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Research Article

Innovative Assessment of Compressive Strength in Reinforced Concrete Columns Confined with Geopolymer Adhesive Jackets

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ABSTRACT

The upgrade and reconstructing of the reinforced concrete (RC) buildings/structures are still some of the biggest challenges in construction and infrastructural development across the globe. Conventionally the fiber reinforced composites has been used for this purpose. But their use is often constrained by issues to do with cost, environmental unfriendliness and some shortcoming related to epoxy adhesives most of which include poor heat resistance. This work seeks to explore this problem by comparing the feasibility of using a locally available and cheaper geopolymer adhesive paste. The experimental work includes the seven RC columns confined with seven fiber-reinforced geopolymer adhesive jackets using different materials such as carbon fiber, jute fiber, steel wire mesh, window mesh fabric and polyethylene meshes having a weave of 3×3 mm & 4×4 mm.The result shows that geopolymer adhesive paste is a viable solution of bond several confinement material. In the tested jackets, carbon fiber had the best performance with enhanced load-bearing capacity 3.146 times and deformation capacity 3.68 times of unconfined RC columns. However, the cost of this system stands at $34 per square meter and is therefore the most expensive option. In contrast, jute fiber and steel wire mesh jackets offered better cost-effective solution with remarkable performance augmentations where load improvement ratios of 1.79 and 1.7 along with deformation capacities of 2.43 and 16.2 were realised. Based on the study, fiber reinforced geopolymer adhesive jackets can be recommended for strengthening and reconstruction of RC columns in regions with elevated temperature since epoxy systems are not convenient in such an environment. The findings of this research show that geopolymer adhesives for structural repair and strengthening have resource, cost, and environmental benefits.

1. INTRODUCTION

The repair and retrofit of infrastructures have emerged as global concerns because of the degradation resulting from age, weather and climate change, and pressure for improvements that meet current requirements. Steel reinforcement bars used in reinforced concrete (RC) columns which are critical to structural stability and integrity are highly vulnerable [1,2]. Enduring both axial stress and bending moments, these columns present possibilities of failure features that include brittle failure under high load and bending[3] due to such aspects as unequal moments at beam-column joints, lateral loads such as winds or forces due to earthquake, or overloads. Several methods have been proposed in civil engineering research on how to enhance the RC columns, among which use of external confinement through fiber reinforced polymer (FRP) is current [4,5]. This method provides good improvement on strength and ductility of RC columns, its performance greatly depends on type of confinement material and the interfacial bond between the confinement layer and concrete surface [6-8].

[9] This work performed experimental investigation on RC columns confined with carbon fiber strips (50 mm wide) which bonded epoxy adhesive and tested under axial load. These variables were the number of confinement layers: one, two and three. Data shown depicted high effectiveness of limiting axial deformation with an increase in the number of layers introduced. The study also noted improved durability of RC columns wrapped with these strips. This is on the backdrop of a study [10] which looked at the axial compressive capacity of high strength concrete circular sections confined with internal dual techniques of TRC and TSR as well as externally with FRP. They establishing that samples restrained by means of the TRC-TSR system had far superior compressive strength and ductility. However, columns confined with the

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FRP-TSR system were shown to perform better than those with conventional TSR and TRC-TSR owing to the ability of the former to prevent early spalling of the concrete cover.

However, FRP confinement techniques have some restrictions, especially when epoxy adhesive is employed; Wang et al. research [11] investigated bond properties of epoxy-coated carbon fiber reinforced polymer (CFRP) sheets to concrete at the high -temperature. Based on their studies, the authors found out that raising the temperature of the epoxy adhesive significantly decreased the bond strength. At 50°C adhesive failure and concrete rupture were noted, faster strength loss was observed if the temperature range was between 60°C and 70°C as these reduced the mechanical properties of the adhesive. To overcome these problems, various solutions were proposed where the use of geopolymer adhesive was studied. In [12,13] compressive strength of fly ash (FA) and ground granulated blast furnace slag (GGBFS) geopolymer pastes was investigated. When FA was replaced fully with GGBFS with a complete omission of FA, the improvement in the compressive strength was much more prominent, with 74% and 62% of gain when contrasted with the reference specimens at 7 days and 28 days.

