MSW MANAGEMENT -Multidisciplinary, Scientific Work and Management Journal
ISSN: 1053-7899
Vol. 36 Issue 1, 2026, Pages 4503-4508

A REVIEW OF BFRP-STRENGTHENED GEOPOLYMER CONCRETE CYLINDERS

P.Rajeswaran[1] and S.Saravanan[2]
[1]*Assistant Professor, Department of Civil Engineering, Sethu Institute of Technology, Kariapatti, Virudhunagar, Tamilnadu.*
[2]*PG Scholar, Department of Civil Engineering, Sethu Institute of Technology, Virudhunagar, Tamilnadu.*

Abstract
Geopolymer concrete (GPC) has gained considerable attention in recent years as a sustainable alternative to conventional cement-based concrete due to its reduced greenhouse gas emissions and efficient utilization of industrial by-products such as fly ash and ground granulated blast furnace slag. However, the brittle nature of GPC under compressive loading restricts its application in structural elements requiring adequate ductility and energy absorption capacity. To address this limitation, external confinement using basalt fiber-reinforced polymer (BFRP) composites has emerged as an effective strengthening and retrofitting technique. This paper presents a comprehensive review of the behavior of BFRP-confined geopolymer concrete cylinders subjected to axial compression. The confinement provided by BFRP jackets enhances the mechanical performance of GPC by generating lateral confining pressure, which delays crack initiation and restricts crack propagation. As a result, the stress–strain behavior of confined specimens transitions from brittle to ductile, exhibiting improved post-peak response and higher deformation capacity. Experimental studies indicate significant improvements in compressive strength, ultimate strain, and energy absorption, with the extent of enhancement depending on factors such as the number of BFRP layers, confinement stiffness, and material properties of the geopolymer matrix. The failure mechanism of BFRP-confined GPC is typically characterized by rupture of the BFRP wrap after the development of internal microcracks in the concrete core. Compared to unconfined GPC, the failure is more gradual and controlled. Although several analytical models exist for FRP-confined conventional concrete, their applicability to geopolymer concrete is limited, highlighting the need for modified predictive models. Overall, BFRP-confined geopolymer concrete demonstrates strong potential as a high-performance and environmentally sustainable construction material, warranting further investigation for practical design and field applications.

Keywords: Geopolymer Concrete, BFRP Confinement, Axial Compression, ductility, Stress–Strain Behavior, Sustainable Construction, Structural Performance.

1. INTRODUCTION

The rapid growth of the construction industry has led to a significant increase in the consumption of conventional Portland cement concrete, resulting in high carbon dioxide emissions and environmental degradation. In response to these concerns, geopolymer concrete (GPC) has emerged as a sustainable alternative, utilizing industrial by-products such as fly ash and ground granulated blast furnace slag as primary binding materials. The geopolymerization process not only reduces dependence on cement but also contributes to waste management and environmental protection. Due to its superior resistance to chemical attack, high-temperature stability, and lower shrinkage, GPC has gained attention for various structural applications.Despite these advantages, geopolymer concrete exhibits brittle behavior under compressive loading, similar to conventional concrete. This brittle nature limits its ability to undergo significant deformation before failure, which is a critical requirement in structural elements subjected to dynamic or seismic loads. Therefore, enhancing the ductility and strength of GPC is essential for its wider adoption in engineering practice.In recent years, fiber-reinforced polymer (FRP) composites have been extensively used for strengthening and confinement of concrete structures. Among the various types of FRP, basalt fiber-reinforced polymer (BFRP) has attracted considerable interest due to its high tensile strength, good corrosion resistance, thermal stability, and cost-effectiveness. Additionally, BFRP is considered more environmentally friendly compared to synthetic fiber-based composites, making it compatible with the sustainability goals of geopolymer materials.

The external confinement of concrete using FRP jackets enhances its mechanical performance by providing lateral pressure, which delays crack propagation and improves both strength and ductility. While extensive research has been conducted on FRP-confined conventional concrete, studies on BFRP-confined geopolymer concrete are relatively limited. The behavior of GPC differs from ordinary concrete due to its distinct microstructure and bonding characteristics, necessitating dedicated investigation.

This study aims to review and analyze the behavior of geopolymer concrete cylinders confined with BFRP composites under axial compression. The focus is on understanding stress–strain characteristics, strength enhancement, failure mechanisms, and key influencing parameters. The outcomes of this study are expected to contribute toward the development of reliable design models and promote the use of sustainable construction materials in modern infrastructure.

2. OBJECTIVES

The primary objective of this study is to investigate the mechanical behavior of geopolymer concrete cylinders confined using basalt fiber-reinforced polymer (BFRP) composites under axial compression. The specific objectives are as follows,

- To evaluate the compressive strength of geopolymer concrete cylinders with and without BFRP confinement.
- To study the stress–strain behavior of BFRP-confined geopolymer concrete and compare it with unconfined specimens.
- To assess the improvement in ductility and energy absorption capacity due to BFRP confinement.
- To examine the effect of key parameters, such as number of BFRP layers, confinement stiffness, and properties of geopolymer concrete, on overall structural performance.
- To analyze the failure modes and cracking behavior of confined and unconfined specimens under axial loading.
- To compare the performance of BFRP-confined geopolymer concrete with conventional concrete systems reported in literature.
- To evaluate the applicability of existing analytical models for predicting the behavior of confined geopolymer concrete.
- To identify research gaps and propose recommendations for future studies and practical design applications.

