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Fibrous Geopolymer Adhesive Jackets for Confining of Reinforced Concrete Columns

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ABSTRACT

The strengthening and rehabilitation of reinforced concrete structures is an important issue all over the world. Fiber-reinforced composites (FRC) are mainly used for the strength and rehabilitation of concrete members. However, its use is limited due to its high price and environmental effects and its adoption of epoxy as an adhesive, where epoxy is considered inefficient at high temperatures and loses most of its properties. The solution to this problem leads to the use of low-cost locally available geopolymer adhesive paste, with the possibility of adding fibers to improve the mechanical properties. This paper presents the experimental results of the circular RC columns confined by carbon fiber reinforced geopolymer adhesive (CFRGA) with fibers at geopolymer adhesive (GPA). Variables included; Geopolymer adhesive with or without fibers and type of fiber added to GPA (micro steel fibers, carbon fibers, and polypropylene fibers) with the volumetric ratio of (2%, 0.4%, 0.2%), respectively. The results where it was found that confinement by carbon fiber reinforced fibrous geopolymer adhesive improved the columns compressive strength estimated by (215%) and the axial strain improved by (268%). When adding (micro steel fibers, carbon fibers, and polypropylene fibers) to the adhesive led to an improvement in the strength of about (16.1%, 8.4%, and 7.96%) respectively, compared with the confined RC column without fibers at (GPA). Finally, confinements by carbon fiber reinforced geopolymer adhesive are more suitable for use in strengthening and rehabilitation of RC columns in areas with a hot climate.

1. Introduction

Structures in the world need to rehabilitate and strengthen the cause of their deterioration resulting from actual use, aging, and exposure to various environmental conditions or modernization in proportion to the requirements of age [1]. An important component that needs rehabilitation is RC columns, being subject to combinations of axial stress and bending moment. It is considered an important member of the performance and safety of structures. However, RC columns are brittle members, affected by bending and high loads due to vastly different factors, such as unbalanced moments when connecting beams, lateral forces from wind, seismic activity, or unexpected overloads, and civil engineering researchers have found many of the techniques for strengthening the RC columns, one of these techniques is the external confining which is represented by confining the RC columns with FRP techniques [2]. It is an effective technique in improving the strength and ductility of columns but the efficiency of these techniques depends on the type of material used for confinement and the bonding material between the granulation material and the concrete member. But this technique has drawbacks, including the use of epoxy as an adhesive between the fibers and the columns,

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where epoxy is a low-efficiency material and loses most of its mechanical properties at high temperatures and is not recommended in areas with hot climates [3-5]. Gamage, et al 2005 [6]. studied the behavior of the bond at high temperatures between CFRP sheets and concrete. The main result of these tests was the failure load at different temperatures for the epoxy adhesive. The results showed that the increment of epoxy temperature led to a decrease in the bond strength. At (50° C), the mode of failure was an adhesive failure and concrete rupture, at a temperature higher than (60° C), the failure was shown at the CFRP sheet, mat (60 to 70) °C, quick strength loss was noted because of the adhesive losing its mechanical properties. So, the researchers suggested replacing epoxy with an environmentally friendly and highly efficient material, as was reported by Hadi et al, 2020 [7], The geopolymer adhesive based on slag is considered an effective and highly efficient material at high temperatures and is environmentally friendly. It is the ideal alternative to epoxy. It can be used in construction sites where it is treated at room temperature. Geopolymer paste is an effective adhesive with high compressive strength, but low tensile strength. Sachet et al, 2020 [8,9], suggested the use of different types of fibers to improve the mechanical properties of the geopolymer paste and its processing in ambient conditions. The micro steel fibers (SF), carbon fibers (CF), and polypropylene fibers (PPF) were used with the volume of the fraction of (1%, 2%, and 3%) of micro steel fibers, and (0.2%, 0.4, and 0.6%) of both carbon fibers and polypropylene fibers, for which the best proportions were determined for (micro steel fibers, carbon fibers, and polypropylene fibers) were (2%, 0.2%, 0.4%) respectively. No research has been published on the development of the performance of RC columns using existing confinement technology, carbon fiber jacket, and geopolymer based on slag reinforced with different types of fibers, and their treatment in ambient conditions. Accordingly, this study aims to verify the effect of added fibers to the geopolymer adhesive on the performance of RC columns under axial compression load. Test variables are types of fibers included; micro steel fiber (SF) with volumetric ratio (2%), carbon fiber (CF) with volumetric ratio (0.2%), and polypropylene fiber (PPF) with volumetric ratio (0.4%).

2. The experimental scheme

2.1 Materials

2.1.1. Concrete

Concrete with a compressive strength of 30 MPa was used for all RC columns, where all RC columns were poured at once and vertically. With pouring nine cylinders with dimensions of 300mm height and 150mm diameter, to check the concrete strength at (7 and 28) days, respectively. After opening the molds, the columns were treated for 28 days with water until strengthening.

