

ENHANCEMENT OF CONCRETE COLUMN STRENGTH USING E-GLASS/EPOXY COMPOSITE LAMINATES

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Abstract

This study explores the effectiveness of E-glass/epoxy composite laminates in enhancing the compressive strength of cylindrical concrete columns (CCCs). The research was driven by the need to develop more efficient, lightweight, and cost-effective reinforcement alternatives to conventional materials. To achieve this, cylindrical concrete specimens were fabricated in accordance with ASTM C39 standards and reinforced with one to five layers of E-glass/epoxy laminates using the vacuum bagging method. Compressive strength tests revealed that the application of E-glass/epoxy laminates markedly improved the load-bearing capacity of the columns, supported by statistical analysis including the Shapiro-Wilk test, Levene's test, and ANOVA to ensure the reliability and significance of the results. The findings reveal that specimens wrapped with five layers of E-glass achieved the highest compressive strength, reaching 30.44 MPa-representing a 52% increase compared to unwrapped control specimens. Additionally, scanning electron microscopy (SEM) was employed to investigate interfacial adhesion and damage patterns, revealing intact laminar structures and superior bonding characteristics. The study confirms that E-glass/epoxy laminates significantly enhance the structural integrity and load-bearing capacity of CCCs. These outcomes not only validate the potential of E-glass composites in structural rehabilitation but also contribute to the advancement of sustainable, high-performance materials in modern civil infrastructure applications. These findings highlight the practical potential of E-glass/epoxy laminates as a cost-effective and sustainable solution for strengthening and rehabilitating concrete infrastructure, thereby supporting the development of safer and longer-lasting civil engineering structures.

Keywords: Concrete reinforcement; E-glass/epoxy composite laminate; Compressive strength; Vacuum bagging; Structural durability

Introduction

The use of composite materials in the construction industry has gained significant attention due to their superior mechanical properties and durability (Rajak *et al.*, 2019). Among these, E-glass/epoxy composites have emerged as promising materials

for reinforcing concrete structures. The enhancement of concrete strength using these advanced composites addresses the increasing demand for resilient and long-lasting infrastructure (Zulfikar *et al.*, 2023a). Concrete, despite its

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widespread use, is inherently weak from low tensile strength and is susceptible to cracking under stress (Moudood *et al.*, 2019). Reinforcing concrete with composite materials such as E-glass/epoxy laminates offers a viable solution to these limitations, potentially transforming the durability and performance of concrete structures (Yuhazri *et al.*, 2018; Zulfikar and Yaakob, 2023; Zulfikar, Yaakob, *et al.*, 2024a). Unlike many previous investigations that emphasized tensile, pull-off, or durability properties of composite-reinforced concrete, the present study specifically focuses on evaluating compressive strength to provide a clearer understanding of structural load-bearing performance.

Several studies have investigated various methods to improve the strength and durability of concrete columns. Fakharifar *et al.* (2016) investigated the application of prestressed steel jackets, which significantly enhanced the ultimate strength and plasticity of damaged columns by 115% and 140%, respectively. However, the initial stiffness only recovered to about 84%. This indicates that the structure remains more flexible than its initial state, which could impact its performance under subsequent seismic events (Fakharifar *et al.*, 2016). Sudhakar and Partheeban 2017 demonstrated that wrapping concrete columns with e-glass fibres using the hand lay-up method enhanced compressive strength by up to 30%. However, the implementation of this method is highly dependent on the quality of the application, and the costs are quite high (Sudhakar and Partheeban, 2017). Yu *et al.* (2018) demonstrated that carbon fibre-reinforced polymer (CFRP) wraps can significantly enhance the performance of cylindrical concrete structures in terms of ultimate strength and ductility. However, the success of using CFRP is highly dependent on the quality of installation on concrete and also requires quite high costs (Yu *et al.*, 2018). Despite these advancements, there remain challenges in optimizing these methods for practical, cost-effective applications. While prior studies have demonstrated the effectiveness of steel jackets, CFRP wraps, and even jute-based composites in enhancing the strength and durability of concrete columns, each of these approaches presents inherent limitations. Prestressed steel jackets, although highly effective in improving strength and ductility, are heavy, labor-intensive to install, and prone to corrosion, which compromises long-term durability. CFRP wraps offer excellent mechanical performance but are considerably more expensive, limiting their widespread adoption in cost-sensitive infrastructure projects.

