	2.71	21.00	44.0	2.10	8.0	2677
GFRP-2L	21.8	74.0	87.0	1.73	22.90	45.8	2.00	9.5	2948
GFRP-3L	35.5	83.0	93.0	2.27	23.00	46.5	2.02	13.4	3424

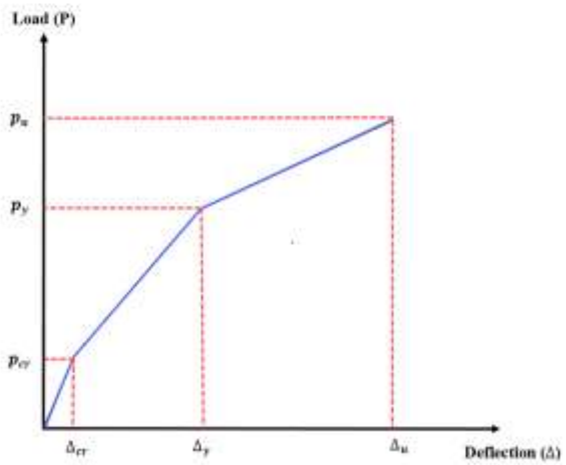


Figure 17. Hypothetical diagram of load-deflection and representation of points of cracking, yield, and ultimate failure

4. 3. 1. Crack Load

Crack propagation of the beams is shown in Figure 18. As can be seen, the use of FSCG in concrete jackets increases the adhesion between the fibers and the aggregates and increases the cohesion between them .In fact, the connection between the fibers and the coarse part can be considered as a hair crack that accelerates the failure of concrete. Lack of adhesion between cement paste and fibers and coarse aggregates compared to adhesion between cement paste and fibers and fine aggregates, has caused this matrix not to act continuously and coherently against tensile loads and stresses are evenly distributed in cement paste. This will reduce the tensile strength and create more cracks. However, the use of FSCG in reinforced concrete jackets improved the behavior of the beams and limited the distribution of cracks.

Corresponding points to the crack loads that give rise to the formation of the first cracks in RC sections are those points where maximum tensile strength is reached at the furthest tensile axis of the section. The concrete loses its tensile strength and the section cracks. The load in which cross-section cracking occurs is called “crack load” (P_{cr}).

The amounts and the increasing percentage of cracking load for all beams are shown in Figure 19. These amounts are derived from the diagram in Figure 16 and correspond to the first breakpoint in the load-deflection curves related to specimens. The corresponding crack load with retrofitted beams using jackets containing 0, 0.25, 0.5, 0.75, 1, and 1.25% GFs increased by 32, 47, 47, 53, 79 and 79%, respectively.

Moreover, the corresponding crack load with retrofitted beams using jackets containing 0, 0.25, 0.5, 0.75, 1 and 1.25% GF and 7% FSCG increased by 53, 111, 121.1, 137, 144 and 147%, respectively. The corresponding crack load with retrofitted beams using one, two, and three layers of GFRP plates increased by

