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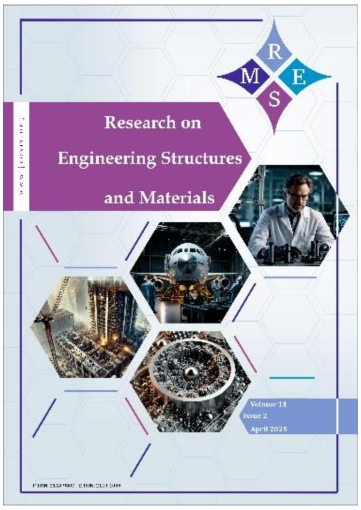

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Research Article

Enhancing mechanical properties of normal and lightweight concrete using ramie fiber-reinforced polymer

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Abstract

This study determines the mechanical properties of normal and lightweight concrete strengthened with ramie fiber-reinforced polymer (RFRP) as an eco-friendly external confinement material. This research examines the tensile strength and modulus of RFRP, as well as the compressive strength, flexural strength, failure modes, stress-strain and force-displacement behaviors of both unstrengthened and strengthened cylindrical and beam samples. Cylinder and beam samples of normal and lightweight concrete were produced and strengthened using RFRP in different configurations (center strip and full jacketing for cylinders and bottom lamination for beams). The RFRP composites with 33.28 ± 4.11 MPa of tensile strength and 1064 ± 91.85 MPa of Young's modulus were used as a strengthened material. The results showed that, compared with unconfined samples, full RFRP jacketing improved the compressive strength by up to 47.9% in normal concrete and 30.2% in lightweight concrete. The flexural strength increased by 8.6% in normal concrete and 25.3% in lightweight concrete. The failure mode shifted from brittle cracking to more ductile and controlled failure in the strengthened samples. The study revealed that fiber confinement improved strain capacity with minimal impact on density, however, the enhancement effect may plateau depending on fiber configuration and concrete type. These findings demonstrate that RFRP is a promising, sustainable solution for enhancing structural performance, particularly in lightweight concrete applications where the strength-to-weight ratio is essential.

1. Introduction

Lightweight concrete has long been utilized in construction due to its lighter weight and excellent thermal insulation properties. However, its lower mechanical properties, such as compressive strength, flexural strength, and elastic modulus, compared to conventional concrete pose challenges in its application for structural elements [1]. To address these limitations, various studies have been conducted on the use of natural fibers as reinforcing materials for concrete, such as jute, abaca, hemp, and cotton fibers. These fibers are not only environmentally friendly but also enhance the mechanical properties of concrete [2]. Bio-based fibers are recognized for their excellent tensile strength, high durability, and ecological properties, making them a promising alternative in the development of sustainable, high-performance composite concrete [3,4].

Lightweight concrete has the advantage of being lighter compared to normal concrete, which reduces structural and foundation costs in construction [5,6]. Nevertheless, it has inherent limitations compromising its performance in structural applications [7,8]. A promising solution involves employing natural fiber composites for strengthening concrete, which can not only increase its mechanical properties but also maintain its sustainability [9,10]. By bridging cracks

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and redistributing stress, natural fibers as external confinement significantly improves the strength, ductility, and durability of confined concrete.

Despite the success of strengthening systems by using synthetic materials, such as carbon fiber reinforced polymer (CFRP) [11], glass fiber-reinforced polymer (GFRP) [12], and aramid fiber-reinforced polymer (AFRP) [13], the current studies and investigations are turning toward for utilizing natural fibers as alternative of structural elements not only for strengthening existing elements but also for retrofitting utilization. Several previous studies have assessed the potential of natural fiber-reinforced polymer (NFRP) to enhance reinforced concrete elements such as columns [14,15], beams [16], and slabs [17].