3. BASALT FIBRES

Basalt fiber is a material made from extremely fine fibers of basalt, which is composed of the minerals plagioclase, pyroxene, and olivine. It is similar to fiberglass, having better physico-mechanical properties than fiberglass, but being significantly cheaper than carbon fiber. It is used as a fireproof textile in the aerospace and automotive industries and can also be used as a composite to produce products such as camera tripods. Basalt fiber is made from a single material, crushed basalt, from a carefully chosen quarry source. Basalt of high Acidity (over 46% silica content) and low iron content is considered desirable for fiber production. Unlike with other composites, such as glass fiber, essentially no materials are added during its production. The basalt is simply washed and then melted. The manufacture of basalt fiber requires the melting of the crushed and washed basalt rock at about 1,500 °C (2,730 °F). The molten rock is then extruded through small nozzles to produce continuous filaments of basalt fiber. The basalt fibers typically have a filament diameter of between 10 and 20 µm which is far enough above the respiratory limit of 5 µm to make basalt fiber a suitable replacement for asbestos. They also have a high elastic modulus, resulting in high specific strength—three times that of steel. They are abundantly available, environmentally safe, nontoxic, non-corrosive, non-metallic and possess high heat stability and insulating characteristics. The tensile strength of continuous basalt fibre is about twice that of E-glass fibre and modulus of elasticity is about 15 to 30% higher than E-Glass fibre. Figure 1 shows the typical orientation of BFRP Sheet.

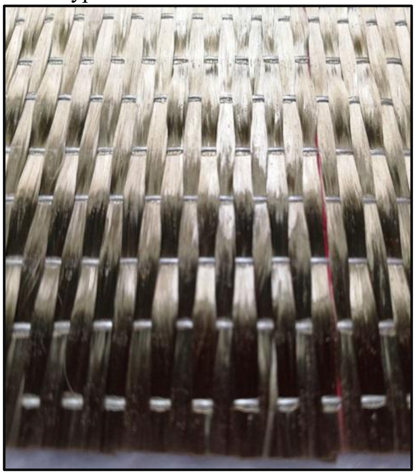

Fig 1 Orientation of BFRP Sheet (Unidirectional)

4. LITERATURE REVIEW

This study investigated the compression behavior of circular concrete columns confined with basalt fiber reinforced polymer (BFRP) stirrups, comparing their performance with traditional steel-reinforced columns. The objective of the study is to assess the impact of the BFRP transverse reinforcements and concrete mix design (CMD) codes on the compressive strength (CS), energy accumulation (GAcc), fracture energy (GF), and ductility of RC cylinders. A total of 81 reinforced concrete (RC) cylinders were prepared using three distinct CMD codes and tested under axial compression. The specimens were confined with 6 mm and 8 mm BFRP and steel spirals/ties at varying rib spacings (45 mm, 60 mm, and 90 mm). The experimental results revealed that closer BFRP spiral/tie spacings (45 mm) significantly enhanced the CS by 7–15 % and GAcc by up to 59 % of the columns due to improved confinement effect, compared to those with larger spacings (60 mm and 90 mm). BFRP ties demonstrated superior performance in terms of CS, GAcc, and GF compared to BFRP spirals, particularly at moderate and larger Spacings. Finite element model (FEM) simulations validated the experimental results with less than 8 % deviation and demonstrate a high degree of correlation between predicted and observed failure behaviors. The study suggests that BFRP spirals/ties reinforcements with optimal spacing can effectively replace steel in structural applications, offering comparable performance in strength, ductility, and energy absorption. These findings encourage the use of BFRP-based reinforcements in durable, lightweight, and eco-friendly concrete constructions. [1]

This paper investigated the axial compression behavior of square reinforced concrete (RC) columns confined by a novel type of rectangular closed basalt fiber-reinforced polymer (BFRP) tie fabricated using a continuous filament winding method, and hybrid steel–BFRP configurations. The proposed ties were developed to overcome common limitations of conventional FRP stirrups, such as reduced tensile strength at bent regions and premature rupture. A total of five RC column specimens were tested under monotonic axial loading: one reference specimen with conventional steel ties, two specimens with BFRP ties spaced at 45 mm and 90 mm, and two hybrid specimens combining steel and BFRP ties. Experimental results showed that the steel-confined column achieved the highest peak axial load of 1793.2 kN and an ultimate strain value of 1.12. The specimen with closely spaced BFRP ties (45 mm) reached 94.7% of the peak load of the steel-confined specimen and exhibited over 137% higher axial strain capacity. The hybrid specimen with two interleaved BFRP ties achieved the highest confinement effectiveness ratio of 1.306. The findings demonstrate that the proposed BFRP ties offer a structurally viable and corrosion-resistant alternative to steel ties, particularly when used in hybrid systems. This research contributes to the development of durable, high-performance confinement strategies for RC columns in seismic and aggressive environmental conditions. [2]

