



Enhancing Flexural Strength of Concrete Incorporating Natural and Recycled Brick Aggregates with Low-Cost Glass and Carbon Fiber-Reinforced Polymer

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Abstract

This study presents a comprehensive experimental investigation aiming at enhancing the flexural strength of plain concrete incorporating natural and recycled brick aggregates. Low-cost glass fiber-reinforced polymer (LoC-GFRP) sheets were employed for this purpose. An extensive experimental program involving 56 beams explored parameters such as compressive strength, type of confinement, presence of anchors, resin type, and quantity of confinement. Through a detailed analysis of 56 beams, several key findings emerged: (1) Anchorage systems were crucial for LoC-GFRP confined beams, with epoxy-based anchors proving insufficient to prevent premature debonding, indicating the need for further anchor optimization; (2) Lower plain concrete strength demonstrated a direct correlation with increased flexural strength improvement, notably achieving up to 326.32% enhancement with a 3-layer LoC-GFRP confinement; (3) Increasing the number of LoC-GFRP layers led to a consistent improvement in flexural strength for all coarse aggregate types, suggesting its efficacy in structural enhancement; (4) While carbon fiber reinforced plastics (CFRP) outperformed LoC-GFRP in flexural strength improvement, the latter demonstrated superior cost efficiency (*i.e.*, CFRP priced at 33% higher than LoC-GFRP) despite differences ranging from 19.18% to 121.23%; (5) The comparison of resin types highlighted the trade-offs between cost and performance, with epoxy-based resin showing delayed debonding and superior flexural strength improvements compared to polyester-based resin, despite the significant cost reduction potential of the latter (up to 93%).

Keywords: Low-cost confinement; Carbon fibers; Anchors; Recycled brick aggregates; Plain concrete.

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1. Introduction

Concrete is a predominant material in diverse construction applications such as buildings, roadways, bridges, and dams, boasting extensive utilization across numerous civil engineering endeavors annually. Nonetheless, the inherent brittleness exhibited by conventional concrete when subjected

to tensile stresses represents a notable drawback.^[1] Concrete finds extensive application in civil engineering construction due to its convenience and cost-effectiveness. However, its susceptibility to brittleness under tensile loading presents a significant disadvantage. This brittleness is attributed to the rapid propagation of a single crack, culminating in uncontrolled specimen failure. Such failure modes yield a low ultimate strain, typically around 0.01%, and sudden, unpredictable failure events.^[2]

Clay bricks are extensively utilized in building construction due to their affordability and widespread availability. As a result, a substantial amount of brick waste is generated annually. In China, approximately 15.5 million tons of construction waste, primarily consisting of concrete and bricks, is produced each year.^[3] As per the 2011 report from the European Union, nearly 1 billion tons of construction and demolition waste are generated within the European Union each year, with bricks constituting a significant portion of this waste stream.^[4] Considering this, clay brick aggregates are

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primarily used in the production of recycled aggregate concrete (RecBAC) to decrease their environmental impact.^[5] The use of RecBAC in structural applications, specifically in load-bearing components, is not presently preferred due to its lower compressive strength, ductility, and stiffness in comparison to natural aggregate concrete.^[6] The main characteristic distinguishing recycled aggregate from natural aggregates is their higher water absorption capacity. This increased porosity is due to the occurrence of adhered mortar, leading to approximately five to ten times greater water absorption compared to natural aggregates.^[7] Furthermore, RecBAC typically displays a 5-15% lower particle density compared to natural aggregate concrete. This difference is ascribed to the reduced density of mortar adhered to recycled aggregate.^[8]

A common tactic to address the inferior properties of concrete is to use external wrapping using various synthetic or natural fiber-reinforced polymer (FRP) sheets. While synthetic FRPs are currently dominant in the rehabilitation of structural members and enhancing the structural properties of reinforced concrete,^[9-15] their high costs remain a significant concern.^[5,16,17] Despite the ability of synthetic FRPs to enhance the properties of RecBAC,^[18-23] researchers have shifted towards cheaper alternatives to address the cost-related issues.^[24-29] The thermal resistance of RC strengthened by FRPs has also been explored.^[30-32] Additionally, the production process of natural FRPs involves substantially lower emissions of CO₂ and offers a relatively environmentally friendly solution. In the past, natural FRPs have successfully been deployed to enhance mechanical properties,^[33,34] flexural strength,^[35,36] and shear strength.^[37-39] While the utilization of locally available natural fiber-reinforced polymers has proven to be highly effective in enhancing the strength and ductility of concrete, their availability remains a challenge in numerous regions worldwide.^[40] Yoddumrong *et al.*^[41] proposed the utilization of low-cost glass fiber-reinforced polymer composites (LoC-GFRPs) for seismic strengthening of RC columns. These LoC-GFRPs are readily available commercially and commonly employed in the boat manufacturing industry. Developed primarily using bi-directional glass fiber sheets and cost-effective resin, the key attributes of LoC-GFRP include its affordability and satisfactory tensile strength. While the tensile strength of LoC-GFRP composite is approximately 350 MPa, conventional GFRP and CFRP composites exhibit tensile strengths of 2500 and 4000 MPa, respectively.^[42] Lam *et al.*^[43] investigated the effectiveness of combining LoC-GFRPs with mechanical anchors to enhance the shear resistance of deep RC beams.

Their findings indicated that the utilization of LoC-GFRP composite sheets alongside mechanical anchors resulted in increased load-carrying capacities and stiffness of the beams. In addition, LoC-GFRPs have successfully been utilized to enhance the mechanical properties of concrete,^[33] flexural enhancement of beams,^[44] and enhancing the performance of non-ductile bridge piers.^[45]

The existing literature indicates that all studies have focused on strengthening and reinforcing concrete members with LoC-GFRPs. However, no investigations have been conducted on the behavior of plain concrete beams. Exploring the suitability of such beams could extend their applicability to corrosion-prone environments and the repair of corroded reinforced concrete members. The objective of this study is to evaluate the effectiveness of LoC-GFRPs in improving the flexural strength of RecBAC. The study investigates the performance of LoC-GFRPs with and without epoxy-based anchors. Additionally, it compares the flexural enhancement provided by LoC-GFRPs to that achieved by carbon fiber-reinforced polymer (CFRP) sheets. Furthermore, three types of RecBAC are employed, including solid clay, hollow clay, and cement-clay interlocking bricks. The research involved an extensive experimental program with 56 beams, allowing for a robust analysis of various parameters, such as compressive strength, confinement types, and resin performance, which provides comprehensive insights into the effectiveness of LoC-GFRP. The study provides a detailed comparison of resin types, illustrating the trade-offs between cost and performance, which is vital for practical applications in construction.