The use of NFRP composites based on natural fibers like jute, sisal, hemp, abaca, or cotton for strengthening plain concrete to enhance its compressive and flexural strength has been confirmed in prior studies. Hussain et al. 2020 [18] reported that the use of NFRP composite based on hemp, cotton, and polyester fibers as a strengthened material could improve the ultimate strength, strain, and deformability of plain concrete. Furthermore, Sen and Paun 2015 [19] highlighted that there is a positive impact of NFRP based on sisal and jute fibers on the strength and modulus elasticity of the cylinder's concrete, with 66% and 48% improvement by sisal- and jute-NFRPs, respectively. On the other hand, Jirawattanasoumkul et al. 2019 [20] reported that the compressive strength of concrete confined with NFRP increases up to 25%, 28%, and 42% by using hemp-, jute-, and cotton-NFRPs, respectively. These studies underscore the potential of natural fibers to enhance the mechanical limitations of plain concrete while promoting the sustainable environment needs.

The NFRP-confined concrete notably increased its compressive strength. For instance, a study conducted by Amalia et al. (2024) [21] reported that the compressive strength of concrete confined by NFRP-based abaca fiber increased by up to 37% compared with that of unconfined concrete. Furthermore, Pimanmas et al. 2019 [22] demonstrated that both circular and square concrete samples exhibited significantly increased strength and deformability when sisal fibers were used for NFRP confinement. In addition, Antonio and Silva 2025 [23] noted that the thickness and number of layers play crucial roles in enhancing the compressive strength. Although extensive research highlights the benefits of NFRP in improving the performance of normal concrete, several gaps persist in optimizing NFRP based on ramie fibers confined in lightweight concrete.

The tensile strength of the RFRP laminate is assessed. The compressive and flexural strength of both normal and lightweight concrete is determined for specimens strengthened by RFRP. The hypothesis driving this work is that the use of RFRP to strengthen normal and lightweight concrete can significantly increase its compressive and flexural strength. The novelty of this study lies in its focus on NFRP based on ramie fibers, an underexplored yet promising natural reinforcement. This work seeks to address critical gaps in the field of optimizing natural fiber, particularly ramie, by exploring its application in lightweight concrete.

2. Experimental Details

2.1. Materials

Portland pozzolan cement (PPC) was utilized in this research as the primary binder material. The PPC is manufactured by grinding Portland cement clinker, gypsum, and several inorganic materials, such as blast furnace slag, pozzolans, silicate compounds, and limestone, with the combined content of inorganic materials ranging from 6% to 35% of the total mass [23]. This type of hydraulic cement is commonly available on the Indonesian market. In this study, the cement had a specific gravity of 3.02, a specific surface area of 327 m^2/kg, initial and final setting time of ≥ 45 minutes and ≤ 7 days (Table 1). The fine aggregate, which has a specific gravity of 2.78, a fineness modulus of 2.40, and an absorption rate of 2.1%, was prepared in accordance with ASTM C33/C33M-23 [24]. Two types of coarse aggregates were used in this study, gravel and pumice aggregates, which were produced according to ASTM C127-15 [25]. Gravel aggregates, with a specific gravity of 2.89, a bulk density of 1785 kg/m^3, an absorption rate of 1.89%, a fineness modulus of 0.8, and a maximum size of 12.7 mm, were utilized to produce normal concretes. Pumice aggregates were used to produce lightweight concrete with a specific gravity of 1.10, a bulk density of 559 kg/m^3, an absorption rate of 35.4%, a fineness modulus of 0.7, and a maximum size of 10 mm. The physical properties of aggregates are shown in Table 2. The granulometry curves of the two kinds of aggregates are given in Fig. 1. The superplasticizers were added in the concrete mixture to improve workability and to reduce water content, which were compliant with ASTM C494/C494M-99a [26]. The materials used in this study to produce normal and lightweight concrete are shown in Fig. 2.

Table 1. Physical properties of PPC

Physical properties	Results
Specific gravity	3.02
Specific surface area, Blaine method (m^2/kg)	327
Initial setting time (minute)	≥ 45
Final setting time (hours)	≤ 7

Table 2. Physical properties of aggregates

Physical properties	Results		
	Sand	Gravel	Pumice
Specific gravity	2.78	2.89	1.10
Fineness modulus	2.40	0.80	0.70
Absorption (%)	2.1	1.89	35.4
Bulk density (kg/m^3)	1680	1785	559