This study proposes a novel approach to replace epoxy with an environmentally friendly and thermally efficient material: Specifically, the green innovative construction material and the geopolymer adhesive paste (GPA). The effects of jacket confinement materials such as carbon fibre, jute fibre, steel wire mesh, window mesh cloth and polyethene meshes including 3.3mm x 3.3mm and 4.4mm x 4.4mm meshes on the compressive behavior of masonry RC columns under axial load are examined. As such, this study seeks to harness the use of GPA to offer an economically viable yet efficient method of increasing the RC columns' cross-sectional dimensions in hot climates

2. MATERIALS AND METHODS

2.1. MATERIALS

2.1.1. Concrete

Feathers RC column was cast using concrete with a Characteristic compressive strength of 30 N/ MM2. All columns were cast in vertical position for a single box section and nine cylindrical test specimens of 300mm height and 150mm diameter. These specimens were used in order to determine the compressive strength of the concrete at the two sets of periods namely; 7 days and 28 days. Subsequent to demolding, the RC columns were immersed inside tap water for 28 days to achieve complete hydration of the cement matrix.

2.1.2. Geopolymer Adhesive

In this study, geopolymer adhesive (GPA) [14,15] was used as the confinement material for RC columns. It cutting cost, hence can be considered as an envioronmentally friendly material as an alternative to epoxy adhesive, in addition, it had high performance at high temperature compared to other adhesive systems. The binder for the preparation of the GPA used in this work was the slag together with an alkaline solution. Sodium hydroxide (NaOH) was dissolved in pure water at a concentration of 10 molar to prepare the alkaline solution, which was then mixed with sodium silicate (Na_2SiO_3) in a ratio of 1:2 (SH/SS) [16,17]. It was prepared a day before use to enhance colony growth as a result of effective chemical activation. A ratio of fluid-to-binder of 0.55 was kept. Table 1 highlights the detailed mix design as follows Table 1 A detailed mix design.

TABLE I. GEOPOLYMER ADHESIVE MIX DESIGN

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

3.1.3. Fabric Jacketing

Different fabrics were used and integrated with the geopolymer adhesive to fabricate confinement jackets for the RC columns. These were chosen as they have demonstrated properties that increases the capacity of columns and enhances their performance. Two selection criteria were used and six types of fabrics were used and mechanical properties confirmed through mechanical tests.

A. **Steel Wire Mes**

Another confinement material was of steel wire mesh in rolls with the width of 1200[mm] (Figure 1-a). The mesh had a mean fiber diameter of 0.2 mm, an opening size of 2 × 1.5 mm, a tensile strength of 384.6 MPa, and an elongation at failure of 4.5%.

B. Carbon Fiber Fabric

Carbon fiber fabric was supplied in rolls of 300mm in width, as illustrated in Figure 1-b. The material properties, as specified by ASTM D3039 [18], are an anticipated elastic modulus of 230 GPa, tensile strength of 2200 MPa, and a maximum rupture strain of 0.0175. Sustained at a nominal thickness of 0.169mm for each layer, the space in-between gave Maruti the flexibility to make their own layout choices.

C. Jute Fiber Fabric

The material for the fabrication of the case came from natural jute fiber in rolls with a width of 400mm (figure 1-c). It provides a mean fiber diameter of 0.27mm, the opening size of 1.5mm × 1.5mm, tensile strength of 350 MPa and elongation at failure of 11.6%.

D. 4×4 mm Mesh Reinforced Woven Polyethylene Fabric

Polyethylene (PE) mesh, a type of plastic material, was received in rolls of 1000mm width as demonstrated in figure 1-d. This fabric had a mean fiber diameter of 0.4 mm, an opening size of 4x4 mm, tensile strength 257 MPa and elongation at failure of 3.3%.