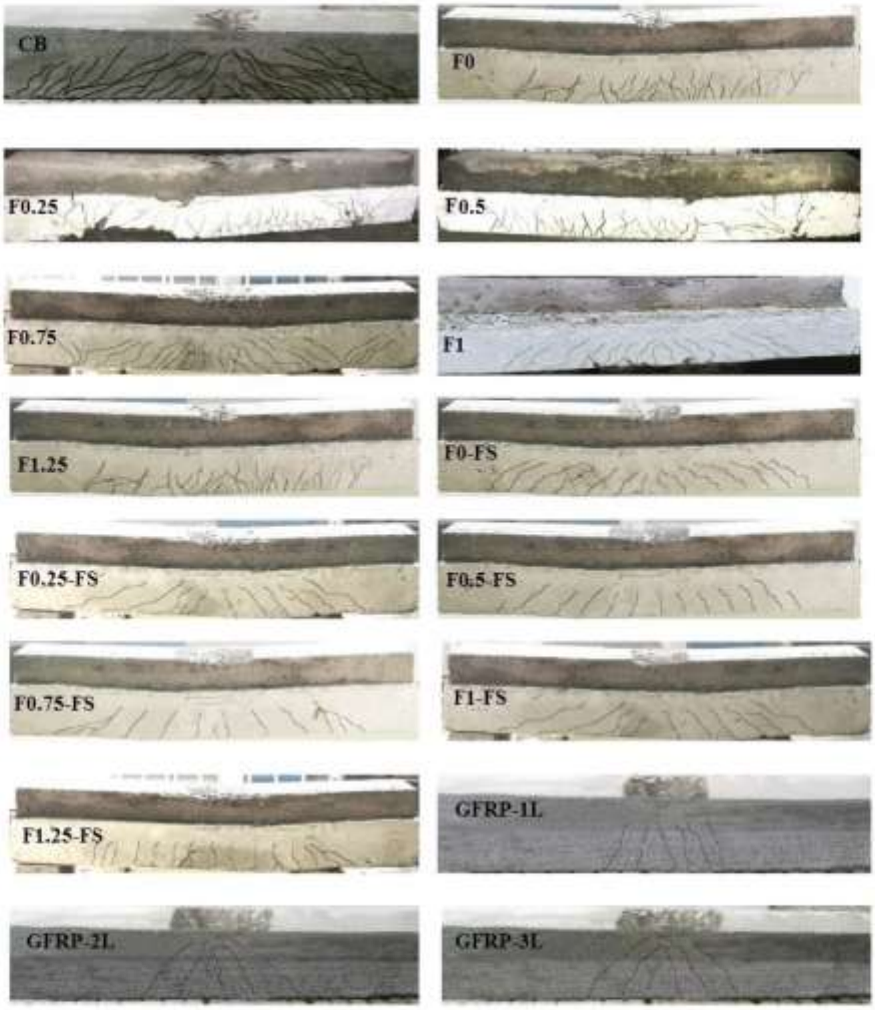


Figure 18. Crack propagation

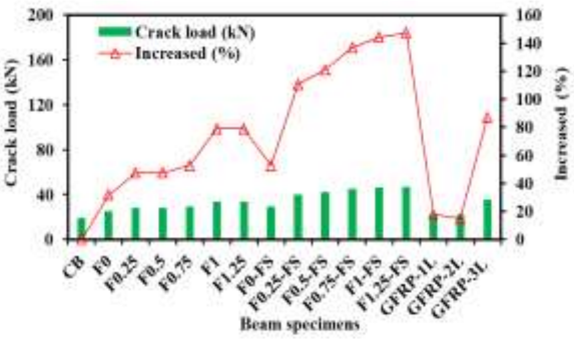


Figure 19. Cracking Load of beams

48, 60, and 71%, respectively. The jackets containing FG and FSCG has more effect on increasing the cracking load of the beams compared to the other two methods, and the first cracking is more delayed. Adding FSCG to the concrete composition, the lime produced in the cement hydration process reacted to silica fume, produced calcium silicate hydrate, and increased concrete strength. In contrast, silica fume particles filled the space between aggregates, prevented them from interlocking, and increased the concrete workability.

4. 3. 2. Yield Load Figure 20 presents the amounts of yield load and the increasing percentage of yield load of the beams. In all cases, the proposed jackets increased yield load; the corresponding yield load of retrofitted beams with jackets containing 0, 0.25, 0.5, 0.75, 1, and 1.25 % of GF increased by 30, 19, 28, 30, 42 and 55 %, respectively. Also, the corresponding yield load to retrofitted beams with jackets containing 0, 0.25, 0.5, 0.75, 1 and 1.25% GF and 7% of FSCG increased by 15, 34, 47, 60, 91 and 102%, respectively. The corresponding yield load to retrofitted beams using one, two, and three layers of GFRP sheets increased by 17, 14, and 86%, respectively. The combination of fiber and silica fume