In this study, the matrix of RFRP consisted of a two-component system comprising unsaturated polyester resin and hardener. The resin was manufactured by PT SHCP Indonesia with a density of approximately 1.10 g/cm^3. The methyl ethyl ketone peroxide was used as a hardener and was produced by the same manufacturer as the resin. The resin and hardener were mixed at a 50:1 weight ratio. The mixture had a pot life of approximately 30 minutes at room temperature. The woven ramie fiber fabric was utilized in this study, with a unit area weight of approximately 200 g/m^2. The average diameter of individual ramie fibers was about 160 to 200 µm (0.16 to 0.20 mm), varying in length from 40 to 200 mm. The single fiber tensile strength reported in the literature is 399.47 ± 178.74 MPa with a modulus of elasticity of 18.30 ± 7.88 GPa [27]. In the present study, the ramie fibers were used in their as-received condition without any chemical or surface pre-treatment.

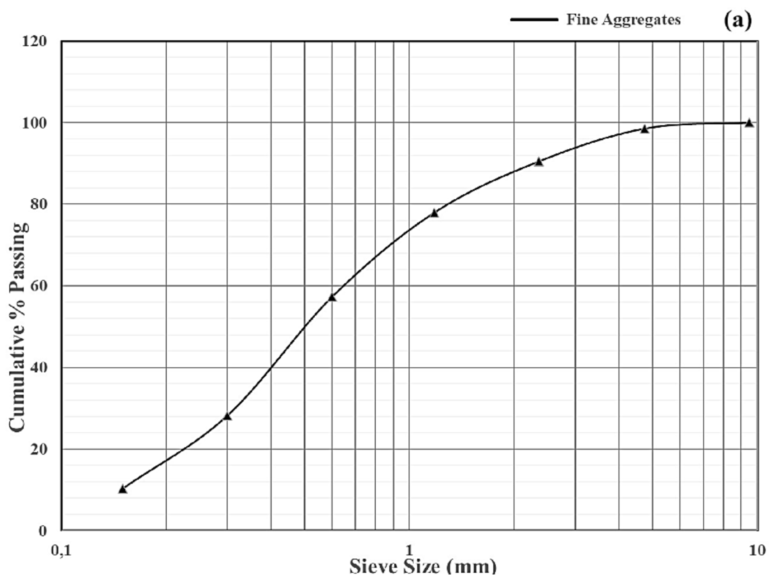

Fig. 1. Aggregate size distribution curves of (a) fine and (b) coarse aggregates

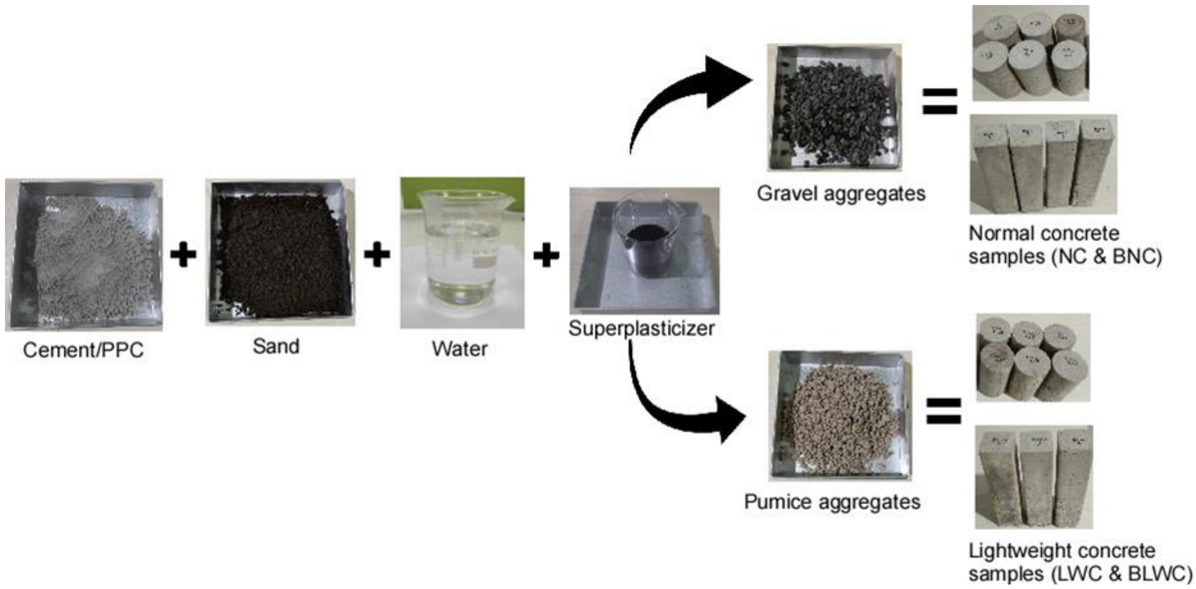

Fig. 2. Material mixes

2.2 Preparation of Samples

The RFRP coupon samples were prepared for conducting a tensile test by mixing polyester resin and hardener. The mixed resin and hardener were applied to the ramie fiber fabric utilizing the hand lay-up method to ensure proper impregnation of the fibers. After lay-up, the RFRP laminates were cured in an oven at a constant temperature of 50°C for 4 hours, and were then allowed to cure at ambient conditions for 2 hours to achieve sufficient cross-linking prior to the tensile test. Two formulations, normal concrete (NC) and lightweight concrete (LWC), were developed via the weight method in accordance with ACI PRC-211.1-22 [27] and ACI 211.2-98 [28], respectively. A suitable mixture of both the NC and LWC consists of 460 kg/m^3 of PPC, 648 kg/m^3 of fine aggregates, and 217 kg/m^3 of water. The W/C ratio and the superplasticizer were maintained at 0.46 and 1.5% by weight of the binder, respectively. The primary difference in the composition of the two types of concrete was in the use of coarse aggregates. The NC used gravel aggregates weighing 1038 kg/m^3, which was designed at a target density of 2300 kg/m^3 concrete. Moreover, the LWC utilized lightweight aggregates from pumice stone at 248 kg/m^3 with a target design density of 1600 kg/m^3 of lightweight concrete. Table 3 shows the mixed proportion details of the NC and LWC.