2. Experimental program

2.1 Details of flexural specimens

The experimental program was designed to assess the effect of the type of external confinement (LoC-GFRP or CFRP), the number of confinement layers (1, 2, or 3 for LoC-GFRP), the type of epoxy (E1 and E2 for epoxy-based and polyester-based resins, respectively), the strength of concrete (two different strengths denoted by LS and HS for the lower and higher values), and the type of recycled bricks (solid clay bricks, hollow clay bricks, and cement-clay interlocking bricks denoted by CBA, CBB, and CBC, respectively). A comprehensive experimental program involving 56 flexural beams of plain concrete was prepared and categorized into four main groups, as shown in Table 1. The categorization was performed to differentiate the type of coarse aggregate. It is noted that specimens in Group 1 were prepared with natural coarse aggregates, whereas recycled brick aggregates of type CBA, CBB, and CBC were incorporated in Groups 2, 3, and 4, respectively, by replacing 50% of the natural coarse aggregates. In each group, two specimens for each concrete strength confined with a single LoC-GFRP layer were further reinforced by four epoxy-based anchors. The details of epoxy-based anchors are presented in subsequent sections. Generally, a four-part nomenclature was adopted to recognize the specimen type. The first, second, third, and fourth letters

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denoted the type of coarse aggregates, the concrete strength type, the type and quantity of external confinement, and the type of epoxy used to attach external confinement to the concrete substrate. For example, Specimen CBA-LS-1G-E2 was constructed by replacing 50% of the natural coarse

aggregates with recycled solid clay bricks with lower concrete strength and strengthened with a single LoC-GFRP layer by using type-2 epoxy. Further details of all specimens are summarized in Table 1. A schematic flow of the experimental framework is shown in Fig. 1.

Table 1: Details of all flexural beams.

c	Name of Specimen	Strengthening	Aggregate Type	Layer	Epoxy
1	NA-LS-CON	None	NA	None	None
	NA-LS-1G-E1	LoC-GFRP	NA	1	Type 1
	NA-LS-1G-E1-4EA	LoC-GFRP	NA	1	Type 1
	NA-LS-2G-E1	LoC-GFRP	NA	2	Type 1
	NA-LS-3G-E1	LoC-GFRP	NA	3	Type 1
	NA-LS-1G-E2	LoC-GFRP	NA	1	Type 2
	NA-LS-1C-E2	CFRP	NA	1	Type 2
	NA-HS-CON	None	NA	None	None
	NA-HS-1G-E1	LoC-GFRP	NA	1	Type 1
	NA-HS-1G-E1-4EA	LoC-GFRP	NA	1	Type 1
	NA-HS-2G-E1	LoC-GFRP	NA	2	Type 1
	NA-HS-3G-E1	LoC-GFRP	NA	3	Type 1
	NA-HS-1G-E2	LoC-GFRP	NA	1	Type 2
	NA-HS-1C-E2	CFRP	NA	1	Type 2
2	CBA-LS-CON	None	CBA	None	None
	CBA-LS-1G-E1	LoC-GFRP	CBA	1	Type 1
	CBA-LS-1G-E1-4EA	LoC-GFRP	CBA	1	Type 1
	CBA-LS-2G-E1	LoC-GFRP	CBA	2	Type 1
	CBA-LS-3G-E1	LoC-GFRP	CBA	3	Type 1
	CBA-LS-1G-E2	LoC-GFRP	CBA	1	Type 2
	CBA-LS-1C-E2	CFRP	CBA	1	Type 2
	CBA-HS-CON	None	CBA	None	None
	CBA-HS-1G-E1	LoC-GFRP	CBA	1	Type 1
	CBA-HS-1G-E1-4EA	LoC-GFRP	CBA	1	Type 1
	CBA-HS-2G-E1	LoC-GFRP	CBA	2	Type 1
	CBA-HS-3G-E1	LoC-GFRP	CBA	3	Type 1
	CBA-HS-1G-E2	LoC-GFRP	CBA	1	Type 2
	CBA-HS-1C-E2	CFRP	CBA	1	Type 2
3	CBB-LS-CON	None	CBB	None	None
	CBB-LS-1G-E1	LoC-GFRP	CBB	1	Type 1
	CBB-LS-1G-E1-4EA	LoC-GFRP	CBB	1	Type 1
	CBB-LS-2G-E1	LoC-GFRP	CBB	2	Type 1
	CBB-LS-3G-E1	LoC-GFRP	CBB	3	Type 1
	CBB-LS-1G-E2	LoC-GFRP	CBB	1	Type 2
	CBB-LS-1C-E2	CFRP	CBB	1	Type 2
	CBB-HS-CON	None	CBB	None	None
	CBB-HS-1G-E1	LoC-GFRP	CBB	1	Type 1
	CBB-HS-1G-E1-4EA	LoC-GFRP	CBB	1	Type 1
	CBB-HS-2G-E1	LoC-GFRP	CBB	2	Type 1
	CBB-HS-3G-E1	LoC-GFRP	CBB	3	Type 1
	CBB-HS-1G-E2	LoC-GFRP	CBB	1	Type 2
	CBB-HS-1C-E2	CFRP	CBB	1	Type 2
4	CBC-LS-CON	None	CBC	None	None
	CBC-LS-1G-E1	LoC-GFRP	CBC	1	Type 1
	CBC-LS-1G-E1-4EA	LoC-GFRP	CBC	1	Type 1

c	Name of Specimen	Strengthening	Aggregate Type	Layer	Epoxy
	CBC-LS-2G-E1	LoC-GFRP	CBC	2	Type 1
	CBC-LS-3G-E1	LoC-GFRP	CBC	3	Type 1
	CBC-LS-1G-E2	LoC-GFRP	CBC	1	Type 2
	CBC-LS-1C-E2	CFRP	CBC	1	Type 2
	CBC-HS-CON	None	CBC	None	None
	CBC-HS-1G-E1	LoC-GFRP	CBC	1	Type 1
	CBC-HS-1G-E1-4EA	LoC-GFRP	CBC	1	Type 1
	CBC-HS-2G-E1	LoC-GFRP	CBC	2	Type 1
	CBC-HS-3G-E1	LoC-GFRP	CBC	3	Type 1
	CBC-HS-1G-E2	LoC-GFRP	CBC	1	Type 2
	CBC-HS-1C-E2	CFRP	CBC	1	Type 2

2.2 Preparation and strengthening of beams

All beams were prepared by using wooden formworks. After a 28-day curing period, beams were removed from the formwork. The wet lay-up process was then adopted to strengthen the beams. Firstly, the concrete surface was epoxy-impregnated by using a hand brush, as shown in Fig. 2(a). The confinement layer was attached to the concrete surface and soaked in epoxy using a roller, as shown in Fig. 2(b). The same procedure was followed for CFRP and LoC-GFRP applications, and it was repeated when a beam was strengthened with numerous sheets.

Some beams were provided with additional strengthening by epoxy-based anchors. Sika-fix epoxy was utilized in conjunction with anchors. The drilling was performed after the application of LoC-GFRP sheets. The screws used were TFSDW-710-500 manufactured by Tora Hardware Thailand. The model of the screws was F7x1". A beam with additional screw support is shown in Fig. 3.

2.3 Material properties

Type I Portland cement was used in this study. Locally available river sand was used as the fine aggregate. The concrete mix proportions for both target strengths are presented in Table 2. ASTM E8/E8M-13 was followed to estimate the properties of LoC-GFRP and CFRP sheets.^[46] The estimated mechanical properties of both sheet types are

presented in Table 3. Typical CFRP and LoC-GFRP sheets are shown in Fig. 4. It is noteworthy that a unidirectional CFRP sheet was utilized with its fibers aligned along the longitudinal axis of the beam, whereas the fibers in LoC-GFRP are randomly oriented, as can be seen in Fig. 4(a). The recycled brick aggregates were acquired from locally available waste and ground to the required size. The maximum size of coarse aggregates was limited to 19 mm. The properties of bricks were estimated by following ASTM C140/C140M-22a.^[47]

Table 4 presents the estimated mechanical properties of all brick types. Fig. 5 shows the ground-recycled brick aggregates.