E. 3×3 mm Mesh Reinforced Woven Polyethylene Fabric

Another polyethylene mesh with smaller grid size of 3 × 3 mm was also used (Figure 1-e). It had a mean fibre diameter of 0.24mm, tensile strength of 215MPa together with an elongation at failure of 2.94 percent.

F. Window Mesh Fabric

Window mesh fabric was supplied in rolls with a specific width of 1200mm as shown in figure 1(f). The properties of this fabric were; the mean fiber diameter was 0.3mm, the opening size of 1.1 x 1.1mm, the tensile strength was 75.5 MPa and elongation at failure of 1.43%.

Fig. 1. Experimental setup and materials for fabric mesh confinement: (a) Steel wire mesh, (b) Carbon fiber sheet, (c) Jute fiber fabric, (d) 4×4 mm Polyethylene woven mesh, (e) 3×3 mm Polyethylene woven mesh, and (f) Window mesh fabric.

2.2. Methods

An experimental investigation was performed on seven RC columns for analysing the implications of various confinement materials of the compressive characteristics. There was one unconfined column which was labelled RCC and the rest six columns were confined by two layers of varying jacketing materials coupled with geopolymer adhesive. These columns are symbolized as follows:

a) **C2LCF**: Carbon fiber
b) **C2LJF**: Jute fiber
c) **C2LSM**: Steel wire mesh
d) **C2LWM**: Window mesh fabric
e) **C2LPM-3mm**: 3×3 mm polyethylene mesh
f) **C2LPM-4mm**: 4×4 mm polyethylene mesh

The four RC columns had circular cross sectional, their dimensions was 600mm high with a diameter of 100mm. Longitudinal rebars of Ø6 mm (380 MPa yield strength) as well as transverse bars of Ø4 mm (420 MPa yield strength) were provided at 100 mm centers as shown in Figure 2.

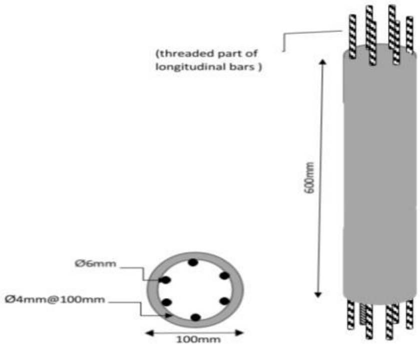
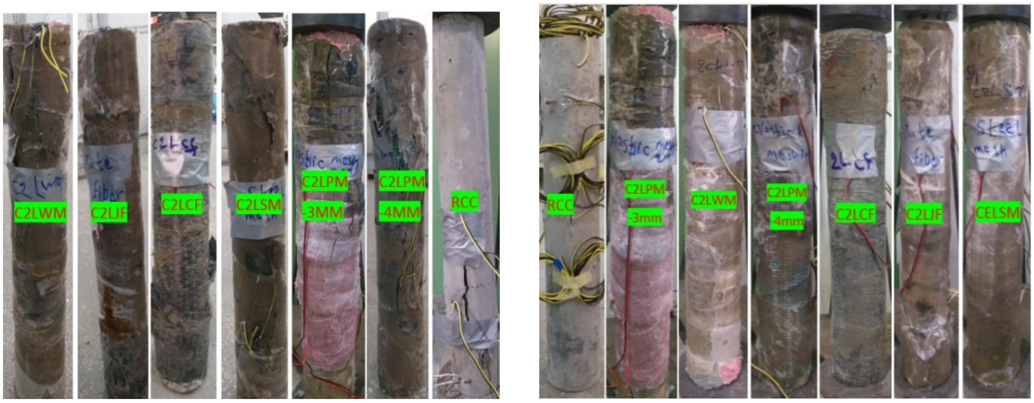


Fig. 2. Dimensions and reinforcement details of RC columns, showing the layout of longitudinal and transverse reinforcement.