Table 3. Mixed proportions

Parameters	Mixes	
	NC	LWC
Target density (kg/m^3)	2300	1600
PPC (kg/m^3)	460	460
Water (kg/m^3)	217	217
W/C ratio	0.46	0.46
Fine aggregates (kg/m^3)	648	648
Gravel aggregates (kg/m^3)	1038	-
Pumice aggregates (kg/m^3)	-	248
Superplasticizer/SP (kg/m^3)	7	7

A total of 36 samples were produced, comprising plain cylindrical and beam of normal and lightweight concrete. The dimensions of the concrete samples were 55 × 110 mm (diameter × height) and 50 × 50 × 200 mm (width × depth × length) for the cylindrical and beam samples, respectively. Subsequent to the molding procedure, the samples were demolded and subjected to curing in a controlled environment at a consistent temperature of 23.0 ± 2.0 °C and a relative humidity of 95% for a duration of 28 days. The samples were prepared to be compatible for strengthening with RFRP after 28 days of curing. For the strengthened specimens, the surface of concrete was first roughened and cleaned to improve adhesion, followed by application of a thin primer coat of mixed resin. Additional mixed resin was spread, and the ramie fabric was placed by hand with longitudinal orientation, after a short dwell time of 2 minutes, ensuring uniform impregnation and removal of air voids using a roller. In this study, the mixed resin curing of the reinforced specimens was carried out in a drying oven for 4 hours at a constant temperature of 50^{o}C. The test programs are summarized in Table 4. The concrete samples were designated in such a way as to represent the research parameters. The cylindrical samples of the concrete control were labeled NC0 or LWC0. Cylindrical samples strengthened with RFRP strips were labeled NC1 or LWC1, whereas those with full jacketing strengthening were labeled NC2 or LWC2. For the beam samples, the concrete control samples were labeled BNC0 or BLWC0. The beams strengthened with one or two layers of RFRP laminates were designated BNC1 or BLWC1 and BNC2 or BLWC2, respectively, where BNC and BLWC refer to beam normal and lightweight concrete, respectively. The unstrengthened and strengthened concrete samples are shown in Fig. 3.