Jute fibre composites, by contrast, are low-cost and environmentally friendly, yet their relatively low tensile strength, poor moisture resistance, and susceptibility to degradation under harsh environmental conditions restrict their structural reliability. In comparison, E-glass/epoxy laminates provide a balanced alternative, combining high tensile strength, superior bonding, and durability with greater affordability than CFRP and better mechanical reliability than jute. This positions E-glass/epoxy laminates as a novel and practical reinforcement solution that bridges the performance-cost gap between natural fibre composites and high-performance synthetic materials.

Recent studies have demonstrated the significant benefits of using E-glass/epoxy composites in concrete reinforcement. For example, research by Naser and Fahad (2018) showed improved adhesion properties and enhanced durability when E-glass was incorporated with epoxy, particularly in pull-off strength and hardness tests (Naser and Fahad, 2018). Similarly, Laghaei *et al.* (2021) found that the addition of cellulose nanocrystals to E-glass/epoxy composites significantly increased tensile strength and fracture toughness (Laghaei *et al.*, 2021). Furthermore, Idrisi *et al.* (2019) highlighted the material's resistance to harsh environmental conditions, such as seawater immersion, which underscores its potential to enhance the longevity of concrete structures (Idrisi *et al.*, 2019). Wang *et al.* (2019) demonstrated that applying Glass fibre-Reinforced Polymer (GFRP) sheets to Encased FRP Confined Concrete Cores (EFCCC) could increase compressive strength by up to 20% (Wang *et al.*, 2019). Similarly, Vijayan *et al.* (2021) reported a 5% increase in compressive strength with a 5 mm GFRP wrap on M20 grade concrete (Vijayan *et al.*, 2021). More recently, Yang *et al.* (2022) highlighted the effective mechanical performance of flax/glass fibres combined with epoxy resin, emphasizing good adhesion and enhanced structural integrity (Yang *et al.*, 2022). These studies collectively underscore the potential of composite materials in concrete reinforcement, yet they also reveal variations in performance based on material type, application methods, and structural contexts.

Despite the promising findings, there remains a gap in understanding the specific impact of E-glass/epoxy composite laminates on the compressive strength of cylindrical concrete columns. Existing literature primarily focuses on general composite applications or other types of fibres and resins, with limited emphasis on E-glass/epoxy laminates. Moreover, the

comparative performance of these laminates against traditional reinforcement materials such as jute has not been extensively explored. Addressing this gap is crucial for optimizing the use of composite materials in concrete reinforcement and advancing construction technologies.

The primary objectives of this research are multifaceted, aimed at advancing the understanding and application of E-glass/epoxy composite laminates in reinforcing cylindrical concrete columns (CCC). Firstly, the study seeks to investigate the impact of these laminates on the compressive strength of CCCs, quantifying the enhancements provided by varying layers of E-glass/epoxy composites. Secondly, the study aims to compare the compressive performance of E-glass/epoxy laminates with concrete columns reinforced using one to five layers of jute, thereby establishing their relative effectiveness. Additionally, the research intends to validate the statistical significance of the observed improvements in concrete strength through rigorous tests, including the Shapiro-Wilk normality test, Levene test for homogeneity of variance, and ANOVA. Another objective is to analyze the damage patterns and structural integrity of E-glass wrapped concrete columns under compressive loads, using visual inspections and SEM analysis to understand the effects of these laminates on the overall structural resilience. Finally, the study aims to contribute to the body of knowledge on advanced composite materials for structural reinforcement, providing empirical data and insights that highlight the potential of E-glass/epoxy laminates in enhancing the durability and strength of concrete structures.

Materials and Methods

The study was conducted over a period of six months, from November 2024 to April 2025, in the Laboratory of Composite Materials at Fakulti Teknologi dan Kejuruteraan Industri dan Pembuatan, Universiti Teknikal Malaysia Melaka, Melaka, Malaysia. The laboratory is equipped with advanced facilities for materials testing and analysis, ensuring accurate and reliable results.