In this case the RC columns were allowed to cure in the tap water for 28 days after casting to allow proper strength to be gained. Subsequently, the confined columns were enveloped by fiber reinforced geopolymer adhesive (FRGA) jackets. Subsequently the specimens were allowed to cure at room temperature and made ready for testing as shown in; Fig 3a. As part of the testing process, the behaviour of the RC columns was captured and the modes of failure witnessed are presented in fig 3b.



(a) (b)

Fig. 3. (a) Preparation of RC columns confined with geopolymer adhesive jackets; (b) Failure modes of RC columns under compressive loading.

2.2.1. Details of the RC Columns and Jacket Materials

The RC columns details utilized in this study are highlighted in table 2 below, together with the jacketing materials and their properties. Each row represents one of the seven RC column types in the study: the unconfined reference column (RCC), and six confined columns with different materials. The details covered in the table include the following:

a) Specimens: A laboratory test includes identification of the columns with unconfined reference column RCC and confined columns C2LCF, C2LJF.
b) Jacket Material: The materials that have been used in confinement besides the carbon fiber are jute fiber, steel wire mesh, window mesh fabric and polyethene meshes of 3×3 mm and 4×4 mesh size.
c) Price ($/m²): Also displays the cost of each jacket material by the square meter and thus indicates the relative cost-effectiveness of each. Carbon fiber being the most efficient one among all the options in this research is also the costliest option while jute fiber and polyethylene meshes are comparatively cheaper.
d) Thickness (mm): The tip defines the thickness of each confinement layer and to is different for different types of used material. For instance, carbon fiber has the thinnest dimension in the measure of 0.017 mm whereas jute fiber and polyethene mesh are relatively thicker in space.
e) Opening Size (mm²): Describes the weave of the mesh materials (jute fiber 1.5×1.5 mm, 4×4 polyethene mesh) and affects the confinement bar's performance and its interaction with the geopolymer adhesive.
f) Yield Strength (Fy, MPa): It stands for the ability of the jacket materials that give a tensile strength. A comparison of yield strength: carbon fibre yields the highest yield strength of 2200 MPa while steel wire mesh yields 384.6 MPa. Some additional materials with lower strength, such as window mesh — 75.5 MPa, are also considered to compare performance on different strength levels.

g) Elongation at Failure (%): This shows the level of ductility in the materials and their capability of deformation before the failure. For instance, jute fiber obtains higher elongation at failure 5.6% than window mesh 1.43%.

TABLE II. DETAILS OF RC COLUMNS AND JACKET MATERIALS

No.	**Specimens**	**Jacket Material**	**Price ($/m²)**	**Thickness (mm)**	**Opening Size (mm²)**	**Yield Strength (MPa)**	**Elongation at Failure (%)**
1	RCC	-	-	-	-	-	-
2	C2LCF	Carbon fiber	34	0.017	-	2200	4.9
3	C2LJF	Jute fiber	0.25	0.27	1.5×1.5	350	5.6
4	C2LSM	Steel wire mesh	0.33	0.2	2×1.5	384.6	4.5
5	C2LPM-4mm	4×4 mm polyethylene	0.30	0.4	4×4	257	2.94
6	C2LPM-3mm	3×3 mm polyethylene	0.30	0.24	3×3	215	3.3
7	C2LWM	Window mesh fabric	0.30	0.3	1.1×1.1	75.5	1.43

3. RESULTS AND DISCUSSION

3.1. Failure Modes of RC Columns

The failure modes of the RC columns after the tests are presented in the following figure-Figure 4. In all the RC columns, the confinement jackets were observed to have ruptured along the upper half of the column, a behaviour that has been noted by other researchers [19], [20]. This failure can be blamed on the vertical casting process where the use of a vibrator and the force of gravity kept the large aggregates at the base of the pavement and the small ones at the top. Therefore, a new weak area was created at the upper portion of the column cross-section and therefore more dominant to expansion and or crushing under axial load. These findings correspond to other documented failure modes in RC columns wrapped with fibre-reinforced composites where tensile forces produced by the action of axial loads are transferred on the confinement Slee to rupture failure.