Table 2: Mix proportions of concrete.

Mix Ingredients kg/m ³	Low concrete strength (15 MPa)	Low concrete strength (35 MPa)
Cement	242	444
Fine aggregates	726	605
Coarse aggregates	605	504
Brick aggregates	605	504

Table 3: Mechanical properties of confinement sheets.

Composite type	Thickness (mm)	Tensile strength (MPa)	Ultimate strain (%)	Elastic modulu (GPa)
CGSM	0.50	180	2.1	
CFRP	0.12	350	1.5	250

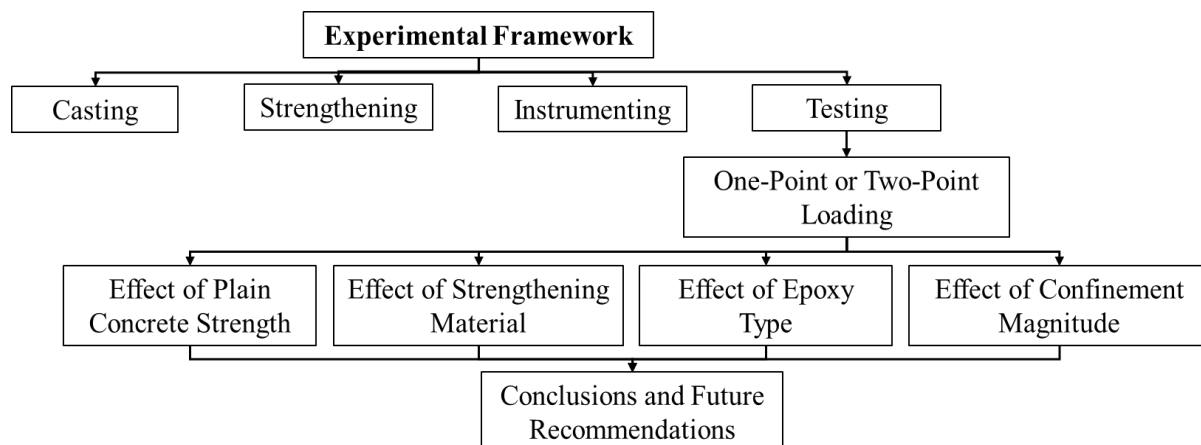


Fig. 1: Flow of the devised experimental framework.

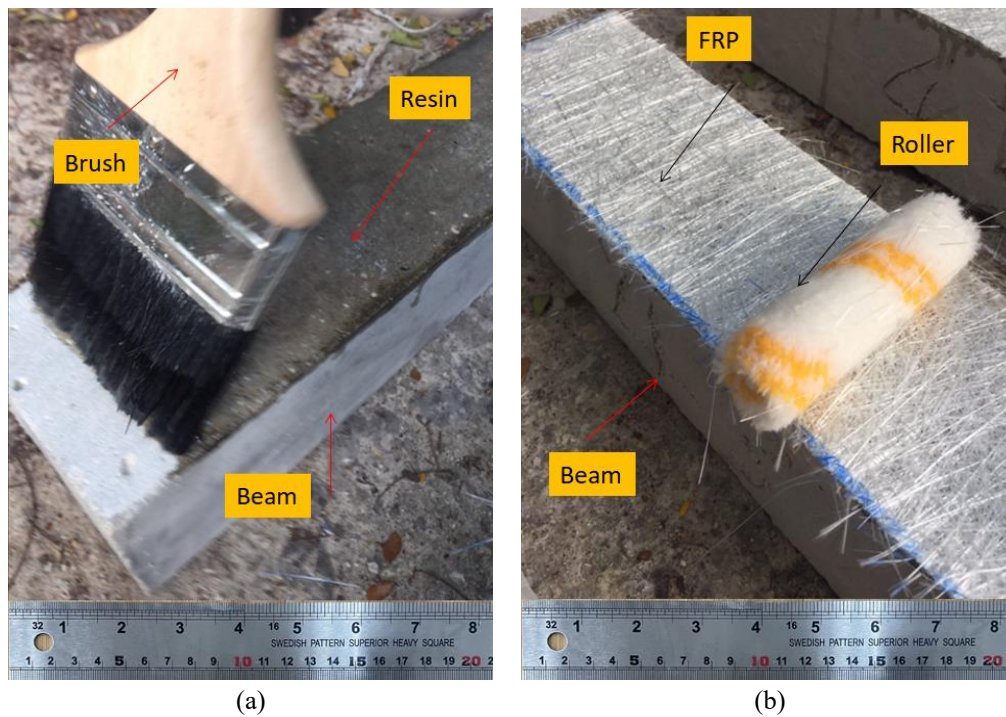


Fig. 2: Strengthening process: (a) the concrete surface is impregnated before the application of the confinement layer, and (b) the confinement layer is attached and soaked with the resin.



Fig. 3: Beam strengthened with LoC-GFRP with additional support from epoxy-based anchors.

2.4 Test setup

All beams were subjected to a four-point bending scheme, as shown in Fig. 6. A Universal Testing Machine with a 500 kN capacity was utilized to apply the load, whereas the intensity of the applied load was measured by using a load cell arranged

directly under the loading plate. A displacement transducer monitored the vertical deflection at each load interval at the midspan.

3. Experimental results

3.1 Failure modes

Fig. 7 shows typical failure modes of beams strengthened with LoC-GFRP confinement. It can be observed that the location of the flexural fracture was similar for both natural and RecBAC. The comparison is made in Fig. 7 for beams with and without epoxy-based anchors. It is vital to note that the

Table 4: Mechanical properties of recycled bricks.

Mechanical Properties	CBA	CBB	CBC
Density (kg/m ³)	120	140	145
Compressive Strength (MPa)	3.14	8.10	6.26
Water Absorption (%)	23.2	16.5	12.3

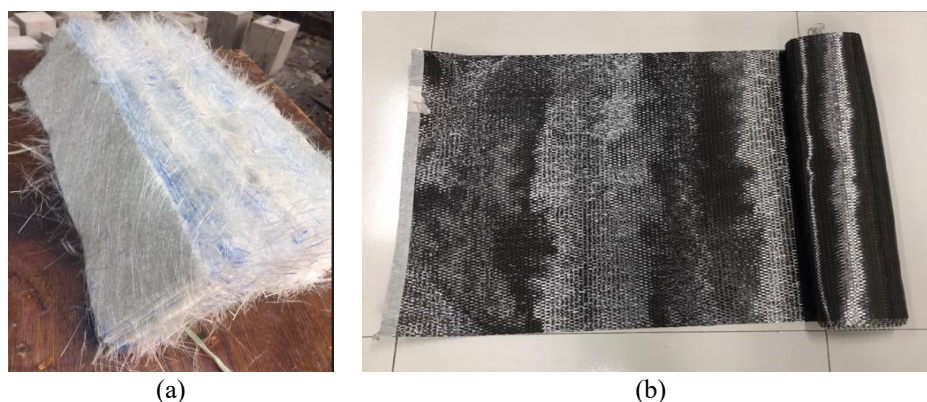


Fig. 4: Typical confinement sheets: (a) LoC-GFRP and (b) CFRP.



Fig. 5: Recycled brick aggregates originated from brick: (a) CBA, (b) CBB, and (c) CBC.