This study investigates how external wrapping with CFRP enhances the mechanical and structural performance of recycled concrete structures, with the aim of optimizing the use of recycled aggregate concrete (RAC) in civil engineering applications. An experimental and numerical investigation was conducted on the axial compressive behavior of 30 RAC columns and 15 basalt fiber-reinforced concrete (BFRC) columns confined with CFRP sheets. The study examines the effects of recycled coarse aggregate (RCA) replacement ratio, cross-sectional shape, CFRP wrapping configuration, and basalt fiber (BF) addition on failure mode, axial stress–strain behavior, load–displacement response, and ultimate load-carrying capacity of CFRP-confined RAC columns. The results indicate that an increase in the RCA replacement ratio leads to a reduction in ultimate hoop strain by 15.2–47.8%. However, when the RCA replacement ratio increases from 0% to 50% and 100%, the ultimate load-carrying capacity of CFRP-confined recycled concrete short columns increases by 13.2% and 5.6%, respectively. Partial and full CFRP wrappings are found to be more effective in enhancing axial deformation capacity and load-bearing capacity, respectively. Additionally, increasing the number of CFRP layers significantly improves both properties. It is also observed that, under uniform confinement, circular columns exhibit higher enhancement in ultimate strain and load-carrying capacity compared to square columns. The inclusion of basalt fibers significantly improves the axial compressive performance of unconfined RAC columns and provides marginal improvement in CFRP-confined RAC columns, although it reduces the relative gain in ultimate load capacity due to CFRP confinement. Furthermore, a predictive model for ultimate load-carrying capacity and a finite element model for CFRP-confined RAC columns were developed and validated, demonstrating strong agreement with the experimental results. [3]

The aim of this studied is to evaluate the axial compressive behavior of concrete columns strengthened with basalt fiber-reinforced polymer (BFRP) grids. A total of 27 concrete cylinders were tested, including 18 strengthened specimens and 9 control specimens. The study parameters included specimen size and grids quantity, and comparisons were made with specimens strengthened using BFRP sheets. The results indicate that the control specimens exhibited brittle failure, while the strengthened specimens demonstrated ductile failure, with significantly improved compressive carrying capacity and deformation ability. The strength effectiveness of the grids gradually weakened as the specimen size increased. When the number of grids layers was less than two, the strength effect significantly improved with an increase in grids quantity. However, when the number of grids layers exceeded two, delamination between the grids and concrete occurred, and the strength effect became less significant. Compared to BFRP sheets, BFRP grids demonstrated higher strength efficiency. Several existing theoretical models were utilized to predict the peak stress of BFRP grid-strengthened concrete, and the predicted results agreed well with the experimental results. [4]