When axial load was applied, the poorer upper portion of the concrete core ruptured and expanded creating tension which was transferred onto the confinement jacket. These stresses were sustained by the jacket and can be observed to have been averted from the body. This observed failure mode agrees with what has been described for circular confined RC columns in earlier works [21, 22].

3.2. Load Enhancement Ratio and Deformation Capacity

Table 3 gives the summary of test results of the RC column and the load-strain Graph of RC columns is shown in Fig 5 while the axial load vs column diameter graph is shown in Fig.6. The observed experimental results reveal enhancement in load carrying and deformation capacities of all confined RC columns in compared to the unconfined reference RCC. The geopolymer adhesive, when married with a variety of jacket materials, provided the necessary matrix to react to the stresses transmitted from the concrete core during testing. The load enhancement ratios and deformation capacities for the tested specimens are as follows:

- **C2LCF (Carbon Fiber)**: 3.146 and 3.68
- **C2LJF (Jute Fiber)**: 1.79 and 2.43
- **C2LSM (Steel Wire Mesh)**: 1.7 and 2.16
- **C2LPM-4mm (4×4 mm Polyethylene)**: 1.5 and 2.87
- **C2LPM-3mm (3×3 mm Polyethylene)**: 1.4 and 2.22
- **C2LWM (Window Mesh)**: 1.15 and 1.16

TABLE III. KEY TEST RESULTS OF RC COLUMNS

Specimens	**Pu (kN)**	**εu (mm/mm)**	Pu/Pu,RCC	$\varepsilon u/\varepsilon u$,RCC).	**Failure Mode**
RCC	179.6	0.0032	-	-	-
C2LCF	565.0	0.0118	3.146	3.68	Rupture
C2LJF	322.5	0.0078	1.79	2.43	Rupture
C2LSM	305.9	0.0069	1.7	2.16	Rupture
C2LPM4MM	268.0	0.0092	1.5	2.87	Rupture
C2LPM3MM	251.0	0.0071	1.4	2.22	Rupture
C2LWM	206.0	0.0037	1.15	1.16	Rupture

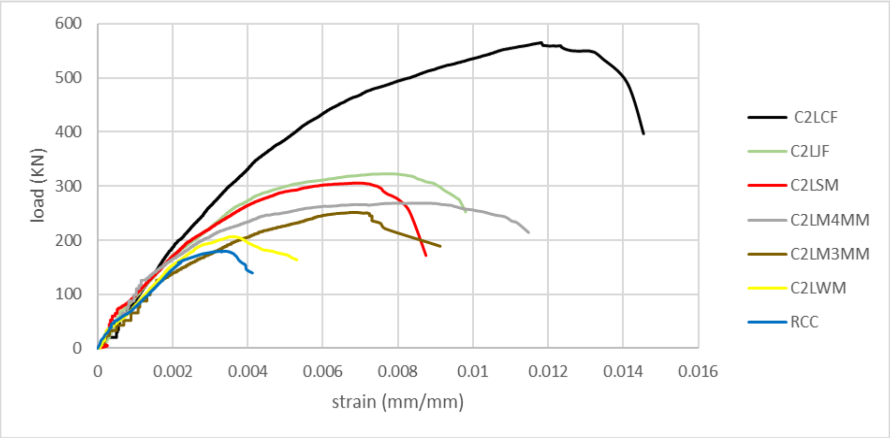


Fig. 5. Load-strain curves of RC columns, highlighting the enhanced strain capacity achieved with confinement.