The primary materials utilized in this study were cylindrical concrete columns (CCC) and E-glass/epoxy composite laminates. The concrete mixture was prepared using standard M20 proportions, with a composition of 1:1.5:3 for cement, sand, and aggregate, respectively, to ensure uniform consistency and quality. The E-glass fibres, selected for their high tensile strength and durability, were combined with epoxy resin to

create the composite laminates. Concrete specimens were moulded according to ASTM C39 standards, with a diameter of 50 mm and a length of 150 mm (Figure 1a and Figure 1b). The specimen size was selected in accordance with ASTM C39 standards to ensure reliable compressive strength testing. Although smaller than full-scale columns, this dimension allows consistent specimen preparation, easier laminate application, and efficient material use without compromising the validity of results. The chosen scale thus balances experimental feasibility with standardized accuracy. The specimens were cured in water for 28 days and air-dried for an additional 28 days to ensure stable weight. After curing, the columns were wrapped with varying layers of E-glass/epoxy composite laminates, ranging from one to five layers, using the vacuum bagging method (Figure 2a). The E-glass used in this study had an areal density of 600 g/m² and a thickness ranging from 0.45 to 0.60 mm. The wrapping process involved applying a layer of epoxy resin on the concrete surface, followed by the placement of E-glass fibre sheets and another layer of epoxy resin, ensuring proper adhesion and uniform thickness (Figure 2b). Three specimens were prepared for each layer variation, and three control specimens were left unwrapped. The epoxy system employed in this study was Eposchon 1011A resin and 1011B hardener, mixed at a 1:1 ratio. The curing period, as recommended by the manufacturer, ranged from 6 to 24 h.

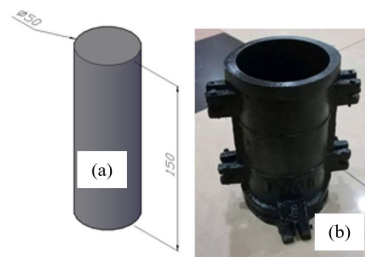


Figure 1. Cylindrical Concrete Column (a) specimen dimensions, (b) moulds



Figure 2. Specimen preparation: (a) vacuum bag, and (b) e-glass skin

The experimental setup aimed to evaluate the compressive strength of the reinforced concrete columns. The specimens were divided into six groups: Control Specimen (CS), Specimen with one layer of E-glass (G1), Specimen with two layers of E-glass (G2), Specimen with three layers of E-glass (G3), Specimen with four layers of E-glass (G4), and Specimen with five layers of E-glass (G5). Both wrapped and unwrapped specimens were subjected to compressive strength tests using the UTM WEW-300D (Figure 3). Each specimen underwent compressive testing three times to ensure the accuracy and reliability of the results. The average compressive strength for each group was calculated and documented. During testing, the specimens were placed perpendicular to the base stand and parallel to the loading axis, with a loading rate set at 0.1 mm/min. The compressive strength values were recorded and analyzed to evaluate the performance of the E-glass/epoxy composite laminates. This comprehensive methodology ensures a rigorous evaluation of the potential benefits of using E-glass/epoxy composite laminates to enhance concrete column strength, contributing valuable insights to the field of structural engineering.



Figure 3. Position of the compression test specimen on the UTM

The validity of the data was assessed using the Shapiro-Wilk normality test and ANOVA. The Shapiro-Wilk test was employed to check the normality of the data distribution, yielding a statistical value W of 0.9599 and a p -value of 0.6909, indicating a good fit to the normal distribution (Khatun, 2021). The homogeneity of variance was confirmed using Levene's test, which produced a p -value of 0.7989 (Kim and Cribbie, 2018). ANOVA was conducted to evaluate the impact of E-glass fibre layers on compressive strength, with a calculated F value of 4.0569 surpassing the critical F value of 3.478 and a p -value of 0.0329, indicating significant differences among the groups (Abdelal *et al.*, 2019).