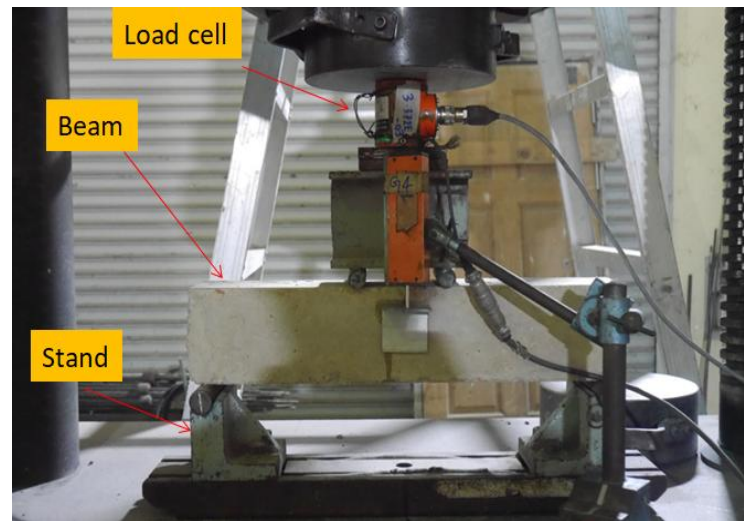


Fig. 6: The four-point bending test setup.

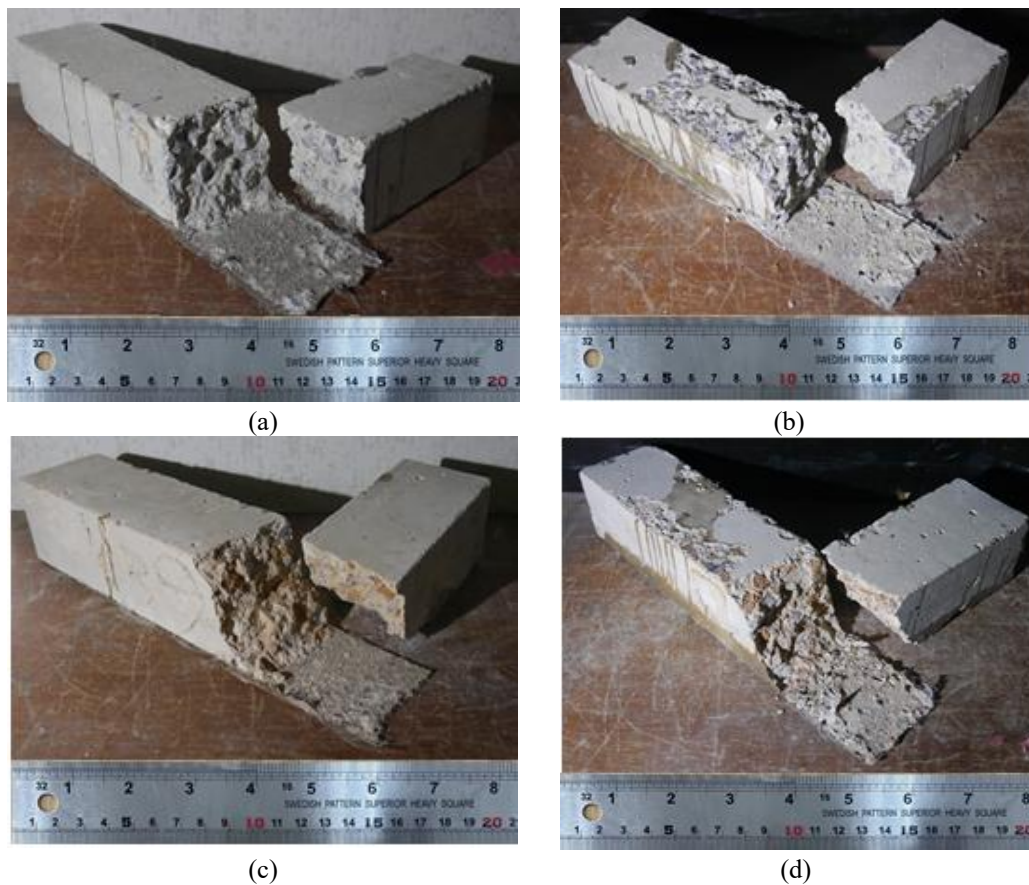


Fig. 7: Typical failure modes of beams strengthened with LoC-GFRP confinement: (a) NA-HS-1G-E1, (b) NA-HS-1G-E1-4EA, (c) CBA-LS-1G-E1 and (d) CBA-LS-1G-E1-4EA.

debonding of confinement accompanied the fracture of beams, highlighting that the current state of confinement could not achieve its full capacity due to premature debonding. Moreover, the provision of four epoxy-based anchors could not prevent the debonding mechanism, urging the need for a stronger anchorage system. Thus, it is recommended that this work be extended by employing several anchors in future studies. The confinement by CFRP sheet also demonstrated a similar failure, *i.e.*, the debonding of CFRP from the soffit in addition to the fracture of beams, as shown in Fig. 8.

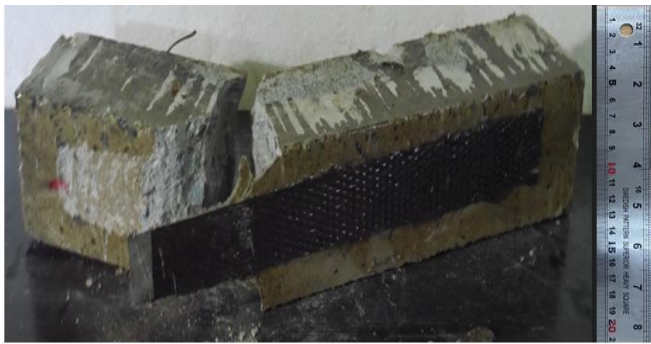


Fig. 8: Typical failure observed for CFRP-confined beams.

Importantly, the fracture of recycled brick aggregates was observed along the fracture plane, as highlighted in Fig. 9. On the contrary, the failure plane passed through the interfacial transition zone between natural coarse aggregates and mortar. Similar observations have been made by Liu *et al.*,^[48] where it is argued that the breakdown of natural aggregate concrete typically begins at the interfacial transition zone between the natural coarse aggregates (NCA) and mortar, identified as the weakest point in natural aggregate concrete. However, within the coarse aggregate skeleton system of concrete containing both natural and recycled brick aggregates, the recycled brick aggregates emerge as the weakest link. Integrating recycled brick aggregates into concrete can consequently trigger premature failure of the concrete, resulting in an anticipated reduction in mechanical properties. Liu *et al.*^[48] also reported similar results, suggesting that the fracture of recycled brick aggregates became prominent as soon as the replacement ratio surpassed 30%.