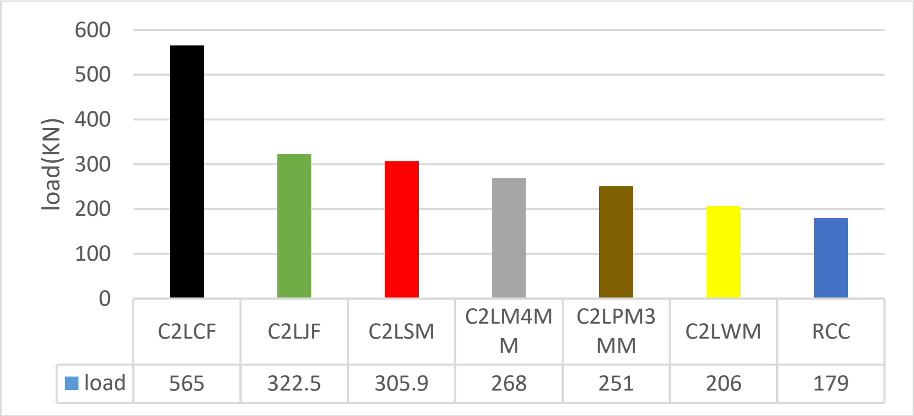


Fig. 6. The axial load capacity of RC columns demonstrates the significant improvement in load-bearing capacity with different confinement materials.

The improvements are the result of the mechanical properties of the jacket material such as the thickness of the jacket, the size of the opening, the elongation at failure and the tensile strength of the material used in the jacket. Percent improvement in ultimate load capacity for each specimen over the control, unconfined RCC column is shown in Fig. 7. According to the cost and efficiency analysis, steel wire mesh and jute fiber turns out to be the most preferable.