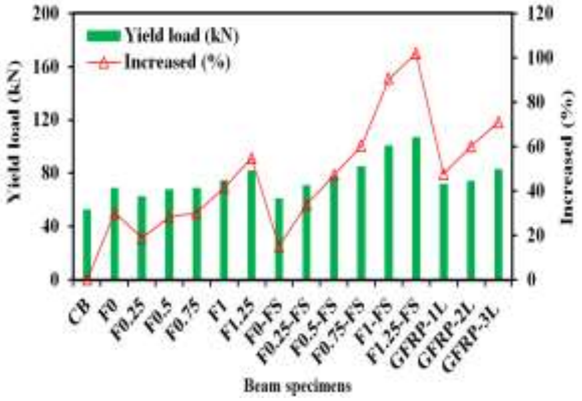


Figure 20. Comparison of the yield load of beams

made the rebars yield later and increased the yield strength of the beams. By creating more consistency, the superplasticizer used in FSCG caused the fine particles of silica fume powder to move into the concrete and move into the voids between the larger aggregates, which filled the void between them increased the concrete strength.

4. 3. 3. Ultimate Bearing Capacity (Ultimate Load) Figure 21 shows the amounts of maximum bearing capacity. Concrete jackets containing GF increased the maximum load from 27% to 75%, depending on GF amount. Also, concrete jackets containing GF and FSCG enhanced the the maximum load from 82% to 150%, depending on the consumed amount of GF. On the other hand, using GFRP sheets also increased the final bearing capacity by 47 to 71 %, depending on the number of used layers. The reason for improving bearing capacity in reinforced specimens with GF and FSCG compared to specimens without fiber is that GF does not allow for further separation of the concrete by increasing the tensile strength and inhibition in crack generation and by creating a bridge between the two sides of the crack. FSCG improves the ultimate load by enhancing the tensile strength. In both types of the studied jackets, increasing GF amount affects increasing flexural capacity, so the highest increase in bending capacity of beams was achieved using 1% of GF (Figure 22).

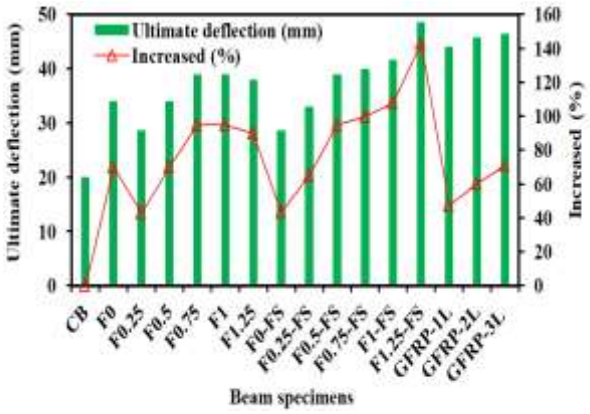


Figure 21. Comparison of ultimate bearing capacity

4. 3. 4. Deflection Ductility To calculate the deflection ductility, the ultimate deflection (Δ_u) and yield deflection (Δ_y) values need to be available [52-55]. These parameters are obtained from the load-displacement curve. Deflection ductility is calculated by Equation (5).

$$\mu = \frac{\Delta_u}{\Delta_y} \tag{5}$$

Concrete jackets containing GF and FSCG shows greater bending stiffness, greater flexural capacity compared to jackets containing GF and GFRP. They also have a much better performance in ductility. The ductility of strengthened beam with jackats comprising of GF, jackats comprising of FSCG, and GFRP increased by about 11 to 17%, 18 to 28% and 31 to 36%, respectively. The strengthened beams with RC jackets comprising of GF and FSCG have more strength. The GFRP debonded

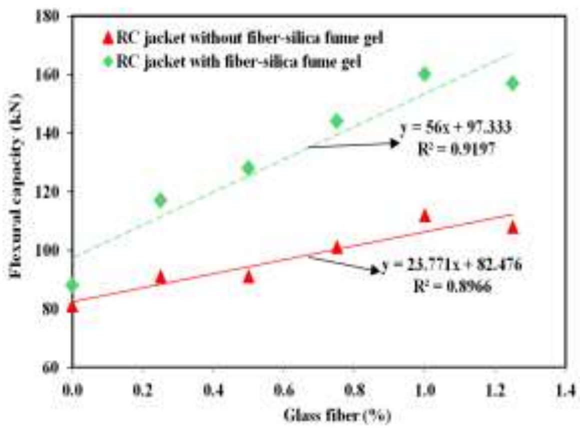


Figure 22. The effect of GFs on bending capacity of RC beams retrofitted with concrete jackets