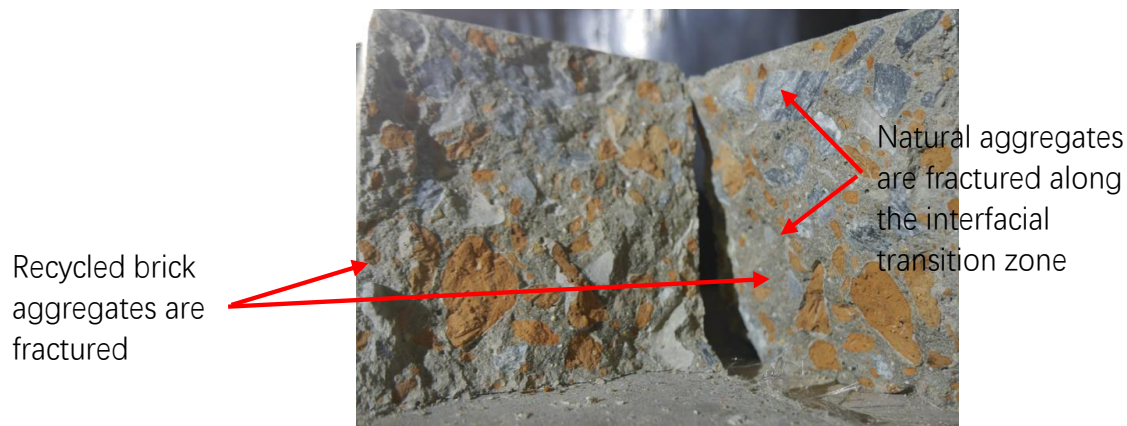


Fig. 9: Failure mechanisms of recycled brick and natural coarse aggregates.

3.2 Flexural strength of natural and RecBAC

The summary of flexural strength and the improvements corresponding to their respective control beams are presented in Table 5. This study considered numerous parameters to assess the performance of LoC-GFRP confinement. Therefore, the effect of each parameter needs to be discussed separately, as shown in the preceding sections. However, in general, the increase in flexural strength for both natural and RecBAC is evident in Table 5. The flexural strength increased by up to 283.79% and 127.81%, respectively, for lower and higher plain concrete strength specimens in Group 1. In Group 2 (*i.e.*, for specimens incorporating recycled brick aggregates originating from solid clay bricks), the same improvement was observed at 219.67% and 164.93%, respectively. Similarly, the maximum improvements in Groups 3 and 4 were 467.99% and 284.69%, respectively. The effects of the concrete strength, number of LoC-GFRP layers, confinement types, epoxy types, and type of brick aggregates are discussed in the following sections.

3.3 Effect of concrete strength

The effect of plain concrete strength on the improvement in flexural strength is graphically shown in Fig. 10. It is evident that a larger improvement was observed for the lower plain concrete strength. Apart from specimens 2G-E1 and 1G-E2 in Group 2, all beams demonstrated a larger flexural strength improvement when the plain concrete strength was low. Interestingly, this difference was largest in Group 3, which comprised beams constructed with 50% replacement of natural coarse aggregates with recycled brick aggregates sourced from hollow clay bricks. This difference was 174.01, 281.95, and 326.32% for 1, 2, and 3-layer LoC-GFRP confinement, respectively (for polyester resin), in Group 3. This means that the difference in the improvement increased as the number of LoC-GFRP layers increased. Furthermore, an analogous effect of compressive strength was observed in the case of CFRP confinement. It may be noted that the existing work by Yooprasertchai *et al.*^[49] reported no clear trend in the improvement of flexural strength by incorporating steel fibers into the concrete made by CBA, CBB, and CBC-type

Table 5: Summary of flexural strength and its improvement.

Specimen	Flexural Strength (kN)	Increase (%)	Specimen	Flexural Strength (kN)	Increase (%)
NA-LS-CON	0.45	-	CBA-LS-CON	0.47	-
NA-LS-1G-E1	0.78	74.55	CBA-LS-1G-E1	0.87	86.74
NA-LS-1G-E1-4EA	0.82	82.27	CBA-LS-1G-E1-4EA	0.94	100.00
NA-LS-2G-E1	1.19	165.67	CBA-LS-2G-E1	0.96	106.28
NA-LS-3G-E1	1.72	283.79	CBA-LS-3G-E1	1.49	219.67
NA-LS-1G-E2	1.31	192.32	CBA-LS-1G-E2	1.11	138.26
NA-LS-1C-E2	1.60	255.50	CBA-LS-1C-E2	1.21	157.44
NA-HS-CON	0.72	-	CBA-HS-CON	0.42	-
NA-HS-1G-E1	0.98	35.47	CBA-HS-1G-E1	0.72	72.12
NA-HS-1G-E1-4EA	1.01	40.19	CBA-HS-1G-E1-4EA	0.79	88.10
NA-HS-2G-E1	1.12	55.75	CBA-HS-2G-E1	1.17	179.19
NA-HS-3G-E1	1.64	127.81	CBA-HS-3G-E1	1.11	164.93
NA-HS-1G-E2	1.57	117.45	CBA-HS-1G-E2	1.18	182.76
NA-HS-1C-E2	2.20	205.56	CBA-HS-1C-E2	1.35	221.43
CBB-LS-CON	0.20	-	CBC-LS-CON	0.39	-
CBB-LS-1G-E1	0.67	233.90	CBC-LS-1G-E1	0.66	70.12
CBB-LS-1G-E1-4EA	0.74	270.10	CBC-LS-1G-E1-4EA	0.98	153.47
CBB-LS-2G-E1	0.92	362.26	CBC-LS-2G-E1	0.97	150.87
CBB-LS-3G-E1	1.14	467.99	CBC-LS-3G-E1	1.49	284.69
CBB-LS-1G-E2	0.95	375.10	CBC-LS-1G-E2	1.24	219.21
CBB-LS-1C-E2	1.11	455.10	CBC-LS-1C-E2	1.40	258.97
CBB-HS-CON	0.62	-	CBC-HS-CON	0.64	-
CBB-HS-1G-E1	0.78	27.03	CBC-HS-1G-E1	0.93	44.01
CBB-HS-1G-E1-4EA	0.90	46.39	CBC-HS-1G-E1-4EA	0.96	49.09
CBB-HS-2G-E1	1.11	80.31	CBC-HS-2G-E1	1.07	65.75
CBB-HS-3G-E1	1.49	141.67	CBC-HS-3G-E1	1.21	87.62
CBB-HS-1G-E2	1.66	169.45	CBC-HS-1G-E2	1.47	128.77
CBB-HS-1C-E2	2.00	222.58	CBC-HS-1C-E2	2.24	250.00

aggregates. Moreover, the maximum increase in flexural strength was limited to 50.26%, which is significantly lower than the improvements reported in the present study. The effect of unstrengthened concrete strength on the improvement in mechanical properties has also been reported to have an adverse effect, *i.e.*, the improvement in mechanical properties reduces as the strength of unstrengthened concrete increases.^[50,51]

3.4 Effect of LoC-GFRP Layers

The improvement in the flexural strength as a function of the number of LoC-GFRP layers is graphically depicted in Fig. 11. A larger improvement in the flexural strength was observed when the number of LoC-GFRP layers increased. This trend was consistent in all groups, *i.e.*, irrespective of the type of coarse aggregates. An outlier was observed in the case of high compressive strength specimens in Group 2, where the beam strengthened with a 2-layer LoC-GFRP confinement demonstrated a slightly greater improvement than the beam

with a 3-layer confinement. It is noteworthy that the improvement in flexural strength was not proportional to the number of LoC-GFRP layers. Nonetheless, greater flexural strength may be expected by increasing the number of LoC-GFRP layers.