In this present experimental study to investigated the Rapid repair of geopolymer concrete members reinforced with polymer composites: Parametric study and analytical modeling. To minimize the carbon production from the cement industry, geopolymers are the suitable replacement cementitious materials in concrete structures. Furthermore, glass fiber-reinforced polymer (GFRP) rebars can play a vital role in replacing the corrosive steel reinforcement in structural components due to their extraordinary performance in humid and aggressive environments. The current research aims to determine the performance efficiency of the rapid repairing process of partially damaged GFRP-reinforced recycled aggregate geopolymer concrete (RGC) compressive members subjected to various types of loading. The behavior of 18 repaired steel- and GFRP-reinforced RGC compressive members was compared using experiments, analytical modeling, and finite element analysis (FEA) in ABAQUS. The rapid repair process was completed using high-strength carbon fiber reinforced polymer (CFRP) sheets. The effectiveness of external CFRP wrapping on the failure modes, strength index, stiffness index, ductility index, peak axial loading capacity, and axial shortening behavior of the repaired members was carefully evaluated. Moreover, FEA and analytical models were proposed to accurately predict the axial behavior of the repaired RGC compressive members. A parametric study is carried out to investigate the effects of various parameters of repaired columns. Both experimental and numerical outcomes discovered that the proposed rapid repair method could considerably recover the peak axial capacity and axial shortening capacity of pre-damaged RGC compressive members. [5]
In the present experimental study to investigate the Behavior of BFRP-confined geopolymer-based coral aggregate concrete columns under axial compression: Effects of specimen sizes. Fiber-reinforced polymer (FRP) confined concrete significantly enhances the axial compressive behavior and durability of the internal core concrete, demonstrating promising applications in marine environments. However, this strengthening effect is highly influenced by the number of FRP layers and the size of the specimens. Additionally, the use of ordinary Portland cement (OPC) in traditional concrete preparation is associated with high energy consumption and substantial carbon emissions. This study explores the utilization of sustainable geopolymers as an alternative to OPC to develop geopolymer-based seawater coral aggregate concrete (GPCAC) in marine engineering. This approach contributes to the increased utilization of marine resources, reduced greenhouse gas emissions, and saved construction costs. Furthermore, basalt-FRP (BFRP) jackets were employed to wrap GPCAC, aiming to develop an innovative BFRP-confined GPCAC composite column for marine construction. The axial stress-strain behavior of BFRP-confined GPCAC cylinders with different BFRP jacket layers and specimen sizes was investigated. The studied results revealed that the BFRP jacket confinement was an effective means in strengthening the load-bearing capacity and deformability of GPCAC and cement-based CAC cylinders. The failure modes observed in the BFRP-confined GPCAC were analogous to those of BFRP-confined CAC. In addition, as the BFRP confinement stiffness strengthened, the slope of the stress-strain curves at the rising branch, axial compressive strength (fcc), and ultimate axial strain (εcc) of BFRP-confined specimens exhibited enhancement. Compared with un-confined GPCAC cylinders, the fcc and εcc values of 6-ply BFRP-confined GPCAC cylinders with a diameter of 100 mm were enhanced by about 2.09 and 4.55 times, respectively, whereas those with a diameter of 150 mm were improved by about 0.94 and 6.11 times, respectively. This increased effect in fcc and εcc was linearly related to the ratio of BFRP layer thickness to the diameter of the cylinders (T/D). Finally, the expressions in fcc and εcc for BFRP-confined CAC and GPCAC were developed, and the applicability of these proposed models was assessed by comparing them with experimental values of FRP-confined CAC reported in the literature. [6]
This paper presents the Axial behavior of concrete cylinders retrofitted with a hybrid system of CFRP textile grid and engineered geopolymer composite Fiber-reinforced polymer (FRP) textile grid-reinforced engineered cementitious composites (ECCs) are effective in strengthening concrete structures. Considering environmental interest, engineered geopolymer composites (EGCs) have been employed as an alternative to ECC. In this study, we present a retrofit scheme for CFRP textile grid-reinforced EGC matrix composites for concrete cylinders and compare the axial behavior of strengthened concrete cylinders with a conventional FRP-reinforced ECC strengthening system. Axial compressive specimens were tested for various parameters, including the number of FRP textiles, original concrete strength, and damage level of the original concrete cylinder. The results indicated that the strengthened concrete cylinders failed in a ductile manner owing to the progressive rupture of the CFRP textile grids. The CFRP-EGC strengthening layers improved the axial bearing capacity, stiffness, and ductility of the concrete cylinders. The axial bearing capacity increased by 89.4%–170.4 %; therefore, the contribution of enhanced confinement effect was 36.7–113.6 %. The confinement effect provided by the grids ranged from 0.805 to 1.958 MPa and played a major role in the CFRP-EGC strengthening layers. Comparatively, the CFRP grid utilization is more efficient in the EGC matrix than in the traditional ECC matrix. Moreover, the influence of the pre-damage on the behavior of the concrete cylinders was compensated for by the strengthening layers. [7]
The constitutive behavior of CFRP-confined normal- and high-strength geopolymer concrete: Experiments and modelling. The constitutive behavior of geopolymer concrete (GPC), which is essential to the design of GPC structures, has not been well explored, especially in multi-axial stress state. This study therefore performs an investigation on the constitutive behavior of normal- and high-strength GPC confined by carbon fiber-reinforced polymer (CFRP) jacket. A total of 36 CFRP-confined GPC specimens are fabricated, which cover six GPC mixtures and three thickness of CFRP jacket. A dataset comprising of 24 specimens is employed to develop the models for ultimate condition and axial stress-strain curve. Two testing datasets, one consisting of the rest 12 specimens and the other composed of six specimens collected from the literature, are exploited to test the models. A linear function of actual confinement ratio is competent for modelling the compressive strength, whereas a nonlinear function is capable of characterizing the ultimate axial strain. The average absolute error of predicted compressive strengths and ultimate axial strains is less than 8.0 % and 15.0 % for both testing datasets. A single four-parameter function originally proposed for OPCC can be extended to represent the axial stress-strain curve of CFRP-confined GPC by formulating expressions for the parameters. The correlation coefficient between predicted and measured curves is more than 0.96. [8]
Axial Compressive Behavior of CFRP and MWCNT Incorporated GFRP Confined Concrete Cylinders after Exposure to Various Aggressive Environments. Fiber-reinforced polymer confinement is considered to be effective in the retrofitting of concrete structures. The current study explores the effectiveness of one- and two-layer carbon fiber reinforced polymer (CFRP) and multi walled carbon nanotube (MWCNT) incorporated three-layer glass fiber reinforced polymer (GFRP) confinement on concrete cylinders under aggressive exposures, such as acid, alkaline, marine, water, and elevated temperatures. At 1 wt.% MWCNT by weight of the epoxy matrix, mechanical characteristics of the laminate show a significant improvement. In the case of acid exposure, the axial load-carrying capacity of concrete specimens with single-layer CFRP confinement was equal to that of MWCNT incorporated three-layer GFRP confinement (GF3C1-AC). The axial strain of GF3C1-AC was 23% and 12% higher than one and two-layer CFRP confinement. After exposure at 400 °C, in comparison with one- and two-layer CFRP confinement, the axial strain of MWCNT incorporated three-layer GFRP confined specimens increased by 50% and 20%, respectively, which proved the efficacy of MWCNT as a heat-resistant nano filler. The ultrasonic pulse velocity (UPV) test indicates that the confinement system protects the concrete core from sudden failure by impeding crack propagation. The test results proved that the MWCNT incorporated FRP system can be considered as a prospective substitute for CFRP systems for retrofitting applications in severe environmental conditions. [9]
The objective of this study was to investigated the effectiveness of different confinement materials in strengthening geopolymer concrete (GP) columns subjected to axial compression loading. This research encompassed both experimental and numerical analyses. The experimental phase involved testing seven circular GP columns, while the numerical phase involved developing 3D finite element (FE) models using ABAQUS software. The primary focus of this study was to assess the impact of using outer and inner steel tubes, as well as an outer polyvinyl chloride