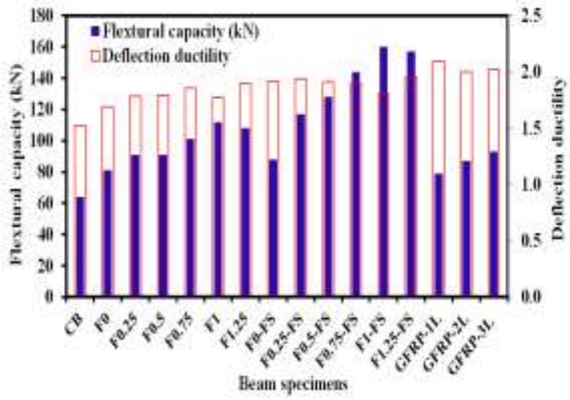


Figure 23. Comparison of flexural strength and deflection ductility of the beams

from the beams surfaces and this leaded to bear less forces. The RC jacket can have better performance in seismic zones in compared to the GFRP method.

4. 3. 6. Energy Absorption Capacity (Flexural Toughness) Energy absorption capacity is one of the parameters to be analyzed for the loading performance of RC members (Figure 24). RC jackets containing GF and FSCG increased the beams' energy absorption capacity by about 89 to 463%, depending on the percentages of GFs. RC jacket containing GF and FSCG delays the growth of the primary crack and it can significantly increase the maximum load. Also, GFRP sheets have poorer performance compared to the proposed method due to separation from the surface of the strengthened beams, and their load-bearing capacity and energy absorption are lower. Also, the energy absorption capacity of retrofitted beams with RC jackets containing GFs increased from 83 to 226%, depending on GFs contents. On the other hand, the energy absorption capacity of retrofitted beams with GFRP plates increased from 47 to 71%, depending on the number of layers.

Considering each of the parameters of bearing capacity, ductility, stiffness, energy absorption capacity and deformation, the use of 7% FSCG and 1.25% GF in the proposed self-compacting reinforced concrete jacket had a better performance compared to the other percentages.

4. 3. 7. Comparison of the Proposed Strengthening Method with Similar Studies Figure 25 compares the proposed strengthening method with similar studies. The ultimate load (flexural capacity) of the retrofitted beams with concrete jackets to the flexural capacity of control beams and the $(A_c f_c A_s f_y)_{jacketed}/(A_c f_c A_s f_y)_{original}$ are shown in Figure 25. In $(A_c f_c A_s f_y)_{jacketed}$, A_c is the RC cross-sectional area, f_c is the original beam compressive strength and the concrete compressive strength of the jacket, A_s is the area of the longitudinal bars used in the jacket, and the main beam and the f_y is the yield stress of the longitudinal bars of the cross-section. Also, in $(A_c f_c A_s f_y)_{original}$, Ac is the area of the original beam, f_c is the concrete compressive strength of the control beam, A_s is the area of the longitudinal bars in the main beam, and f_y is the yield stress of the longitudinal bars. The points from other related experimental studies presented in Figure 25 are a set of points obtained from the strengthening of several beams and columns using concrete jackets. As it can be seen, the strengthening method had a good load carrying capacity, and using GF and FSCG increased the bending capacity of the beams considerably.