3.5 Comparison between CFRP and LoC-GFRP confinement

A comparison of the improvement in flexural strength imparted by LoC-GFRP and CFRP confinements is provided in Fig. 12. For a given compressive strength, the efficiency of the CFRP was better than that of LoC-GFRP, and this was consistent in all groups. The minimum difference was observed in low compressive strength beams of Group 2, *i.e.*, 19.18%, whereas the maximum difference was observed in high compressive strength beams of Group 4, *i.e.*, 121.23%. It is noted that this comparison is made for 1-layer LoC-GFRP confined beams that utilized epoxy resin. It is mentioned that the cost of CFRP is approximately 100 USD per square meter

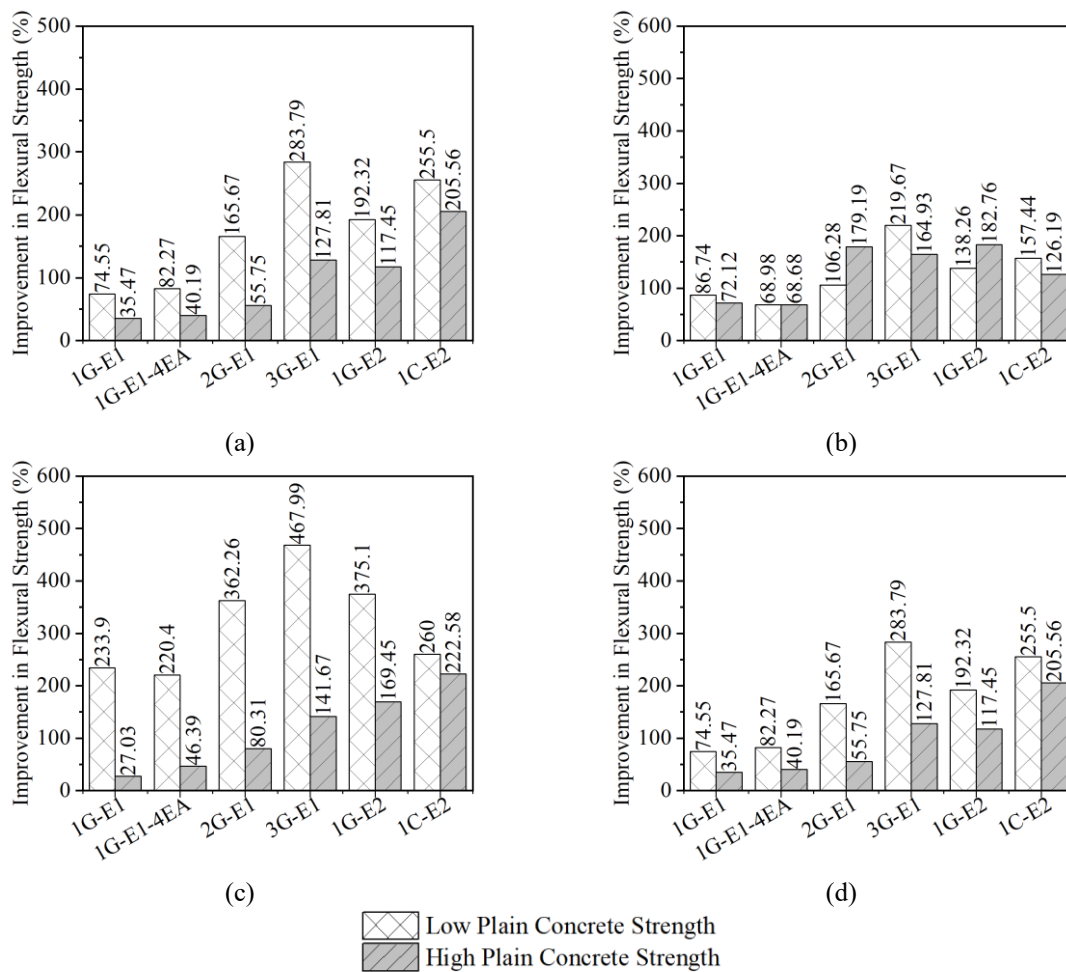


Fig. 10: Comparison of the improvement in flexural strength for low and high concrete strength beams in: (a) Group 1 (natural aggregates), (b) Group 2 (solid clay brick aggregates), (c) Group 3 (hollow clay brick aggregates), and (d) Group 4 (cement-clay interlocking brick aggregates).

per layer.^[41] On the contrary, the cost of LoC-GFRP is less than 3 USD, which is only 3% of the cost associated with CFRP confinement. Given this comparison, the authors believe that the efficiency of LoC-GFRP is better than that of CFRP. However, other factors, such as its resistance to corrosive environments and excessive heat, are still in question. Therefore, it is recommended that the durability of LoC-GFRP be assessed in future studies. Rodsin *et al.* ^[44] strengthened the shear performance of RC beams by strengthening them with LoC-GFRP and CFRP layers. The enhancement in shear capacity provided by CFRP was comparable to that imparted by LoC-GFRP.

3.6 Effect of the epoxy type

This study utilized polyester-based (E1) and epoxy-based resins to accompany the application of LoC-GFRP confinement. The cost of the resins E1 and E2 is approximately 100 THB and 1500 THB per kg, respectively. Thus, up to a 93% reduction in the cost is expected by utilizing the polyester-based resin. However, whether its efficiency matches that of an epoxy-based resin is discussed in this section. This comparison is made in Fig. 13 for specimens

strengthened with a single layer of LoC-GFRP in each group but utilizing different epoxies (*i.e.*, E1 or E2). Notably, beams that incorporated epoxy-based resin delayed the onset of debonding of LoC-GFRP. The least difference in flexural strength improvement was observed in low compressive strength beams of Group 2. Interestingly, this matches the findings reported on the effect of confinement type. The maximum difference was observed in Group 4 with low compressive strength beams, reported at 149%. Despite the better performance of epoxy-based resin, its cost might limit its application.^[49]

3.7 Effect of anchors

This study assessed the efficiency of LoC-GFRP confinement with and without epoxy-based anchors. However, this comparison was made only for a single LoC-GFRP confinement, as graphically shown in Fig. 14 for all groups. Notably, beams with additional support from anchors demonstrated greater flexural strength improvements in all groups. However, the application of four anchors could only delay the onset of debonding. It is believed that a better distribution of a larger number of anchors could have