(PVC) tube and a carbon-fiber-reinforced polymer (CFRP) sheet. To validate the FE models, the experimental results were utilized for comparison. The findings of this study revealed that the outer steel tube provided superior confinement effects on the GP column's concrete core compared to the PVC tube and CFRP sheet. The axial capacities of the columns confined with steel, PVC, and CFRP materials were observed to increase by 254.7%, 43.2%, and 186%, respectively, in comparison to the control specimens. Furthermore, the utilization of all confinement materials significantly enhanced the absorbed energy and ductility of the columns. The FE models demonstrated a reasonably close match to the experimental results in terms of load–displacement curves and deformation patterns. This correspondence between the numerical predictions and experimental data confirmed the reliability of the FE models and their suitability for generating further predictions. In summary, this study contributes to the field by exploring the efficacy of various confinement materials in strengthening GP columns. The results highlight the superior performance of the outer steel tube and demonstrate the positive influence of PVC and CFRP materials on enhancing the structural behavior of the columns. The validation of the FE models further supports their reliability and their potential for future predictions in similar scenarios. [10]

In this research studied, the performance of geopolymer concrete (GPC) in-filled fibre-reinforced polymer (FRP) composite (GPC-FRP) columns exposed to compressive loading is examined using the finite element (FE) analysis. The load–deflection behaviour is investigated by considering the impact of the strength of concrete, different fibre orientations and thicknesses of FRP tubes in terms of the diameter/thickness (D/t) ratio, surface friction in between the concrete and enclosing FRP tube, the lateral confinement and the axial stress distribution characteristics. The load-carrying capacity (LCC) of the GPC-FRP composite columns and cement concrete (CC) in-filled FRP composite (CC-FRP) columns is compared and the results imply that the LCC of the GPC-FRP composite columns is (0.9 to 2.04%) greater than the CC-FRP composite columns. The improvement in the LCC and lateral confining pressure of the GPC-FRP composite columns is observed as the thickness of the FRP tube increases. The LCC of the GPC-FRP composite columns with a D/t ratio of 30 was almost (12.70 to 14.23%) greater than the GPC-FRP composite columns with a D/t ratio of 50. The GPC-FRP composite columns with a fibre orientation in the axial and hoop directions (0°) exhibit (8.4 to 11.39%) better performance than the columns with any other orientations (30° and 53°). The LCC of the GPC-FRP composite columns with a coefficient of friction of 0.25 and 0.5 are quite comparable. The axial stress distribution in the GPC-FRP composite columns with different tube thicknesses is explored in this research. This FE model is validated with the experimental results obtained by Kim et al., (2015) and the load and deflection are predicted with the validation error of 6.5 and 6.1%, respectively. [11]

In the present experimental studied to investigate the compressive behavior of concrete stub column confined by a composite material originated from basalt rock, basalt fiber reinforced polymer. In this study confinement with FRP jackets is a useful reinforcement technique to improve the strength and ductility of concrete column subjected to axial compression loads, especially in those that have a stub column and concrete column. A basalt sheet is used for this project to increase the stability of the concrete structure. The ultimate load carrying capacity of externally bonded BFRP concrete stubs are evaluated experimentally. A stub column specimens and circular column specimens were casted with different aspect ratios (B/D=1, B/D=1.56, B/D=1.93) with different layers of BFRP wrapping (1layer, 2layer, 3layer) and different grade of mix (M25 & M45). A total of 72 specimens were tested under monotonic axial compression under the effect of 3 parameters (Different grade, and FRP layers). The axial compressive load applied for the element and to check the stability of the concrete. The properties of concrete such as compressive strength, split tensile strength, flexural strength and density were determined. [12]

This paper presented the results of an experimental study on the compressive behavior of thermally damaged circular concrete cylinders repaired with BFRP jackets. The specimens were divided into three series: three reference cylinders tested at ambient temperature, 12 thermally damaged concrete cylinders tested without strengthening, and 36 thermally damaged concrete cylinders tested after repaired with different layers of BFRP jackets. The thermally damaged concrete cylinders were initially exposed to various elevated temperatures ranging from 200 ◦C to 800 ◦C with a heating duration of 2.5h and then cooled down to the ambient temperature. The experimental results, including the failure modes, axial stress-strain curves, compressive strengths, ultimate axial strains, and the hoop strain-to-axial strain relationships of the thermally damaged concrete, were investigated to evaluate the efficiency of BFRP jackets for repairing purpose. Two typical concrete confinement models were then modified by considering the residual mechanical properties of concrete to predict the compressive behavior of the thermally damaged concrete wrapped with BFRP jackets. The comparisons between the model predictions and the test results are presented, and the accuracy of the concrete confinement models are examined and discussed. [13]