To further analyze the structural integrity and damage patterns, Scanning Electron Microscopy (SEM) was performed on selected specimens. SEM analysis focused on the interface between E-glass fibres and concrete under compressive load. Specimens were prepared by cutting small sections of the tested columns and mounting them for microscopic examination. The SEM image, at 50x magnification, revealed the intact laminar structure of the E-glass and the extent of fibre damage, primarily caused by shear forces. This analysis provided detailed insights into the quality of the bond between the laminate and the concrete, as well as the overall durability of the composite under compressive stress.

Results and Discussion

Table 1 presents data on the compressive strength of CCCs reinforced with E-glass/epoxy laminate composites. Figure 4 illustrates the trend of improved average performance data for GFRP (Glass fibre-Reinforced Polymer) compression. The discussion of results begins with the lowest recorded performance, at 18.28 MPa for G1, and concludes with the highest performance of 30.44 MPa achieved by G5. These findings confirm that the use of five layers of e-glass fibre significantly enhances concrete strength by up to 52% compared to the control specimen (CS). Notably, there was a slight reduction in compressive performance of 8.21% observed for G1 at 18.28 MPa when compared to CS. The average compressive strength of the control specimen (CS) was slightly higher than that of the single-layer E-glass laminate specimen (G1). This minor reduction can be attributed to the introduction of an additional interface between the concrete surface and the single composite layer, which may not have provided sufficient confinement or stress distribution. However, the difference is not substantial when compared to specimens reinforced with multiple layers (G2-G5), which demonstrated progressively higher compressive strengths. This indicates that effective confinement and performance enhancement are achieved only when additional laminate layers are applied, whereas a single layer may be insufficient to significantly alter the load-bearing capacity. Furthermore, the compressive strengths of the fourth and fifth layers showed a minimal difference of 1.45%, recorded at 30.00 MPa for G4 and 30.44 MPa for G5 respectively. Statistically, the Tukey's HSD test indicated that this difference was not significant ($p > 0.05$), and practically, the variation is negligible compared to the data variability (SD approximately

3-4 MPa). Therefore, the addition of a fifth layer does not provide any substantial advantage over four layers. These findings align with Wang *et al.* (2019), who reported a 20% increase in compressive strength using GFRP sheets in EFCCC systems, and with Vijayan *et al.* (2021), who observed a 5% gain with a 5 mm GFRP wrap on M20 concrete. However, the present study achieved up to a 52% improvement through multilayer E-glass/epoxy laminates applied via vacuum bagging, highlighting the superior confinement efficiency of this reinforcement method. (Wang *et al.*, 2019; Vijayan *et al.*, 2021).

differences when compared with G3, G4, and G5, further highlighting the insufficiency of a single layer in modifying the compressive response. Conversely, no significant differences were detected among G2, G3, G4, and G5, implying that compressive strength tends to stabilize beyond two layers of reinforcement. Overall, these findings confirm that multi-layer confinement provides a statistically significant enhancement in compressive strength, whereas the effect of the first layer remains negligible.

Table 1. Compressive strength of CCC reinforced e-glass/epoxy laminate composite skin

Var.	Compressive Strength (MPa)			Avr. (MPa)	Std. Dev
	Test 1	Test 2	Test 3		
CS	18.34	20.63	20.75	19.91	1.36
G1	18.18	16.23	20.42	18.28	2.09
G2	25.43	22.30	25.28	24.34	1.76
G3	29.43	26.76	23.53	26.58	2.96
G4	25.87	25.13	39.00	30.00	3.14
G5	27.94	28.67	34.72	30.44	3.72

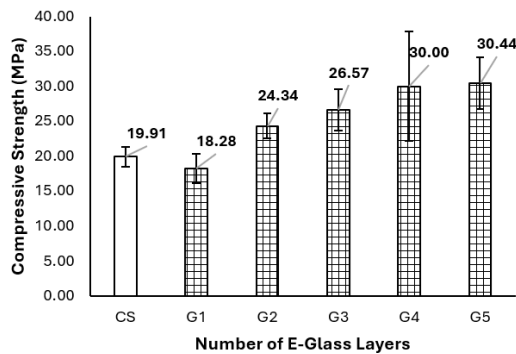


Figure 4. Compressive Strength performance of e-glass/epoxy laminate composite skin