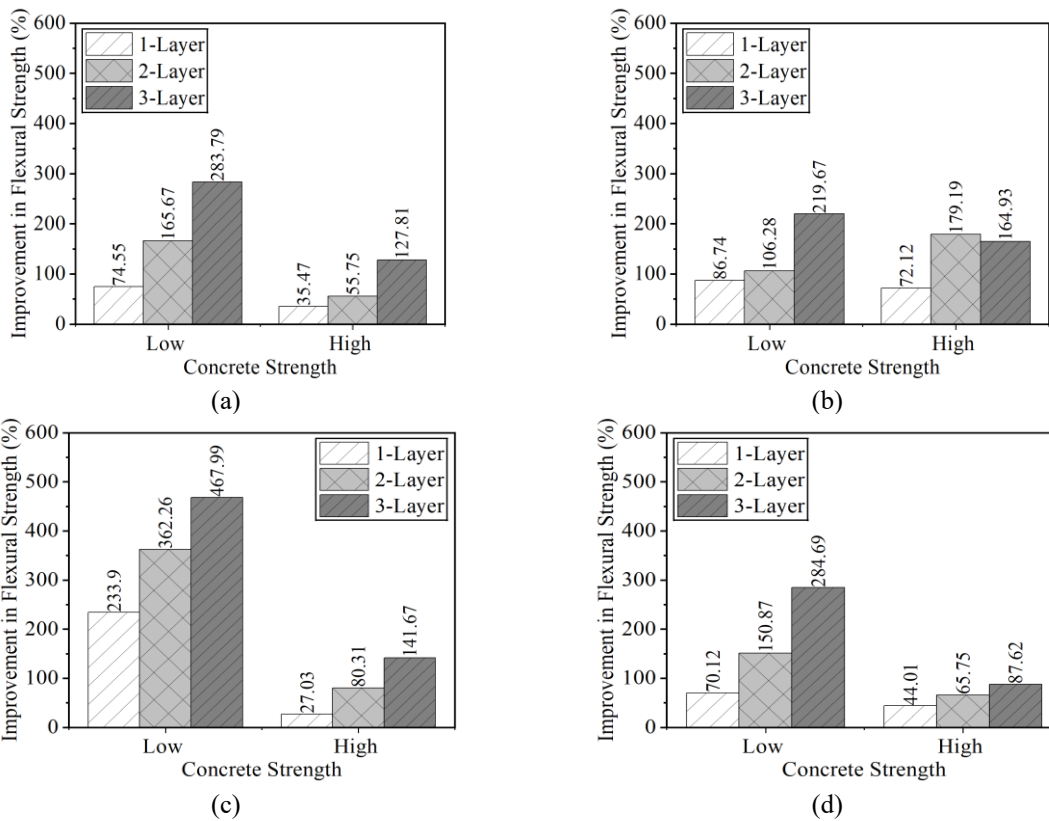


Fig. 11: Comparison of the improvement in flexural strength as a function of LoC-GFRP layers in: (a) Group 1 (natural aggregates), (b) Group 2 (solid clay brick aggregates), (c) Group 3 (hollow clay brick aggregates), and (d) Group 4 (cement-clay interlocking brick aggregates).

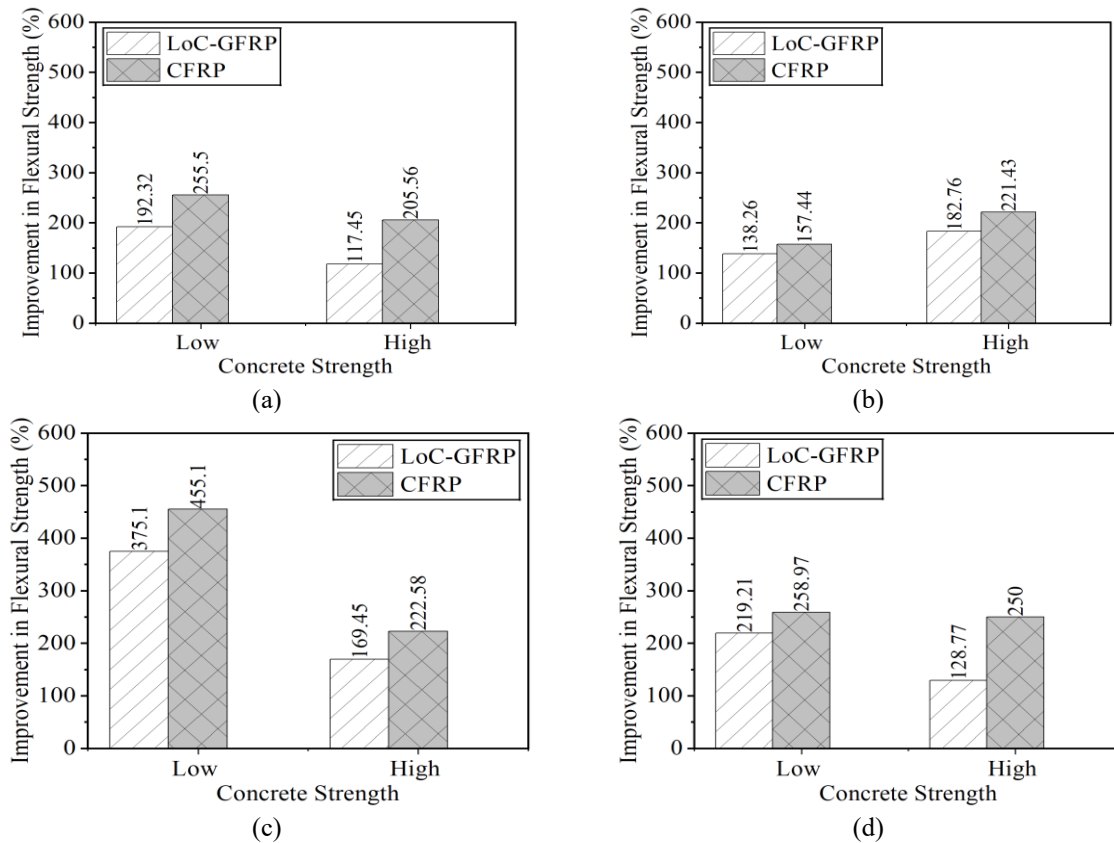


Fig. 12: Comparison of the improvement in flexural strength as a function of confinement type in: (a) Group 1 (natural aggregates), (b) Group 2 (solid clay brick aggregates), (c) Group 3 (hollow clay brick aggregates), and (d) Group 4 (cement-clay interlocking brick aggregates).