2.1.2. Geopolymer adhesive

The geopolymer adhesive (GPA) was used as the adhesive in confined the RC columns. Where GPA is efficient, sustainable, environmentally friendly, and most importantly, it operates at high temperatures. The geopolymer adhesive is prepared from slag as a binder and alkali solution. To prepare the alkaline solution has Dissolved the flakes with pure water at a concentration of 10 molars, to prepare the sodium hydroxide (NaOH) solution, then mixed with sodium silicate (Na2SiO3) solution in an (SH/SS) ratio of 1:2, respectively, prior 24 hours from casting. A fluid to binder ratio (F/B) of 0.55 was utilized. Table (1) shows the mixed design.

Table 1: Geopolymer adhesive GPA Mix

Binder slag (mg)	**F/B**	**Na_2SiO_3 (mg)**	**NaOH (mg)**
2100	0.55	770	385

2.1.3 Discrete fibers

Three types of discrete fibers have been added to geopolymer adhesive, to develop the bonding properties of the geopolymer adhesive between the carbon fiber fabric layers that was obtained from a commercial supplier in Baghdad. The fibers used are shown in Figure (1). The first type is the micro steel fiber (SF), that commonly used in concrete mixtures because of its ability to improve fatigue resistance, shear, and flexural strength. The second type is carbon fiber (CF), that have been many good properties, including high tensile strength, reduced weight, resistance to chemical attack, and low thermal expansion. While the last type is polypropylene fibers (PPF) have good properties, including low thermal conductivity, good resistance to acid, alkali, corrosion attack, and improves tensile strength. Table (2) shows the properties of the fibers used.

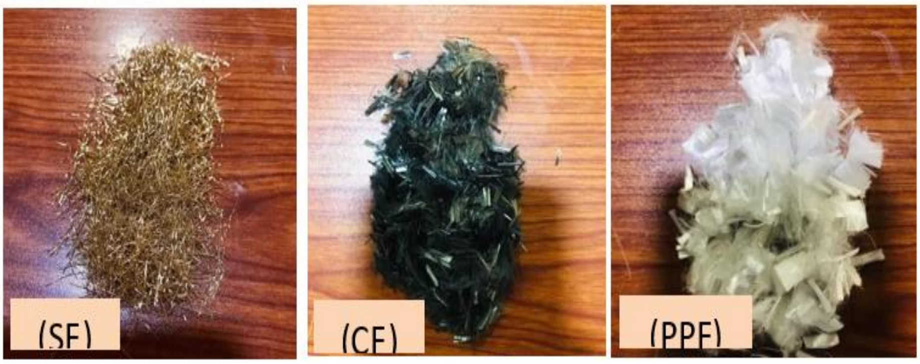


Figure 1. Fibers used in geopolymer adhesive

Table 2: Properties of discrete fibers

Properties	**SF**	**CF**	**PPF**
Length (mm)	6	8	12
Aspect ratio	30	1140	600
Tensile strength (MPa)	2500	3500	300-400
Density (g/m3)	7850	1750	910

2.1.4 Carbon fiber fabric

Carbon fiber materials are equipped in rolls with a width of 300 mm. The properties of Sika Wrap- 300 C carbon fiber sheet are illustrated by the suppliers according to ASTM D3039 standard [10]. The average elastic modulus of carbon fabric was 230GPa according to the nominal thickness of 0.169mm/layer, the tensile strength of 2200MPa, while the average rupture strain was 0.0175. The fibers used are shown in Figure (2).