Table 2 presents the results of the post-hoc analysis conducted using Tukey's HSD test. The analysis indicates that the compressive strength of the control specimen (CS) did not differ significantly from that of the single-layer E-glass specimen (G1), suggesting that a single layer of reinforcement does not yield a meaningful improvement. In contrast, significant differences were observed between CS and specimens wrapped with three, four, and five layers (G3, G4, and G5), demonstrating that the reinforcement effect becomes statistically evident only from the third layer onward. Similarly, G1 exhibited significant

Table 2. The post-hoc analysis using Tukey's HSD

Comparison	Mean Diff	p-adj	Signification ($\alpha=0.05$)
CS – G1	$\approx +1.63$	> 0.05	Insignificant
CS – G2	≈ -4.43	> 0.05	Insignificant
CS – G3	≈ -6.67	< 0.05	Significant
CS – G4	≈ -10.09	< 0.05	Significant
CS – G5	≈ -10.53	< 0.05	Significant
G1 – G2	≈ -6.06	> 0.05	Insignificant
G1 – G3	≈ -8.30	< 0.05	Significant
G1 – G4	≈ -11.72	< 0.05	Significant
G1 – G5	≈ -12.16	< 0.05	Significant
G2 – G3	≈ -2.24	> 0.05	Insignificant
G2 – G4	≈ -5.66	> 0.05	Insignificant
G2 – G5	≈ -6.10	> 0.05	Insignificant
G3 – G4	≈ -3.42	> 0.05	Insignificant
G3 – G5	≈ -3.86	> 0.05	Insignificant
G4 – G5	≈ -0.44	> 0.05	Insignificant

The examination of data validity involves conducting normality testing (Shapiro-Wilk test) and homogeneity of variance testing (Levene test). According to the Shapiro-Wilk normality test, the statistical value W was found to be 0.9599, indicating a good fit to the normal distribution. Additionally, the p-value obtained was 0.6909, which exceeds the threshold of 0.05. Therefore, it can be concluded that the data are normally distributed. Figure 5 shows the residual plot or Q-Q plot of the test data. Based on the graph, the residual points follow a normal straight line, indicating a normally distributed residual. Moreover, the Levene test for homogeneity of variance produced a p-value of 0.7989, which is also greater than 0.05. Consequently, it can be concluded that the variances in the compressive strength test results across different groups are homogeneous. The ANOVA findings in this study, which demonstrate statistically significant differences in compressive strength among groups of reinforced concrete columns, closely align with the methodological principles outlined by Ahmed (2024). Ahmed emphasized that the validity of ANOVA rests upon prior verification of data normality and homogeneity of variance, typically assessed using

the Shapiro - Wilk and Levene's tests. In this research, both assumptions were satisfied, thereby ensuring that the subsequent ANOVA results - indicating that multiple layers of E-glass/epoxy laminates significantly enhance compressive strength - reflect genuine treatment effects rather than statistical artifacts. Thus, the present findings exemplify Ahmed's assertion that rigorous application of inferential statistics allows researchers to draw valid and reliable conclusions from clinical or experimental data. (Ahmed, 2024). The ANOVA results in this study, which revealed significant differences in compressive strength among reinforced concrete column groups, are consistent with the methodological insights of (Nwobi and Akanno, 2021). They highlighted that ANOVA provides reliable outcomes when its fundamental assumptions - normality and homogeneity of variances - are satisfied, while violations may compromise statistical power compared to non-parametric alternatives such as the Kruskal-Wallis's test. In the present research, both assumptions were confirmed through Shapiro - Wilk and Levene's tests, thereby validating the use of ANOVA and ensuring that the observed significant effects reflect genuine structural improvements rather than assumption violations. (Nwobi and Akanno, 2021).