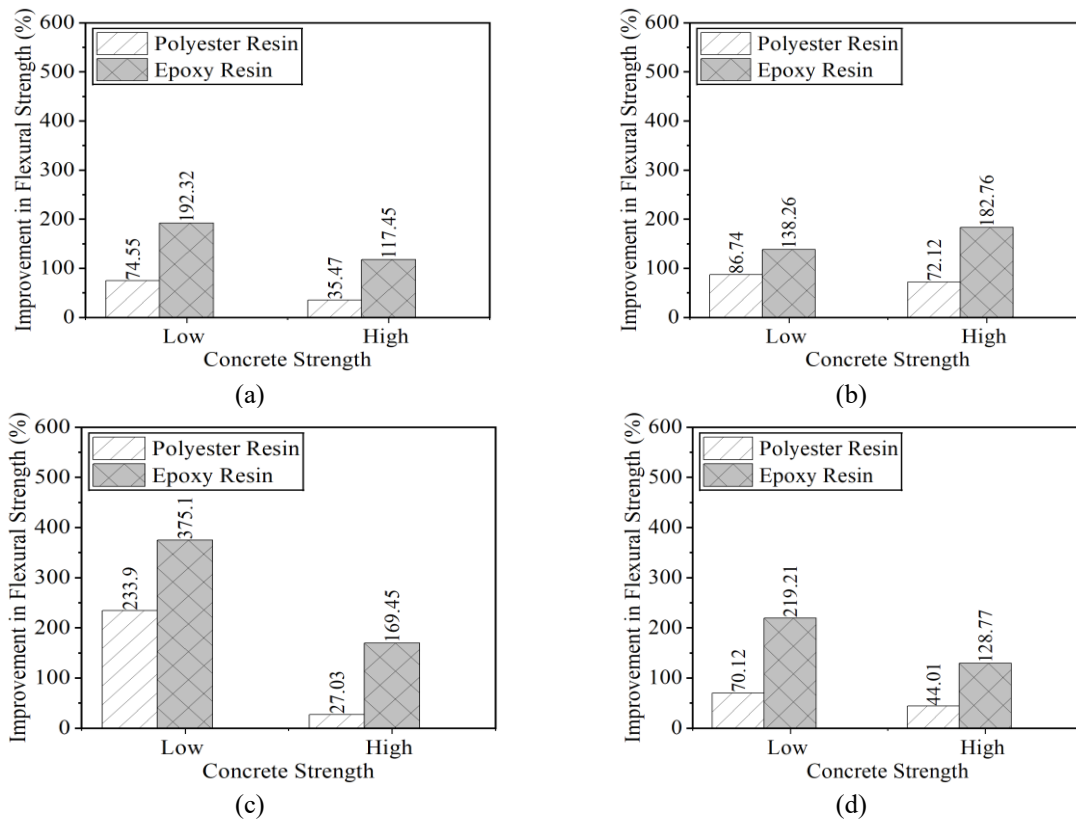


Fig. 13: Comparison of the improvement in flexural strength as a function of resin type in: (a) Group 1 (natural aggregates), (b) Group 2 (solid clay brick aggregates), (c) Group 3 (hollow clay brick aggregates), and (d) Group 4 (cement-clay interlocking brick aggregates).

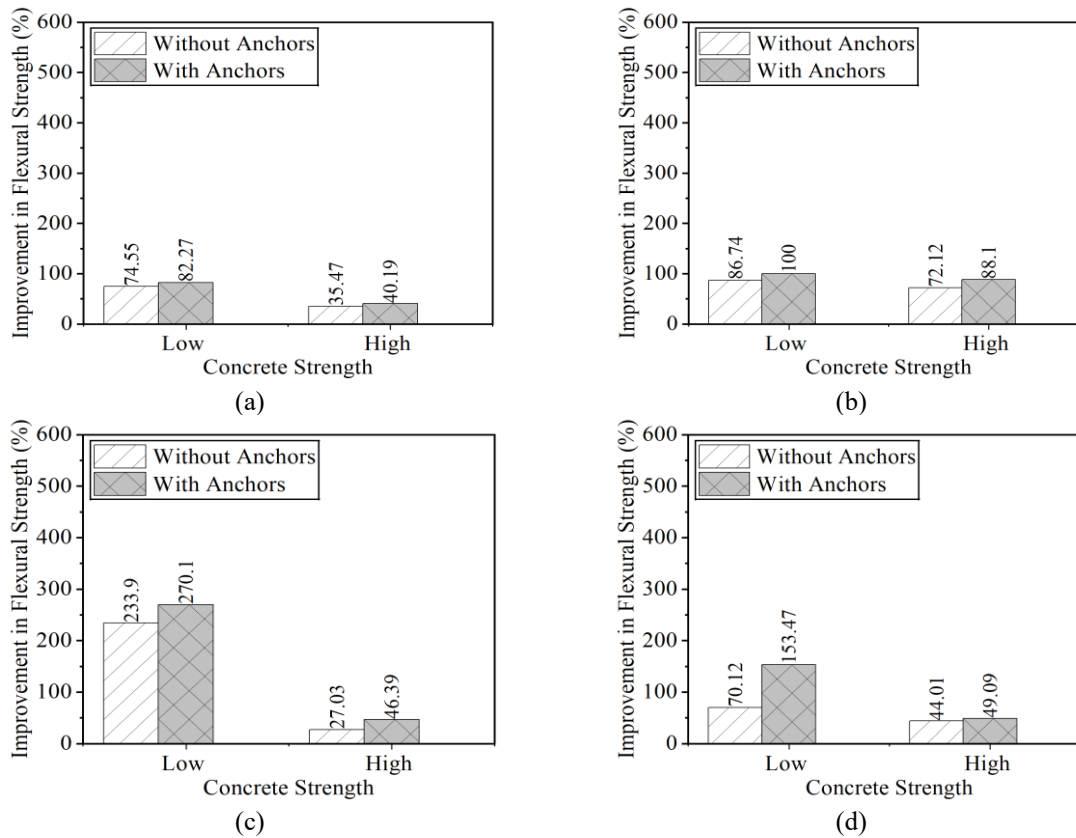


Fig. 14: Comparison of the improvement in flexural strength by LoC-GFRP with and without anchors: (a) Group 1 (natural aggregates), (b) Group 2 (solid clay brick aggregates), (c) Group 3 (hollow clay brick aggregates), and (d) Group 4 (cement-clay interlocking brick aggregates).

delay the onset of debonding. It is believed that a better distribution of a larger number of anchors could have prevented the debonding of LoC-GFRP layers. This is an aspect that is recommended for future studies. However, other researchers also reported similar results.^[43,52,53]

4. Conclusion

This study aimed to enhance the flexural strength of plain concrete made with natural and recycled brick aggregates. A comprehensive experimental program involving 56 beams was conducted with parameters including the compressive strength, type of confinement, presence of anchors, type of resin, and the quantity of confinement. Based on experimental findings, the following conclusions are summarized.

1. The analysis of failure modes in beams with LoC-GFRP confinement highlights the critical role of anchorage systems in improving structural performance. Premature debonding persisted even with epoxy-based anchors, indicating the need for a stronger anchoring technique. Future studies should investigate increasing the number of anchors to address this issue. Similar failure patterns observed in CFRP sheet confinement and the identification of recycled brick aggregates as the weakest component emphasize the complexities of material integration. These findings stress the importance of carefully assessing the impact of recycled materials on mechanical properties to avoid potential performance reductions

2. The study demonstrates a clear link between lower plain concrete strength and greater flexural strength improvement, particularly in beams with recycled brick aggregates. In Group 3, with a 50% replacement of natural coarse aggregates, a 3-layer LoC-GFRP confinement using polyester resin achieved a 326.32% improvement. This highlights the superior performance of LoC-GFRP reinforcement compared to steel fibers in enhancing the flexural strength of RecBAC.

3. The experimental findings reveal a consistent trend: as the number of LoC-GFRP layers increases, there is a larger improvement in flexural strength across all groups, regardless of the type of coarse aggregates used. Overall results imply that increasing the number of LoC-GFRP layers could lead to greater enhancements in flexural strength.

4. The results show that CFRP consistently outperforms LoC-GFRP in flexural strength enhancement, with differences ranging from 19.18% to 121.23%. Despite CFRP being about 33 times more expensive, LoC-GFRP offers better cost efficiency. Further research is essential to assess LoC-GFRP's durability in corrosive environments and high temperatures, which are key factors for its structural application viability.

5. The study examined the efficiency of polyester-based (E1) and epoxy-based resins (E2) in LoC-GFRP confinement.

While E1 offers a cost reduction of up to 93% compared to E2, epoxy-based resin demonstrated delayed debonding of LoC-GFRP and greater flexural strength improvements. However, the higher cost of epoxy-based resin may limit its widespread application.

By improving the flexural strength of concrete through the use of low-cost glass fiber-reinforced polymer (LoC-GFRP), the study contributes to creating structures that can better withstand loads, environmental stresses, and potential impacts. Enhanced strength and durability are critical for resilience, especially in areas prone to natural disasters like earthquakes or severe weather. The study highlights the cost-effectiveness of LoC-GFRP compared to traditional materials like CFRP. Resilience in infrastructure often hinges on the ability to implement solutions that are both effective and economically viable, especially in developing regions or communities with limited budgets.

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Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

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