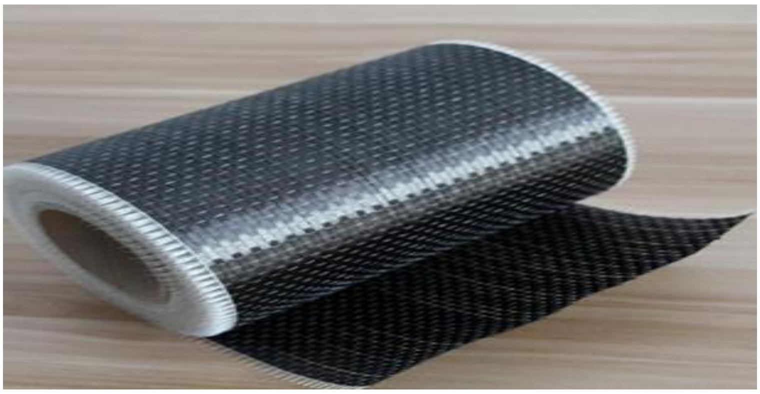


Figure 2. Carbon fiber fabric

2.2 Experimental procedure

An experimental study was consisting of five RC columns. One RC column is unconfined and symbolized it RCC. one RC column is confined by two layers of carbon fiber jacket without fibers at geopolymer adhesive (GPA) and symbolized it C2LCF, three RC columns confined by two layers of carbon fiber jacket with fibers at GPA, used three types of fibers included; micro steel fiber (SF) with volumetric ratio (2%), carbon fiber (CF) with volumetric ratio (0.2%)and polypropylene fiber (PPF) with volumetric ratio (0.4%), These ratios were determined from a previous paper [8], which were designed and fabricated .symbolized by (C2LCF-sf, C2LCF-cf, C2LCF-ppf). Also, Three prismatic forms of geopolymer paste with standard dimensions (40 x 40 x 160) mm were cast with each form to check the compressive and tensile strength of each type of paste. All RC columns have a circular cross-section with dimensions of 600 mm Height and 100 mm diameter and reinforced with six bar Ø (6mm) with 380MPa yield strength used in the main longitudinal reinforcement, and bar Ø (4mm) with 420MPa yield strength in the transverse reinforcement with 100mm spacing between them, as shown in Figure 3. After casting the RC columns and cured them for 28 days, they were confined by fiber-reinforced geopolymer adhesive FRGA and cured at room temperature, and prepared for the test as shown in Figure 4, and Details of RC columns are presented in Table (3).

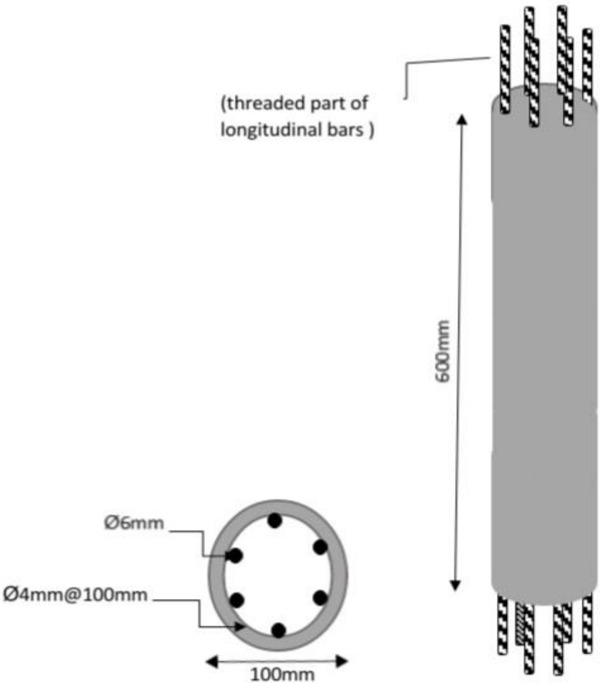


Figure 3. Dimensions of RC columns

Table 3: Details of RC columns

No.	Specimens	Fibers SF %	CF %	PP F%	f_{cu} (MPa) GPA	F_r (MPa) GPA
1	RCC	-	-	-	-	-
2	C2LCF	-	-	-	57	2.1
3	C2LCF-sf	2	-	-	78	6.8
4	C2LCF-cf	-	0.2	-	71	5.3
5	C2LCF-ppf	-	-	0.4	64	4.5