Table 1 Comparative Literature Reviews

Ref.	Material / System	Type of Study	Key Parameters	Major Findings	Limitations
[1]	BFRP-confined RC columns	Experimental + FEM	Stirrup spacing, diameter, CMD	Closer spacing improved strength (7–15%) and energy absorption (up to 59%)	Limited to cylinder specimens
[2]	BFRP ties & hybrid steel-BFRP RC columns	Experimental	Tie spacing, hybrid reinforcement	Hybrid system showed highest confinement efficiency; improved ductility	Small sample size
[3]	CFRP-confined RAC columns	Experimental + Numerical	RCA ratio, wrapping type, layers	Strength increased up to 13.2%; circular columns better	Reduced hoop strain with higher RCA
[4]	BFRP grid-strengthened concrete	Experimental	Grid layers, specimen size	Improved strength & ductility; grids efficient	Delamination at higher layers
[5]	CFRP-repaired geopolymer concrete	Experimental + FEM	Repair technique, loading	Restored strength and stiffness	Focused on repaired members
[6]	BFRP-confined geopolymer coral concrete	Experimental	Layer thickness, specimen size	Strength ↑ up to 2.09×; strain ↑ up to 6.11×	Marine-specific
[7]	CFRP textile grid + geopolymer composite	Experimental	Textile layers, damage level	Strength ↑ up to 170%; improved ductility	Complex system
[8]	CFRP-confined geopolymer concrete	Experimental + Modeling	CFRP thickness, mix type	Accurate stress-strain models	Limited multi-axial analysis
[9]	CFRP & MWCNT-GFRP confined concrete	Experimental	Exposure, layers	Improved durability in harsh conditions	Complex material
[10]	Confined geopolymer columns (steel, PVC, CFRP)	Experimental + FEM	Confinement material	Steel best; CFRP effective	Limited specimens
[11]	GPC-filled FRP tubes	FEM	Fiber orientation, thickness	Improved load capacity	Mostly numerical
[12]	BFRP-wrapped concrete stub columns	Experimental	Layers, aspect ratio	Strength improved with layers	Conventional concrete
[13]	BFRP repair of thermally damaged concrete	Experimental + Modeling	Temperature, layers	Restored strength	Damage-focused

5. RESEARCH GAP ANALYSIS

Table 2 Analysis of Research Gap from Literature Reviews

Ref.	Focus Area	Key Findings	Identified Gap	Future Scope
[1]	BFRP confinement	Improved strength & energy absorption	Limited to small-scale specimens	Full-scale structural validation
[2]	Hybrid BFRP-steel ties	High confinement efficiency	Limited seismic analysis	Seismic performance studies
[3]	CFRP-confined RAC	Strength improved with RCA	Durability not studied	Long-term durability analysis
[4]	BFRP grids	Efficient strengthening method	Bond/delamination issues	Improved bonding techniques
[5]	CFRP repair systems	Effective strength recovery	Only compressive loading	Multi-loading conditions
[6]	BFRP-confined GPC	High strength & strain enhancement	Marine-specific study	General structural applications
[7]	CFRP-EGC system	High ductility improvement	Complex application	Simplified field techniques
[8]	Constitutive modeling	Accurate predictions	Limited validation data	Expanded datasets
[9]	FRP in harsh environments	Improved durability	High cost/complexity	Cost-effective alternatives
[10]	Different confinement materials	Steel most effective	Limited sustainability focus	Eco-friendly materials
[11]	FRP tube systems	Improved load capacity	Mostly numerical	Experimental validation
[12]	BFRP wrapping	Strength improved	Conventional concrete focus	Geopolymer application
[13]	Thermal repair using BFRP	Restored strength	Limited cyclic loading study	Cyclic & fatigue analysis

6. CONCLUSION

The present study critically examined the performance of concrete columns confined with fiber-reinforced polymer (FRP) composites, with particular emphasis on basalt fiber-reinforced polymer (BFRP) systems applied to geopolymer and recycled aggregate concrete. The findings clearly demonstrate that FRP confinement significantly enhances the structural response of concrete under axial compression by improving strength, deformation capacity, and overall ductility. Among the various materials considered, BFRP emerges as a viable and sustainable alternative to traditional confinement materials due to its resistance to corrosion, cost-effectiveness, and environmental benefits. The effectiveness of confinement was found to depend largely on key parameters such as the number of FRP layers, spacing of transverse reinforcements, and geometric configuration of the columns. In general, closer spacing and increased layering resulted in better confinement efficiency. Additionally, circular specimens consistently showed superior performance compared to non-circular sections because of the more uniform distribution of lateral confining pressure. The use of geopolymer concrete and recycled aggregates further supports sustainable construction practices by reducing dependence on conventional cement and natural resources. Although higher replacement levels of recycled aggregates may slightly affect strain characteristics, the application of FRP confinement successfully mitigates these limitations and maintains structural integrity. Analytical and numerical models developed in previous studies have shown good agreement with experimental results, indicating their reliability in predicting the behavior of confined systems. However, most investigations have been limited to controlled laboratory conditions and do not fully represent real-world structural scenarios. In conclusion, BFRP-confined geopolymer concrete systems offer a promising solution for the development of durable, eco-friendly, and high-performance structural elements. Further research focusing on long-term durability, cyclic loading, and large-scale applications is essential to enable wider implementation in practical engineering design.