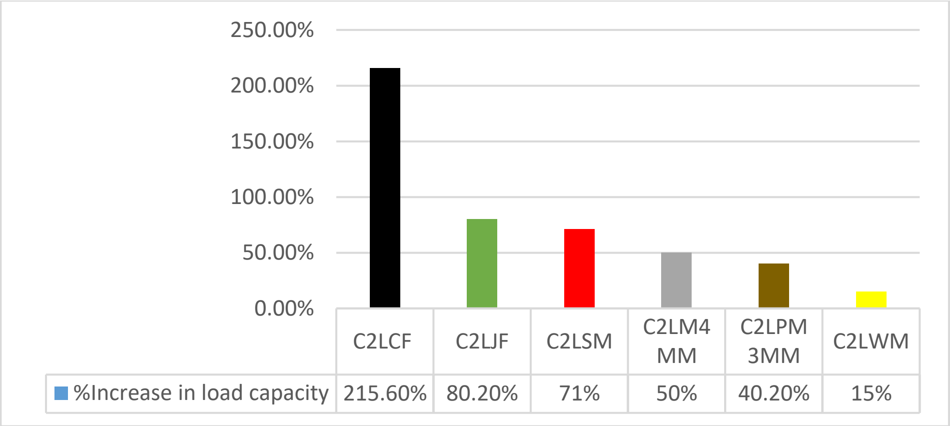


Fig. 7. Percentage increase in ultimate load capacity of RC columns

3.3. Jacket Strain

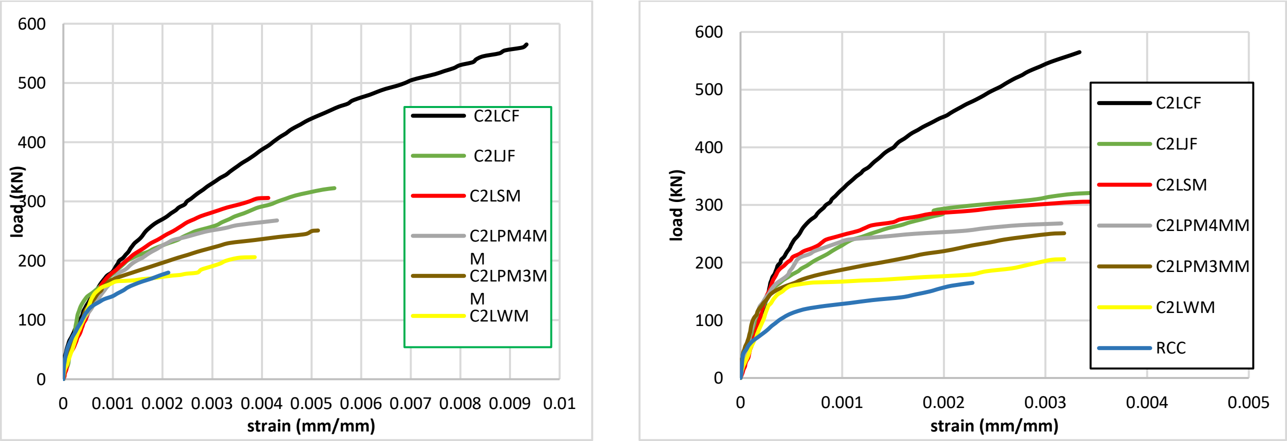
Table 4 shows the jacket strain measurements while FIG. (8a, b) shows the load – longitudinal and load–transverse strain relation for the jackets. Poisson's ratios analysed reflected the mechanical behaviour of the confinement jackets differing greatly. The reduction in Poisson's ratio for the different specimens is as follows:

- **C2LCF**: 0.59
- **C2LJF**: 0.58
- **C2LSM**: 0.84
- **C2LPM-4mm**: 0.78
- **C2LPM-3mm**: 0.65
- **C2LWM**: 0.88

TABLE IV. JACKET STRAIN MEASUREMENTS FOR CONFINED RC COLUMNS

Specimen	Ultimate Longitudinal Strain (εlu)	Ultimate Transverse Strain (εtu)	Poisson's Ratio (v)
C2LCF	0.0062	0.0037	0.59
C2LJF	0.0045	0.0026	0.58
C2LSM	0.0038	0.0032	0.84
C2LPM4MM	0.0046	0.0036	0.78
C2LPM3MM	0.0046	0.0030	0.65
C2LWM	0.0035	0.0031	0.88

These variations suggest appreciable transverse reinforce strength about longitudinal strength. Deformation was poorly endured by the jackets with lower tensile strength and poor ductility and the best-performing jackets had carbon fibre and steel wire mesh as their components.



(a) (b)

Fig. 8. (a) Load-longitudinal strain behaviour of concrete in RC columns. (b) Load-transverse strain behaviour of concrete in RC columns.

3.4. Concrete Strain

Table 5 presents the test results for the concrete strain in RC columns under axial compression. The results include the ultimate longitudinal strain (εlcu), ultimate transverse strain (εtcu), longitudinal deformation capacity relative to the reference column ($\varepsilon lcu/\varepsilon lcu$, **RCC**), transverse deformation capacity relative to the reference column ($\varepsilon tcu/\varepsilon tcu$, **RCC**), and Poisson's ratio (**v**).

TABLE V. KEY TEST RESULTS OF CONCRETE STRAIN IN RC COLUMNS

Specimen	Ultimate Longitudinal Strain (εlcu)	Ultimate Transverse Strain (εtcu)	Longitudinal Deformation Capacity ($\varepsilon lcu/\varepsilon lcu, RCC$)	Transverse Deformation Capacity ($\varepsilon tcu/\varepsilon tcu, RCC$)	Poisson's Ratio (v)
RCC	0.00212	0.0023	-	-	1.08
C2LCF	0.0093	0.00419	4.38	1.82	0.45
C2LJF	0.0055	0.0039	2.59	1.70	0.70
C2LSM	0.0042	0.0035	1.98	1.56	0.83
C2LPM4MM	0.0043	0.00315	2.00	1.37	0.73
C2LPM3MM	0.0051	0.0032	2.40	1.39	0.63
C2LWM	0.0038	0.0032	1.80	1.39	0.84

3.5. Analysis of Concrete Strain Data

From Table 5, it is clear that jacketing the steel confinement steel enhanced the strain capacity of RC columns in comparison to the reference unconfined RC column (RCC). These changes are most pronounced in the ultimate longitudinal stain εlcu and ultimate transverse strain εtcu, which can quantify the efficiency of the geopolymer adhesive and mechanical properties of the jacketing materials.