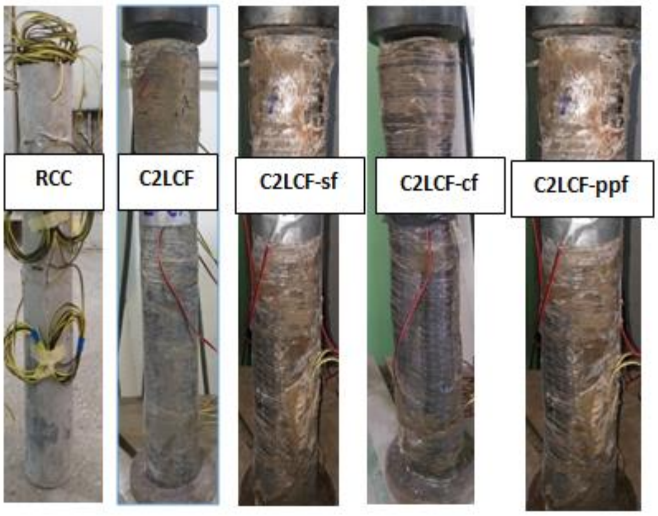


Figure 4. RC columns Prepared to test

3. Results and discussion

3.1 Failure modes of RC columns under axial load

RC columns after testing are shown in Figure 5. The unconfined RC columns showed failure in the upper quadrant of the column. The reason for this may be due to the method of casting, where the casting was performed in a vertical manner corresponding to the reality with the use of vibrators, and as a result of gravity and weight, this led to the collection of coarse aggregates at the bottom of the column and fine aggregates at the top, which made the upper part of RC column the weakest area, the RC columns confined by two layer of CFRG without fiber in GPA showed a rupture at the upper quadrant as the weakest area accompanied with a sudden decrease in the applied load, the RC columns confined by two layer of CFRG with fiber in GPA showed a rupture at the first third of the RC columns. Because the core of concrete expanded under axial load led to stresses transferred to carbon fiber jackets and thus tearing the outer jacket. Sounds of an explosion of specimens were heard accompanied by a sudden drop in the applied load. RC columns confined by two layers of CFRG with fiber in GPA showed exhibited a failure to rupture the carbon fibers jackets in the first third of the specimen’s length, the observed failure mode is typical and applies to the observed failure mode of circular confined RC columns [11-13].

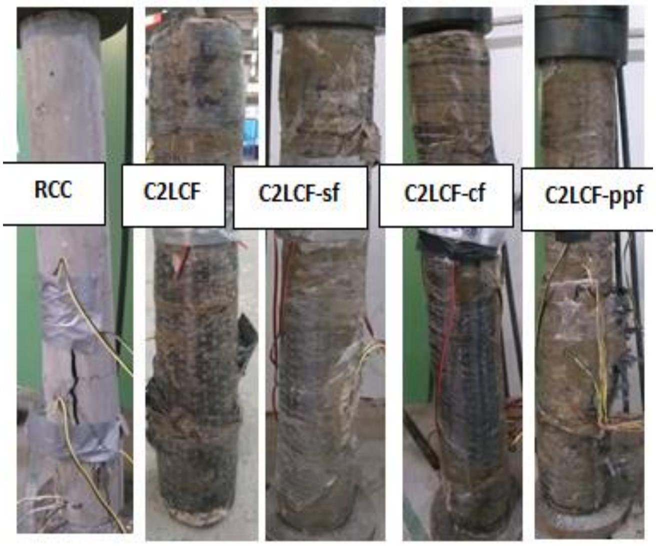


Figure 5. Failure mode of RC columns

3.2 Axial stress-strain response of RC columns

a. Load enhancement and deformation capacity

Table (4) reported ultimate axial load (Pu), ultimate axial strain (εu), load enhancement (Pu/Pu, RCC), and deformation capacity (εu/εu, RCC) of confined RC columns. Figure (6) illustrates the axial load-strain curves of confined RC column; axial strain was measured from the full height "linear variable displacement transformers" (LVDTs) included inside the compression machine.

Table 4: Key test results of RC columns

Specimens	P_u KN	ε_u mm/mm	P_u/P_u, RCC	$\varepsilon_u/\varepsilon_u$, RCC	Failure mode
Rcc	179.6	0.0032	-	-	-
C2LCF	565	0.0118	3.15	3.68	Rupture
C2LCF-sf	656	0.0126	3.65	3.94	Rupture
C2LCF-cf	612.3	0.0119	3.4	3.72	Rupture
C2LCF-ppf	610	0.0139	3.39	4.3	Rupture