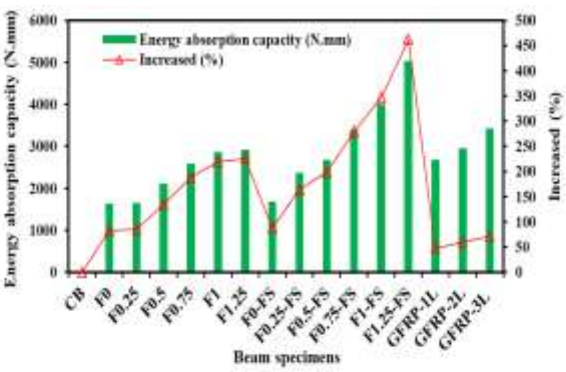


Figure 24. Comparison of energy absorption capacity of the examined beams

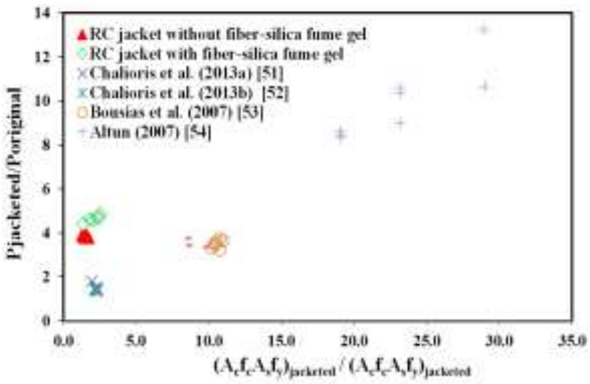


Figure 25. Comparison of the proposed strengthening method with similar studies

5. CONCLUSIONS

The performance of SCC jackets reinforced with GF and FSCG in strengthening of RC beams was investigated. The attributes of fresh concrete were investigated, and then the mechanical attributes were investigated. The microstructure of the concrete samples specimens GF and the concrete specimens containing GF and FSCG were compared using SEM images. The behavior of the beams retrofitted with the proposed concrete jackets was evaluated. A summary of the results of the experiments is provided in this section.

The combined use of GF and FSCG has a significant role in increasing the compressive strength of concrete. So, the compressive strength of specimens containing 7% of FSCG with 0, 0.25, 0.5, 0.75, 1, 1.25% GF increased by 13-24 depending on the percentages of GFs. FSCG increases compressive strength due to prevent cracks, reduction of cracks growth, the contact surface, and further fiber-mortar interaction. The compressive strength of specimens containing GF and FSCG is higher than specimens containing GF. Increasing GF percentage in concrete increases the percentage of entrap.

- ped air in concrete. The higher the percentage of entrapped air is, the higher the porosity of the concrete will be, and consequently, the strength of concrete decreases.

- The SEM images showed that the use of FSCG, which replaces a part of the cement, can significantly improve the strength reduction caused by GF entry into the concrete matrix. Due to their high affinity, these materials improve the cohesion between cement paste and GF, and, on the other hand, their fine particles and high filling ability caused them to penetrate through the pores created by an increase in the percentage of entrapped air in concrete and cover them. This increases the strength and improves the mechanical properties of concrete containing GF.
- The splitting tensile strength of the specimens containing 7% FSCG with 0.25, 0.5, 0.75, 1 and 1.25 % GF were increased by 43.1, 51.8, 58.5, 64% and 68.8%, respectively, compared to the control specimen. The lack of proper cohesion and interaction between fibers and coarse aggregate reduces the tensile strength of concrete containing GF over concrete containing GF and FSCG; so the interaction between fibers and coarse aggregate can be considered as a hairline crack, which accelerates concrete failure. Lack of cohesion between cement paste, fibers, and coarse aggregates compared to cohesion between cement pastes, fibers, and fine aggregate causes this matrix not to work consistently against tensile load.
- GFs in the proposed RC jackets increased the crack, yield, and ultimate loads by 79, 55, and 75%. The combined use of GFs and FSCG increased the crack, yield, and maximum loads by 147, 102, and 150%, respectively. On the other hand, the use of GFRP sheets increased by 71%, 86%, and 71%, respectively, depending on the number of layers.
- Using RC jackets containing FG and FSCG has more effect on increasing the cracking load of the beams compared to the other two methods, and the first cracking is more delayed. Adding FSCG to the concrete composition, the lime produced in the cement hydration process reacted to silica fume, produced calcium silicate hydrate, and increased concrete strength. In contrast, silica fume particles filled the space between aggregates, prevented them from interlocking, and increased the concrete workability.
- The combined use of GF and FSCG has a more influential role in increasing the yield load of rebars. In other words, using the combination of fiber and silica fume made the rebars yield later and increased the yield strength of the beams. By creating more consistency, the superplasticizer used in FSCG caused the fine particles of silica fume powder to move into the concrete and move into the voids between the larger aggregates. This filled the void between them and thus increased the concrete strength.
- In both types of the studied jackets, increasing GF amount affects increasing flexural capacity, so the highest increase in bending capacity of beams was achieved using 1% of GF.
- The use of RC jackets containing GF and FSCG shows greater bending stiffness, greater flexural capacity compared to jackets containing GF and GFRP sheets.
- RC jackets containing GF and FSCG increased the beams' energy absorption capacity by about 89 to 463%, depending on the percentages of GFs. RC jacket containing GF and FSCG delays the growth of the primary crack and it can significantly increase the maximum load. Also, GFRP sheets have poorer performance compared to the proposed method due to separation from the surface of the strengthened beams, and their load-bearing capacity and energy absorption are lower.