REFERENCES

1. Muhammad Sufian, Muhammad Rahman, Xin Wang, Mohamed F.M. Fahmy, Zhishen Wu and Amr M.A. Moussa, “Experimental and numerical study on the axial compression behavior of circular concrete columns confined by BFRP spirals and ties”, Reviews on Advanced Materials Science 2026; 65(1): 20250175, January 13, 2026. https://doi.org/10.1515/rams-2025-0175.
2. Amr M. A. Moussa Arafa, M. A. Ibrahim Ahmed, Elsayed, Zhishen Wu, Ahmed Monier, “Axial Compression Behavior of Square RC Columns Confined by Rectangular BFRP and Hybrid Ti” Infrastructures 2025, 10(8), 206; 8 August 2025. https://doi.org/10.3390/infrastructures10080206.
3. Y. Xu, X. Wang, J.F. Dong, Z.W. Guan, Q.Y. Wang, “Experimental and numerical study on the compressive behaviour of CFRP-confined columns with recycled aggregate concrete”, Construction and Building Materials, Volume 461, 31 January 2025, 139916. https://doi.org/10.1016/j.conbuildmat.2025.139916.
4. Peng Liu, Xin Wang, Weidong He, Dengfeng Lu, Zhishen Wu, Xiaofei Zhang, Yongbo Shao, “Axial compressive behavior of concrete columns strengthened with BFRP grids”, Construction and Building Materials, Volume 477, 30 May 2025, 141305. https://doi.org/10.1016/j.conbuildmat.2025.141305.
5. Ali Raza, Abdellatif Selmi, Mohamed Hechmi El Ouni, Muhammad Arshad, Nabil Ben Kahla, “Rapid repair of geopolymer concrete members reinforced with polymer composites: Parametric study and analytical modeling”, Engineering Structures, Vol 299, 2024. https://doi.org/10.1016/j.engstruct.2023.117143.
6. Bai Zhang, Qiang Wang, Hong Zhu, Zhiyuan Yang, Hui Peng, “Behavior of BFRP-confined geopolymer-based coral aggregate concrete columns under axial compression: Effects of specimen sizes”, Journal of Building Engineering, Volume 98, 1 December 2024, 111106.
7. Shan Li, Wentao Ma, Yiyan Lu, Bo He, Zhenzhen Liu, “Axial behavior of concrete cylinders retrofitted with a hybrid system of CFRP textile grid and engineered geopolymer composite”, Journal of Building Engineering, Volume 91, 15 August 2024, 109536.
8. Huafei Zhou, Kaixuan Shi, Ziling Xie, Wenhong Jiang, Xinyi Dong, “Constitutive behavior of CFRP-confined normal- and high-strength geopolymer concrete: Experiments and modelling”, Construction and Building Materials, Volume 438, 9 August 2024, 137173. https://doi.org/10.1016/j.conbuildmat.2024.137173.
9. Sruthi Sreekumar Kavitha, Mini K. Madhavan, Karingamanna Jayanarayanan, Prabir Kumar Sarker, “Axial Compressive Behavior of CFRP and MWCNT Incorporated GFRP Confined Concrete Cylinders after Exposure to Various Aggressive Environments”, Journal of Composite Science, Vol 8(8), 2024. https://doi.org/10.3390/jcs8080313.
10. Aref A. Abadel, “Structural Performance of Strengthening of High-Performance Geopolymer Concrete Columns Utilizing Different Confinement Materials: Experimental and Numerical Study”, Buildings 2023, 13(7), 1709; https://doi.org/10.3390/buildings13071709.

MSW MANAGEMENT -Multidisciplinary, Scientific Work and Management Journal
ISSN: 1053-7899
Vol. 36 Issue 1, 2026, Pages 4503-4508