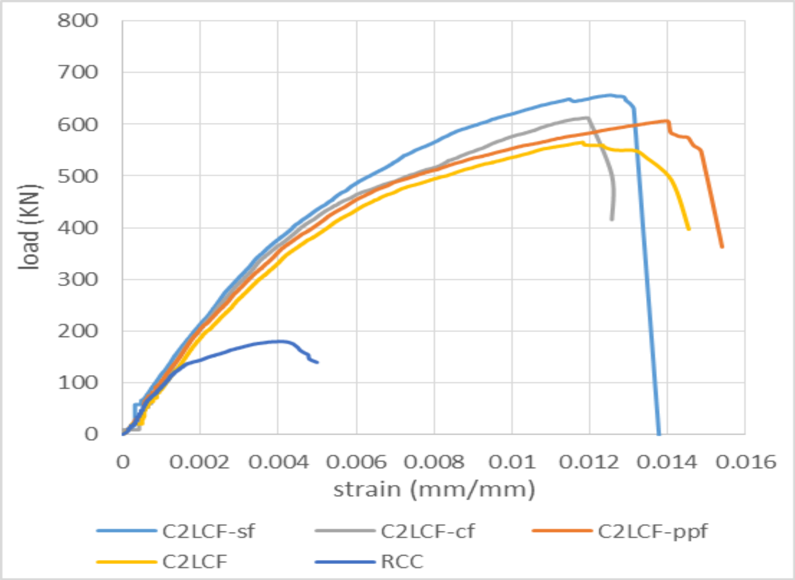


Figure 6. Axial load-strain curves of RC columns

The geopolymer adhesive and the carbon fiber fabric have worked as a matrix to resist the stresses transmitted from core concrete during the test. On the other hand, the addition of fibers to geopolymer adhesive led to the development of bonding strength with the carbon fiber fabric, so providing higher confinement of concrete, hence, increasing resistance to the axial stresses applied. According to experiment results, it is evident that the addition of fibers to geopolymer adhesive led, cause the development of axial load of confined RC columns. Where, the C2LCF-sf, C2LCF-cf, and C2LCF-ppf specimens showing a load enhancement ratio of (3.65, 3.4, and 3.39), and deformation capacity of (3.94, 3.72, and 4.3) respectively. The reason for this return is to increase the interference between the geopolymer adhesive and the carbon fiber fabric layers, in addition to bridge the cracks resulting from the stresses transferred to the carbon jackets, and distributed them regularly through the matrix. the increase in resistance to axial loads for confined specimens with fiber compared to the confined specimen without fibers. as shown in Figure (7).

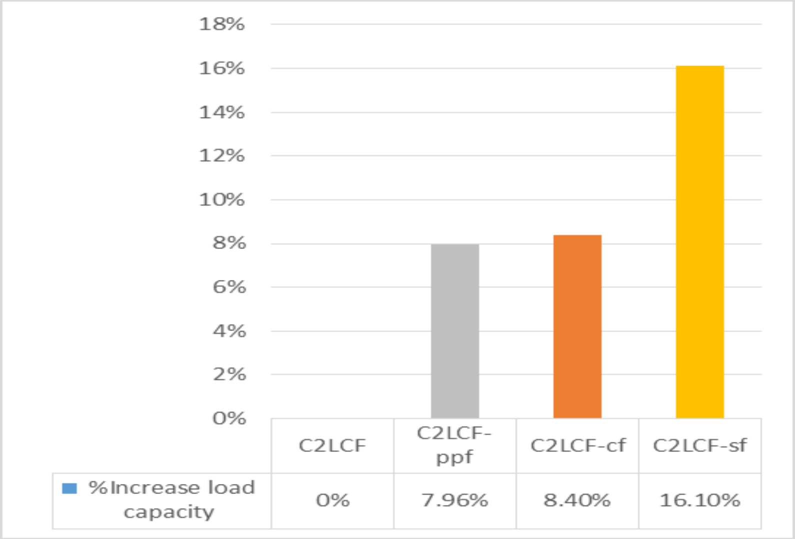


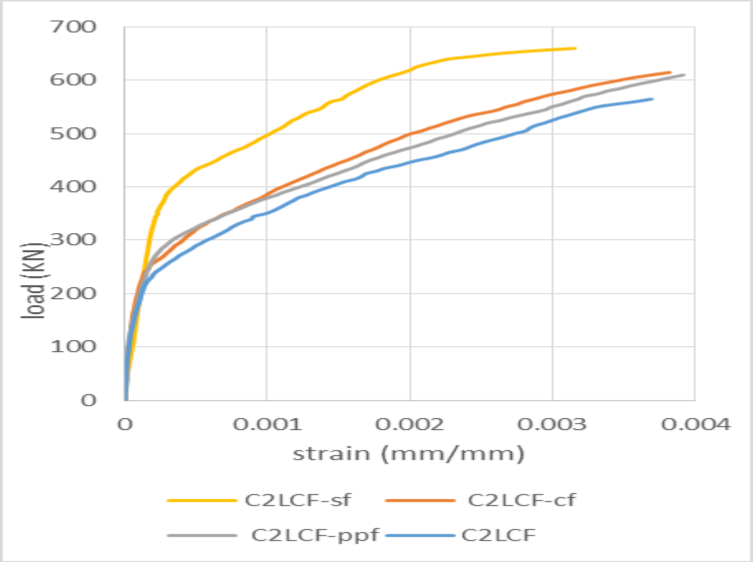
Figure 7. Increase in ultimate loads capacity for fibrous confined RC columns compared to confined RC columns without fibers

b. Jackets strain

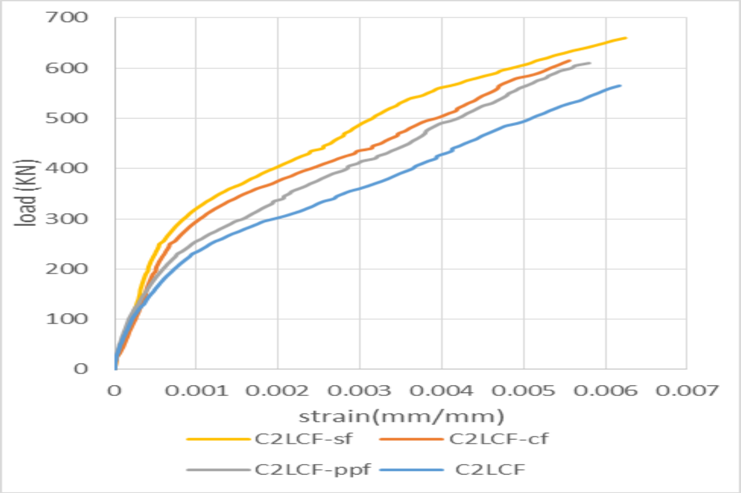
Table (5) reported ultimate longitudinal strain (ε_{lu}), ultimate transverse strain (ε_{tu}), Poisson's ratio(v). Figure (8) illustrates the axial load- longitudinal and transverse Strain in confinement jackets of RC column, strain was measured from the strain gauge installed on the jacket. The focus was on results at 75% of the final load of the unconfined column Because this state of loading (75%) represents the service loading state [14].