An ANOVA test was conducted to assess the impact of applying woven E-glass fibre layers on the improvement of CCC strength. The calculated statistical F value was 4.0569, surpassing the critical F value of 3.478, indicating a significant difference among the tested groups. Additionally, the obtained p-value was 0.0329, which is less than the threshold of 0.05. This signifies that the addition of woven E-glass fibre layers has a significant effect on enhancing the compressive strength of the CCC structure. The results of this analysis are consistent with the findings of Gustina *et al.* (2021), in which a one-way ANOVA revealed that variations in fibre orientation had a significant effect on impact strength ($p < 0.05$), thereby confirming the influence of structural configuration and the

number of layers on mechanical performance (Gustina *et al.*, 2021). These findings are further supported by the study conducted by Zulfikar *et al.* (2023a), which demonstrated that reinforcing cylindrical concrete columns with a hybrid laminated composite comprising jute fibre and E-glass markedly increased compressive strength by up to 150%. Statistical analyses confirmed these results by indicating significant differences among the various reinforcement groups (Zulfikar and Yaakob, 2023).

Figure 6 illustrates the damage patterns of cylindrical concrete column specimens reinforced with e-glass wrapping. The resulting crack patterns form acute angles smaller than 30 degrees, similar to those observed with jute wrapping. However, the application of e-glass wrapping demonstrates a remarkable capacity to withstand applied compressive loads, as evidenced by the intact E-glass sheets despite specimen damage, in contrast to the crack patterns in jute-wrapped specimens. Additionally, the concrete structure enveloped by E-glass wrapping exhibits less severe damage under compressive loads exceeding its capacity compared to those wrapped in jute. Thus, the application of e-glass wrapping shows excellent performance in protecting cylindrical concrete column specimens. These findings highlight the advantages of using e-glass wrapping as a reinforcement material for concrete structures. The findings in this study support the results of studies from several previous researchers who found that adding GFRP skin to concrete would increase its compressive strength performance by 20 to 30% compared to conventional ones (Sangeetha and Shanmugapriya, 2020; Wang *et al.*, 2022). E-glass wrapping not only enhances structural integrity but also offers superior resistance to compressive forces compared to traditional materials like jute. This research provides valuable insights into concrete reinforcement, emphasizing the potential of e-glass as a promising and effective alternative for improving the performance and durability of concrete columns under various load conditions.

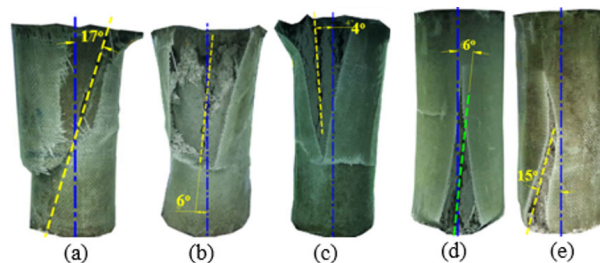


Figure 5. Specimen damage patterns due to compressive loads on variations in the E-glass layer (a) 1 layer, (b) 2 layers, (c) 3 layers, (d) 4 layers, (e) 5 layers

Figure 7 illustrates the results of the SEM testing at the interface between E-glass fibres and concrete under compressive load. The E-glass laminar structure remained intact and undamaged, with fibre damage primarily caused by shear forces slicing through the laminations parallel to the axis of compression. Additionally, the concrete structure exhibited significant damage, characterized by the emergence of relatively large voids. Consequently, there was a detachment of the bond between the laminations and concrete, as evidenced by the disengagement of fibre bonds from the concrete. This demonstrates that the E-glass laminar composite structure exhibits good resilience under compressive loading, as evidenced by a 52% increase in compressive strength compared to the control specimen and the preservation of intact laminar structures in SEM observations, even amidst substantial concrete damage. Therefore, E-glass laminar composites show significant potential for use as protective elements in concrete structures. These findings corroborate the study by Yang *et al.* (2022), which indicated that the interaction between flax/glass fibres and epoxy resin in strengthening concrete demonstrates good adhesion between the resin matrix and flax/glass fibres, thereby ensuring the effective mechanical performance of the composite (Yang *et al.*, 2021).