A. Ultimate Longitudinal Strain:

The longitudinal strain at the end of the test was found to have significant variations among the specimens depending on the performance of the various confinement materials used. The C2LCF (Carbon Fiber) jacket produced the highest ultimate longitudinal strain of 0.0093: 4.38 times greater improvement as compared to the unconfined RCC column. Here the comparison of axial deformation capacity of carbon fiber as a confinement material is described. C2LJF (Jute Fiber) and C2LPM3MM (3×3 mm Polyethylene) were observed to have moderate results with an increase of 2.59 and 2.40 times respectively. On the other hand, the C2LWM (Window Mesh) specimen had the least improvement with a factor of 1.80, clearly indicating that it has a very poor ability to take load against further longitudinal deformation.

B. Ultimate Transverse Strain:

For the ultimate transverse strain, we find a similar trend as established for the conditions in Equation (23). As a result, the C2LCF specimen has the highest transverse strain measurements, at 0.00419, which indicates a 1.82 times enhancement of RCC. C2 LAMJ manifested moderate efficiency; Even though the strain capabilities improved signifying ductile, mechanical strength of the material, C2 LAMJ and C2 LPM4MM (4×4 mm Polyethylene) didn’t give remarkable results. The C2LWM (Window Mesh) specimen had the smallest value of transverse strain, equal to 0.0032, which can point to the comparatively low lateral deformation ability of specimens.

C. Poisson’s Ratio (v):

The Poisson’s ratio of a material defines the lateral strain resistance in comparison to longitudinal strain and the Poisson’s ratio values of the specimens in the present study were quite unsynchronized. The docked thickness of the C2LCF jacket proved the least Poisson’s ratio of 0.45, therefore this material possesses better properties to bear lateral deformation and possesses good structural integrity under axial loads. More specifically, on the contrary, a comparative elevated Poisson’s ratio of 0.84 for the C2LWM (Window Mesh) and 0.83 for C2LSM (Steel Wire Mesh) implied better lateral expandability and lower lateral constraint of the reinforcement.

4. CONCLUSIONS

This paper presents a comprehensive analysis of tests performed on seven reinforced concrete (RC) columns retrofitted with fibre-reinforced geopolymer adhesive (FRGA) jackets to assess the effectiveness of geopolymer adhesive as a sustainable and durable bonding material. The study showed that all the applied jackets were capable of resisting axial load and that the carbon fiber jackets showed the best results with a load enhancement ratio of 3.146 and a deformation capacity of 3.68 but at the highest cost of $ 34 /m2. On the other hand, jute fiber and steel wire mesh jackets provided a reasonable combination of cost and performance with a higher load enhancement ratio of 1.79 and 1.7 respectively and deformation of 2.43 and 16.2 respectively but at a much lower cost ply. The work also paid considerable attention to fabric architecture where fabrics with an open pore structure provided better access and entrapment for the geopolymer adhesive and therefore enhanced adhesion and performance. The current study meant to analyze the performance of the confinement system under its various parameters showed that the tensile strength of the jacketing material and the adhesive used had a profound effect. Geopolymer adhesive jackets seem to be an adequate, economical, and sustainable option for enhancing RC column capability, especially in hot climates where epoxy adhesives do not provide sufficient bond strength. Future research may look at the permanency and efficiency of the geopolymer adhesive jackets under different service environments including freeze-thaw conditions and aggressive environments and the possibility of using these jackets to retrofit large structural members. Further, the appropriateness and effectiveness of geopolymer adhesives could be improved through the enhancement of mix design and the possibility of the applicability of hybrid fabric could also be explored.

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Conflicts Of Interest

The author declares no conflicts of interest with regard to the subject matter or findings of the research.

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