11. Varunkumar Veerapandian, Gajalakshmi Pandulu, Revathy Jayaseelan, Veerappan Sathish Kumar, Gunasekaran Murali, Nikolai Ivanovich Vatin, “Numerical Modelling of Geopolymer Concrete In-Filled Fibre-Reinforced Polymer Composite Columns Subjected to Axial Compression Loading”, Materials 2022, 15(9), 3390; https://doi.org/10.3390/ma15093390.
12. K.Uma Manimegalai, P.Rajeswaran, "Experimental Study on BFRP Confined Concrete in Stub Elements", International Journal of Science and Research (IJSR), Volume 10, Issue 6, June 2021. DOI: 10.21275/MR21529122334. IF: 7.803.
13. Li-Jun Ouyang, Mao-Xiang Chai, Jiang Song, Li-Li Hu and Wan,Yang Gao “compressive behavior of thermally damaged concrete cylinders with basalt fiber-reinforced polymer jackets”, Journal of Building Engineering, Volume 44, December 2021.
14. Bhanavath Sagar and M.V.N.Sivakumar, “Performance evaluation of basalt fibre-reinforced polymer rebars in structural concrete members–a review”, Innovative Infrastructure Solutions, June 2021. DOI:10.1007/s41062-020-00452-2.
15. Batzaya Baasankhuu, Donguk Choi & Sangsu Ha, “Behavior of Small-Scale Concrete Cylinders in Compression Laterally Confined by Basalt Fiber and PEN Fiber Reinforced Polymer Composites” International Journal of Concrete Structures and Materials volume 14, Article number: 8 (2020).
16. Wei Wei, Feng Liu, Zhe Xiong, Fei Yang, Lijuan Li, Hanwei Luo, Effect of loading rates on bond behaviour between basalt fibre-reinforced polymer bars and concrete, Construction and Building Materials, Volume 231, 20 January 2020, 117138.
17. N.Venkata subbaiah and M.Praveen Kumar, Tests on circular and square prismatic high strength concrete specimens, strengthened with external E-glass fiber reinforced polymer (GFRP), a literature review. J. Inst. Eng. India, 2018.
18. Pedram Sadeghian, Brandon Fillmore, Strain distribution of basalt FRP-wrapped concrete cylinders, Case Studies in Construction Materials, Volume 9, December 2018, e00171.
19. Chiadighikaobi and Paschal Chimeremeze, Assessment of Compression strength of Concrete Columns Confined with Basalt Fibre Reinforced Polymer, MATEC Web of Conferences 278, 03001 (2019).
20. Gao Ma, Cheng Wu, Hyeon-Jong Hwang, Jiulin Bai, Zhihu Zeng, Behavior of pre-damaged normal-strength concrete prisms repaired with basalt FRP sheets under axial compressive monotonic and repeated loading, Engineering Structures, Volume 269, 15 October 2022, 114786.
21. Sakol Suon, Shahzad Saleem, Amorn Pimanmas, Compressive behavior of basalt FRP-confined circular and non-circular concrete specimens, Construction and Building Materials, Volume 195, 20 January 2019, Pages 85-103.
22. Venkata subbaiah N, Praveen Kumar M. An experimental study on compressive behavior of concrete cylinders confined with glass and basalt fiber reinforced polymer: a literature review. Int.J.scientific research and review, Vol.7, no. 9, 2018.
24. Kirthika SK, Singh SK. Experimental Investigations on Basalt Fiber-Reinforced Concrete: a literature review. J. Inst. Eng. India Ser. A, pp.9, (2018).
25. Ana de Diego, Sonia Martinez, Jose Pedro Gutiérrez, et al. Experimental study on concrete column confined with external FRP: a literature review. J.ICSECT, DOI. 10.11159, no.113, (2019).
26. Gao Maa, Hui Li, Libo Yan, et al. Testing and analysis of basalt FRP-confined damaged concrete cylinders under axial compression loading: a literature review. J. Construction and Building Materials, vol.169, pp.762-774, (2018).
27. K.Pradeeba1, Dr.A.Rajasekaran2, Dr.P.Anupriya3. Strengthening Of RC Circular Column Wrapped With Carbon Fiber Reinforced Polymer: a literature review. International Journal of Innovative Research in Science, Engineering and Technology, vol.7, no.5, (2018).
28. ArathiKrishna, MiluMary Jaco, K.Saravana Raja Mohan. Experimental Study on Strengthening of RC Short Columns with BFRP Sheets: a literature survey. Int.J.scientific research and review, vol.7, pp.48-52 (2018).
29. Jordan Carter, Aikaterini S. Genikomsou. Investigation on modeling parameters of concrete beams reinforced with basalt FRP bars: a research article. J.civil Engineering Department, no.12-1, (2019).
30. Radhwan Alzeebaree, Abdulkadir Cevik, Behzad Nematollahi, et al. Mechanical properties and durability of unconfined and confined geopolymer concrete with fiber reinforced polymers exposed to sulfuric acid: a literature review. J. Construction and Building Materials, Vol.215, pp.1015–1032, (2019).
31. M. Talha Junaid, Abdalla Elbana, Salah Altoubat et al. Experimental study on the effect of matrix on the flexural behavior of beams reinforced with Glass Fiber Reinforced Polymer (GFRP) bars: a literature review. J. composite structure, vol.222, pp 110-930, (2019).
32. Diptikanta Das, Om Prakash Dubey, Milind Sharma et al. Mechanical properties and abrasion behavior of glass fiber reinforced polymer composites: a case study. J. Materials Today: Proceedings, pp. 2214-7853, (2019).
33. Doo-Yeol Yooa, Nemkumar Banthiab. Impact resistance of fiber-reinforced concrete: a literature review.J. Cement and Concrete Composites, vol.104, pp.103-389, (2019).