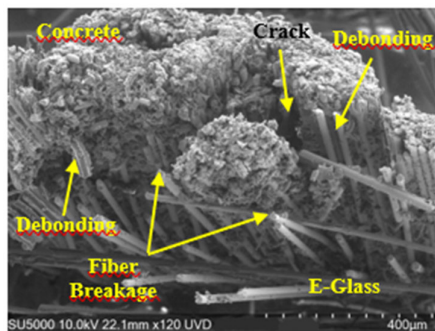


Figure 7. SEM images of e-glass and concrete under compressive load at 120 times magnification

The fundamental mechanism underlying the observed enhancement in compressive strength with increasing numbers of E-glass/epoxy laminate layers can be attributed to several synergistic effects. First, the laminates provide a confinement effect, whereby the external wrapping restricts the lateral expansion of the concrete core under axial loading. This confinement delays the initiation and propagation of microcracks, thereby increasing the

load-bearing capacity. Second, the presence of multiple laminate layers promotes a more uniform stress distribution along the concrete surface, minimizing localized stress concentrations that typically lead to premature failure. As the number of layers increases, the effectiveness of this stress redistribution becomes more pronounced, resulting in improved structural stability. Third, the interfacial bonding characteristics between the epoxy resin, E-glass fibres, and the concrete substrate play a critical role. Strong interfacial adhesion ensures efficient stress transfer across the composite - concrete interface, preventing early debonding and enhancing the synergistic performance of the composite system. The SEM observations in this study, which revealed intact laminar structures and minimal fibre damage under compressive stress, further substantiate this mechanism. Collectively, these principles explain why specimens with three or more layers demonstrated statistically significant strength improvements, while single - layer reinforcement proved insufficient to provide effective confinement or reliable stress transfer.

The study presents a significant advancement in the field of concrete reinforcement by demonstrating the efficacy of E-glass/epoxy composite laminates in enhancing the compressive strength of cylindrical concrete columns (CCC). The application of these laminates yielded a substantial improvement, with the highest recorded strength showing a 52% increase compared to the control specimen. This enhancement was particularly notable in specimens with five layers of E-glass, which achieved compressive strengths of up to 30.44 MPa. The study's findings align with previous research, confirming that E-glass fibres offer superior performance in structural reinforcement compared to traditional materials like jute. The normality and homogeneity of variance tests validate the robustness of the data, while ANOVA results indicate a statistically significant impact of E-glass layers on compressive strength. Additionally, the study highlights the superior damage resistance of E-glass laminates under load, as evidenced by SEM analysis, which showed minimal fibre damage and maintained structural integrity. This research underscores the potential of E-glass laminates as a viable and effective alternative for concrete reinforcement, providing enhanced durability and strength, thereby contributing valuable insights for future applications in structural engineering. The findings of this analysis are supported by similar tests conducted by Joseph *et al.* (2023b), in which the Shapiro-Wilk and Levene tests were employed to verify that the compressive strength data were

normally distributed and exhibited homogeneity of variance before conducting ANOVA. The ANOVA results indicated a significant effect of the number of laminate layers on the compressive strength of cylindrical concrete columns (CCC) (Joseph *et al.*, 2023). Additionally, these findings align with the experimental results reported by Zulfikar *et al.* (2024b), whose investigation of crack patterns in CCCs revealed that the application of four layers of E-glass/epoxy laminate produced minimal damage, suggesting that the material could withstand higher loads before failure. Scanning Electron Microscope (SEM) analysis further confirmed that fibre integrity was preserved even under elevated loading conditions (Zulfikar *et al.*, 2024a).

E-glass outperforms jute in this study due to its superior mechanical characteristics and interfacial behavior. E-glass fibres exhibit significantly higher tensile strength (2-3 GPa) and elastic modulus (~70 GPa) compared to jute (0.3-0.8 GPa strength; 10-30 GPa modulus). This large modulus mismatch enables E-glass laminates to provide more effective lateral confinement, delaying crack initiation and restraining dilation of the concrete core. Additionally, E-glass fibres demonstrate better chemical compatibility with epoxy, ensuring stronger interfacial bonding and more efficient stress transfer across the composite-concrete interface. By contrast, jute fibres are more hydrophilic and prone to moisture absorption, which compromises adhesion and accelerates degradation under stress. Collectively, these factors explain why E-glass laminates provide higher compressive strength gains, with up to a 52% improvement observed in this study, whereas jute-based reinforcement remains structurally limited.