Table 5: Key test results of jacket strain of confined RC columns

Specimens	ε_{lu}	ε_{tu}	v	ε_{lu} at 75%	% Decreases in ε_{lu} at 75%	ε_{tu} at 75%	%Decrease in ε_{tu} at 75%
C2LCF	0.0062	0.0037	0.59	0.004	-	0.0017	-
C2LCF-sf	0.00624	0.0031	0.49	0.0023	42%	0.00046	73%
C2LCF-cf	0.0056	0.0038	0.67	0.0028	30%	0.00132	22.3%
C2LCF-ppf	0.0058	0.0039	0.672	0.0032	20%	0.00148	12.5%



(a)



(b)

Figure 8. load- Strain in jackets of confined RC columns (a) Load-longitudinal strain (b) Load-transverse strain

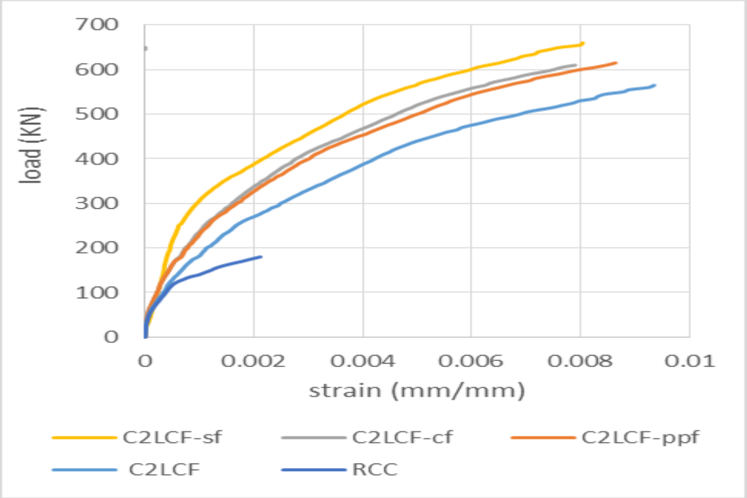
The addition of fibers to the geopolymer adhesive leads to a significant improvement in resistance to lateral stress and longitudinal stress of confinement jackets of confined RC columns. This evolution is evident at 75% of the ultimate load for confined specimens without added fibers, The C2LCF-sf, C2LCF-cf, and C2LCF-ppf specimens give a reduction in longitudinal and transverse strain (42%, 30%, and 20%) and (73%, 22%, and 12.5%), respectively.

c. Concrete strain

Table (6) reported ultimate longitudinal strain (ε_{lcu}) and ultimate transverse strain (ε_{tcu}) in the concrete of RC columns, longitudinal deformation capacity of concrete ($\varepsilon_{lcu}/\varepsilon_{lcu}$, RCC) and transverse deformation capacity of concrete ($\varepsilon_{tcu}/\varepsilon_{tcu}$, RCC), Poisson ratio of concrete (v). Figure (9) illustrates the load- Strain in the concrete of RC columns, strain was measured from the strain gauge installed on concrete.

Table 6: Key test results of the concrete strain of RC columns

Specimens	**ε_{lcu}**	**ε_{tcu}**	**v**	**ε_{lcu} at 75%**	**%Decreases in ε_{lcu} at 75%**	**ε_{tcu} at 75%**	**%Decreases in ε_{tcu} at 75%**
C2LCF	0.009	0.00419	0.45	0.0047	-	0.0017	-
C2LCF-sf	0.008	0.0033	0.41	0.0025	46.8	0.00048	71.5
C2LCF-cf	0.0087	0.00396	0.46	0.0032	32.5	0.00083	51
C2LCF-ppf	0.0079	0.00345	0.44	0.0034	27.6	0.0014	17