The combined use of FSCG and GF in reinforced concrete jackets can be effective in improving the flexural behavior of concrete beams. Examination of the use of this method in other members of reinforced concrete structures (slabs, columns and foundations) can be evaluated in future studies

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Persian Abstract

چکیده

در مطالعه حاضر به بررسی آزمایشگاهی مقاوم‌سازی تیرهای بتن مسلح با استفاده از ژاکت بتنی خود متراکم حاوی الیاف شیشه و ژل میکروسیلیس الیاف دار (FSCG) و مقایسه آن با ورق‌های پلیمری مسلح شده با الیاف شیشه (GFRP) پرداخته شده است. ژل میکروسیلیس الیافدار، به عنوان جایگزین بخشی از سیمان است که دارای پودر میکروسیلیس، الیاف پلی‌پروپیلن، فوق روانساز، انواع آب‌بند بتن، و برخی افزودنی‌های دیگر می‌باشد. بدین ترتیب استفاده از ژاکت بتنی اشاره شده ضمن افزایش سطح مقطع و ممان اینرسی تیر، با توجه به مقاومت کششی نسبتاً بالای بتن‌های مسلح به الیاف، می‌تواند منجر به بهبود مقاومت خمشی تیر شود. مطالعات آزمایشگاهی در سه بخش بررسی خواص بتن تازه، بررسی خواص بتن سخت شده و بررسی ظرفیت خمشی تیرها انجام شد. مقدار الیاف شیشه مورد استفاده در ژاکت بتنی به ترتیب برابر ۰، ۰.۲۵، ۰.۵، ۰.۷۵، ۱ و ۱.۲۵ درصد حجمی بتن، مقدار FSCG در ژاکت بتنی به ترتیب برابر ۰ و ۷.۵ درصد وزنی سیمان و تعداد لایه‌های ورق‌های GFRP (۱، ۲ و ۳ لایه) در نظر گرفته شد. نتایج حاصل نشان داد استفاده از FSCG در ژاکت‌های بتنی، ضعف مقاومتی را که به علت ورود الیاف شیشه به ماتریس بتن ایجاد شده است را می تواند به خوبی جبران کند. این مصالح به علت میل ترکیبی بالایی که دارند، باعث بهبود چسبندگی بین خمیر سیمان و الیاف شیشه شده و از طرفی ریز بودن ذرات آنها و قابلیت پرکنندگی زیادی که دارند، باعث می شود تا در خلل و فرجی که به علت افزایش درصد هوای محبوس در بتن ایجاد شده، نفوذ کرده و آنها را بپوشاند که این امر باعث افزایش مقاومت و بهبود دیگر خصوصیات مکانیکی بتن حاوی الیاف شیشه می شود. از سوی دیگر افزودن ژاکت‌های بتنی حاوی الیاف شیشه و FSCG بسته به مقدار الیاف شیشه ظرفیت جذب انرژی تیرها در حدود ۸۹ تا ۴۶۳ درصد افزایش یافته است. دلیل این موضوع آن است که ژاکت بتنی حاوی الیاف شیشه و ژل میکروسیلیس الیاف‌دار، تشکیل اولین ترک در بتن و تسلیم میلگردهای فولادی را به تاخیر می اندازد و سبب می‌شود که ظرفیت جذب انرژی به طور قابل توجهی افزایش یابد. همچنین ورق‌های GFRP به دلیل جداشدن از سطح تیر ظرفیت جذب انرژی کمتری در مقایسه با سایر روش‌های مورد بررسی دارند.