The mechanism by which E-glass laminates delay crack propagation under axial loading can be explained through the combined effects of confinement, stress redistribution, and interfacial bonding. The E-glass/epoxy layers act as an external confinement system that restricts lateral dilation of the concrete core, thereby suppressing the initiation and growth of microcracks. This confinement mechanism aligns with the fracture mechanics principle that reducing lateral strain delays unstable crack propagation. Furthermore, the laminates facilitate a more uniform transfer of axial stresses along the concrete surface, minimizing localized stress concentrations that typically trigger brittle failure. The strong interfacial adhesion between the epoxy resin, E-glass fibres, and concrete substrate ensures efficient load transfer, preventing premature debonding and enhancing synergistic structural performance. Failure model observations support this mechanism: while the concrete core exhibited severe cracking and void

formation, the E-glass laminates largely retained their integrity, indicating that damage localized within the concrete was effectively bridged by the surrounding composite layers. SEM analysis confirmed that fibre breakage occurred mainly through shear along the laminar axis, demonstrating that the E-glass structure absorbed and redistributed stresses before catastrophic failure. Collectively, these mechanisms explain why multilayer confinement significantly improved compressive strength and delayed crack propagation, with up to a 52% increase observed in specimens wrapped with five layers.

The failure mode observed is mixed brittle-ductile. The concrete core undergoes brittle crushing with shear cracks, while the E-glass/epoxy jacket confines and introduces pseudo-ductile behavior. Intact laminates, shear-induced fibre damage, and localized interfacial debonding confirm brittle concrete failure mitigated by progressive load redistribution within the composite structure.

The stagnation of performance observed between specimens G4 and G5 can be attributed to several interacting factors. Beyond a critical thickness, additional laminate layers may not significantly enhance confinement because the concrete core is already effectively restrained, leading to a saturation effect. Moreover, the probability of local defects - such as micro - delamination or incomplete resin infiltration - increases with additional layers, potentially reducing the efficiency of stress transfer across the composite - concrete interface. Consequently, while multilayer wrapping substantially improves compressive strength up to a certain point, further reinforcement yields diminishing returns due to a balance between effective confinement and the onset of interfacial inefficiencies.

The remarkable resilience of the E-glass laminar composite structure under compressive loading, even in the presence of significant concrete damage, can be attributed to three synergistic mechanisms. First, the laminates provide an external confinement effect, which restricts the lateral dilation of the concrete core and delays the initiation and propagation of microcracks. This confinement enhances load-bearing capacity by suppressing brittle crushing. Second, the multilayer configuration redistributes axial stresses more uniformly across the concrete surface, reducing localized stress concentrations and preventing premature failure. Third, strong interfacial adhesion between the epoxy matrix, E-glass fibres, and concrete ensures efficient stress transfer, preventing early debonding and allowing the composite to bridge cracks that develop in the concrete substrate.

SEM observations in this study confirmed that the laminar structure remained largely intact, with fibre damage primarily limited to shear-induced breakage, while the concrete core exhibited severe voids and cracks. These findings demonstrate that the E-glass laminates not only sustain structural integrity under compressive loads but also introduce pseudo - ductile behavior by delaying catastrophic failure. Collectively, these mechanisms explain the observed 52% improvement in compressive strength and confirm the role of E-glass laminates as an effective confinement system in structural rehabilitation.

Conclusions

The research conclusively demonstrates that the application of E-glass/epoxy composite laminates significantly enhances the compressive strength of cylindrical concrete columns (CCC). The findings reveal that these laminates can increase concrete strength by up to 52%, with the highest performance achieved using five layers of E-glass. This improvement underscores the superiority of E-glass/epoxy laminates over traditional materials such as jute, particularly in terms of structural reinforcement under compressive loads. Statistical validation through the Shapiro-Wilk normality test, Levene test for homogeneity of variance, and ANOVA confirms the significance and reliability of these results. Furthermore, the analysis of damage patterns and SEM images indicates that E-glass laminates provide exceptional resilience and maintain structural integrity even under substantial compressive stress. These outcomes contribute valuable insights into the potential of advanced composite materials, such as E-glass/epoxy laminates, in enhancing the performance and durability of concrete structures. Therefore, this study not only advances the understanding of E-glass/epoxy laminates in concrete reinforcement but also paves the way for their broader application in structural engineering, promoting more durable and resilient concrete infrastructure.

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