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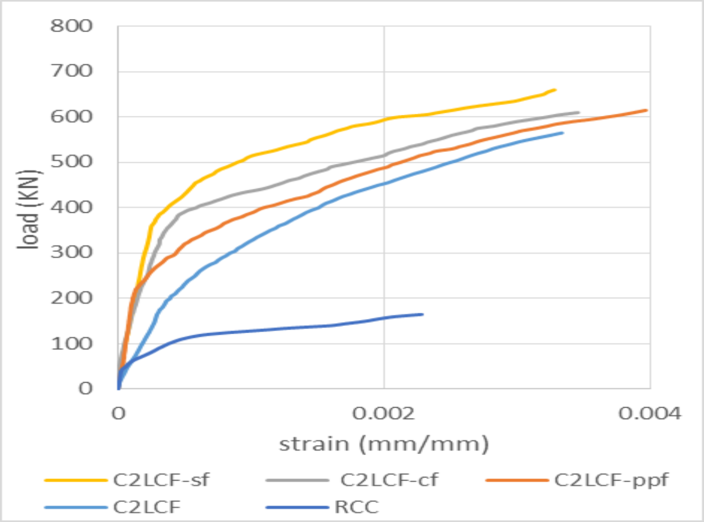


(b)

Figure 9. load- Strain in the concrete of confined RC columns (a) load-longitudinal strain (b) load-transverse strain

It is evident that the addition of fibers to the geopolymer adhesive leads to a significant improvement in resistance to lateral stress and longitudinal stress of confined specimens, this development is reflected positively in reducing the longitudinal and transverse strain of concrete. This evolution is evident at 75% of the ultimate load for confined specimens without added fibers, The C2LCF-SF, C2LCF-CF, and C2LCF-PPF specimens give a reduction in longitudinal and transverse strain (46.8%, 32.5%, and 27.6%) and (71.5%,51%, and 17%), respectively.

d. Steel reinforcement strain

Table (7) reported the ultimate strain of longitudinal steel (ε_{lsu}) and ultimate strain of transverse steel reinforcement (ε_{tsu}) of confined specimens, longitudinal deformation capacity of longitudinal steel reinforcement ($\varepsilon_{lsu}/\varepsilon_{lsu}$, RCC) and transverse deformation capacity of transverse steel reinforcement (ε_{tsu} /ε_{tsu}, RCC) of confined RC columns. Figure (10) illustrates the axial load- Strain at steel reinforcement of RC columns, strain was measured from the strain gauge installed on steel reinforcement. There are some specimens whose readings were not recorded due to a failure of the strain gauge tape during the test.

Table 7: Key test results of steel reinforcement of RC columns

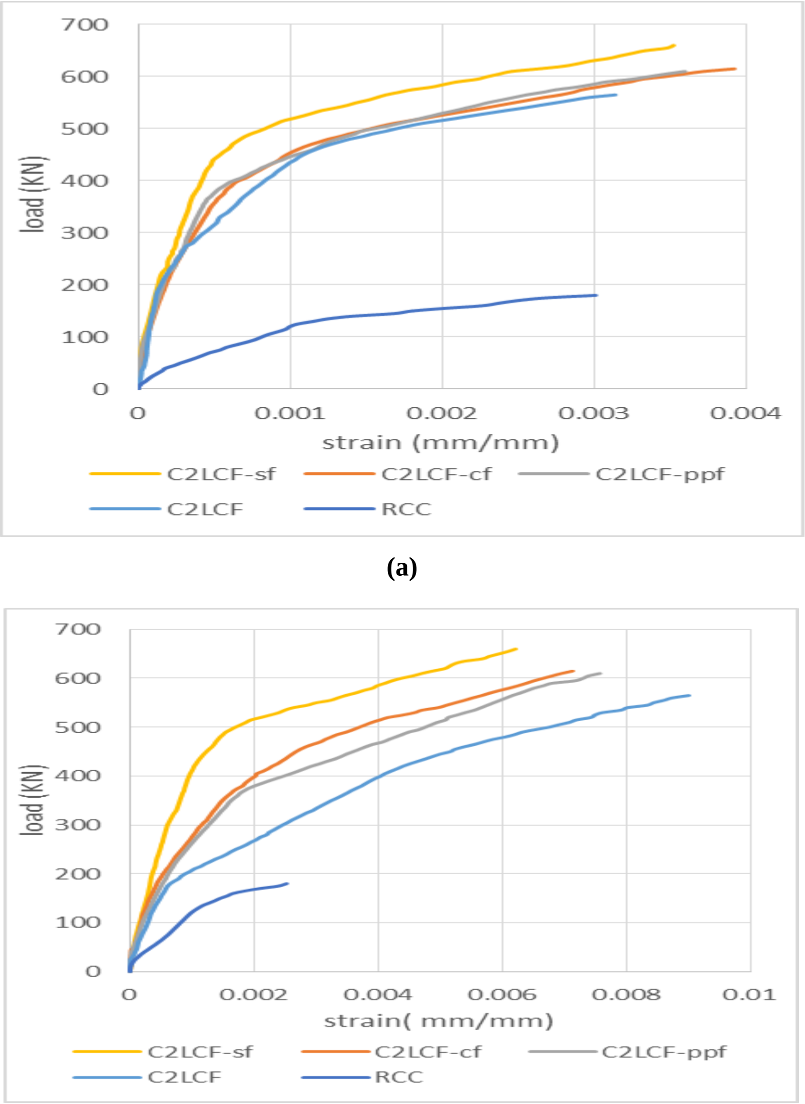
Specimens	ε_{lsu}	ε_{tsu}	$\varepsilon_{lsu}/\varepsilon_{lsu, RCC}$	$\varepsilon_{tsu}/\varepsilon_{tsu}$, RCC
RCC	0.0025	0.003	-	-
C2LCF	0.009	0.0031	3.6	1.05
C2LCF-sf	0.0069	0.0035	2.75	1.16
C2LCF-cf	0.00756	0.0036	3.02	1.2
C2LCF-ppf	0.0071	0.0039	2.84	31

Table 8: Key test results of steel reinforcement strain at 75% of ultimate load of the unconfined column

Specimens	ε_{lsu} at 75%	%Decreases in ε_{lsu} at 75%	ε_{tsu} at 75%	%Decreases inεtsu at 75%
RCC	0.00116	-	0.00125	-
C2LCF	0.0004	65.5%	0.000085	93.2
C2LCF-sf	0.00025	78.4%	0.000073	94.1
C2LCF-cf	0.00027	76.7%	0.000098	92.5
C2LCF-ppf	0.00033	71.5%	0.000093	92.5

Table 9: Key test results of steel reinforcement strain at 75% of ultimate load of the confined specimen without fiber (C2LCF)

Specimens	**ε_{lsu} at 75%**	**%Decreases in ε_{lsu} at 75%**	**ε_{tsu} at 75%**	**%Decreases in ε_{tsu} at 75%**
C2LCF	0.0045	-	0.00095	-
C2LCF-sf	0.0012	73.43	0.00047	73.8
C2LCF-cf	0.0023	49	0.00082	20
C2LCF-ppf	0.0003	33.3	0.0000813	21



(a)

(b)

Figure 10. load- Strain steel reinforcement of RC columns (a) load-transverse strain (b) load-longitudinal strain

The addition of fibers to the geopolymer adhesive leads to a significant improvement in resistance to lateral stress of transverse steel and longitudinal stress of longitudinal steel of confined specimens. This evolution is evident at 75% of the ultimate load for confined specimens without added fibers, the C2LCF-SF, C2LCF-CF, and C2LCF-PPF specimens give a reduction in longitudinal and transverse strain (73.43%, 49%, and 33.3%) and (73.8%, 20%, and 21%), respectively. As shown in Table (9). The reason for this return is to increase the interference between the geopolymer adhesive and the carbon fiber fabric layers, in addition to bridge the cracks resulting from the stresses transferred to the carbon jackets, and distributed them regularly through the matrix.

Table (8): illustrates the decrease in the lateral strain of transverse steel and longitudinal strain of longitudinal steel of the confined specimens at 75% of the ultimate load of the unconfined specimen (RCC). The C2LCF, C2LCF-SF, C2LCF-CF, and C2LCF-PPF specimens give a reduction in longitudinal and transverse strain (65.5%, 78.4% ,76.7%and 71.5%) and (93.2%, 94.1, 92.5% and 92.5%), respectively. The reason for this is the addition fibers to paste increase the bonding between the geopolymer adhesive and the jacket, which leads to an improvement in the confinement jacket that confined specimens and resistance to the lateral strain and distribution of the tensile stresses resulted from the expansion of concrete and longitudinal steel on the jacket.

4. Conclusions

The addition of discrete fibers to geopolymer adhesive with volumetric ratios of (2% SF, 0.2% CF, and 0.4% PPF) led to:

1. Development in load enhancement ratio by (3.65, 3.39, and 3.4) respectively, compared with unconfined RC column.
2. Development in deformation capacity by (3.94, 3.72, and 4.3) respectively, compared with unconfined RC column.
3. Decrease in longitudinal concrete service strain by (46.8%, 32.5% and 27.6%) and transverse concrete service strain by (71.5%, 51% and 17%) respectively.
4. Decrease in longitudinal steel reinforcement service strain by (73.4%, 49%, and 33.3%) and transverse steel reinforcement service strain by (73.8%, 20%, and 21%), respectively.
5. Improved bonding between the geopolymer adhesive and the carbon fiber jackets layers, which led to improvement in RC columns performance.
6. Reducing the longitudinal and transverse steel reinforcement strain. Where the RC columns confined by two jacket layers showed a decrease in longitudinal service strain by 65.5% and transverse service strain by 93.2%. compared with unconfined RC column.

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