Table 4. Details of experimental tests

Specimen	Layers		Type	Number of specimens	Test
	Number	*Position*			
NC0	-	-	Cylinder	3	Compression
NC1	1	Center Strip	Cylinder	3	Compression
NC2	1	Full Jacketing	Cylinder	3	Compression
LWC0	-	-	Cylinder	3	Compression
LWC1	1	Center Strip	Cylinder	3	Compression
LWC2	1	Full Jacketing	Cylinder	3	Compression
BNC0	-	-	Beam	3	Third-Point bending
BNC1	1	Bottom Laminated	Beam	3	Third-Point bending
BNC2	2	Bottom Laminated	Beam	3	Third-Point bending
BLWC0	-	-	Beam	3	Third-Point bending
BLWC1	1	Bottom Laminated	Beam	3	Third-Point bending
BLWC2	2	Bottom Laminated	Beam	3	Third-Point bending

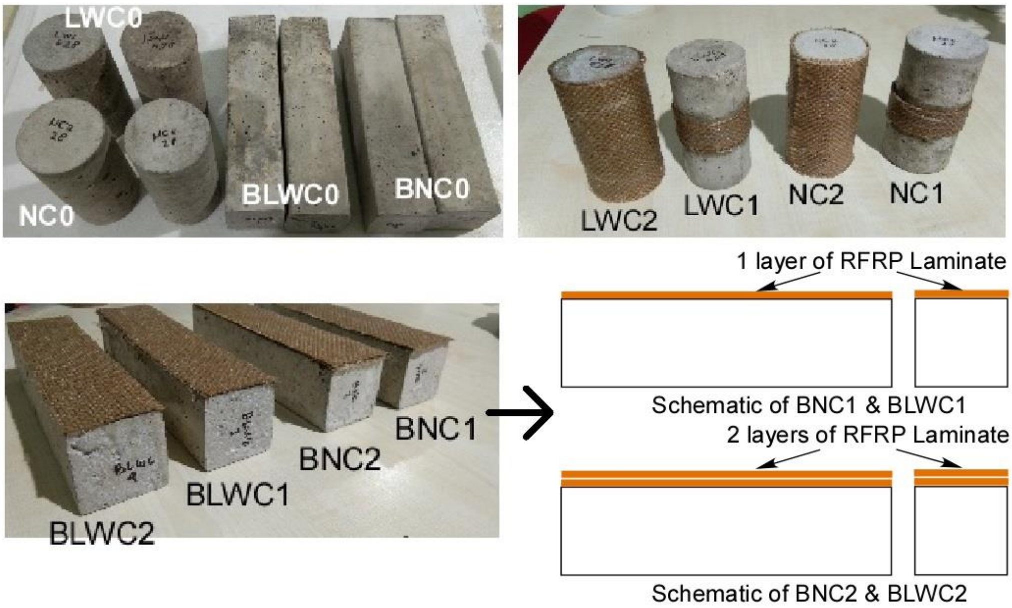

Fig. 3. Details of the unstrengthened and strengthened samples

The woven ramie natural fabric with a density of 1.52 g/cm^3 was used as a strengthened concrete combined with polyester resin as the RFRP. The average thickness of the one-layer RFRP composites was 1.65 mm. To obtain the mechanical properties of the RFRP composite, coupon samples with average widths and lengths of 15.0 mm and 150 mm, respectively, were prepared for tensile tests.

3. Experimental Methods

3.1 Ramie Composite Tensile Test

The RFRP coupon specimens, consisting of a single layer of ramie fiber fabric, had an average thickness of 1.65 mm, a width of 15 mm, and a length of 150 mm. Tensile tests of the RFRP composites were carried out using a 300 KN MTS electromechanical testing machine (Fig. 4a). The rate of pull was set at 0.1 mm/s for all sample tests. Five samples were subjected to these tensile tests, which were in compliance with ASTM D3039/D3039M-17 [29].

3.2 Compression Tests

Unstrengthened cylindrical samples of the NC and LWC samples were tested after 28 days of curing. For strengthened samples (center strips and full jacketing), compression tests were conducted after the curing of the mixed resin of RFRP was completed. In this study, the mixed resin curing of the reinforced or strengthened specimens was carried out in a drying oven at a constant temperature of 50^{o}C for 4 hours. Compression tests were conducted on all cylindrical samples via an MTS electromechanical testing machine in accordance with ASTM C39/C39M-23 [30]. The speed test of the testing machine was set at 0.5 mm/s during the compression test. Fig. 4b shows the compression test results for the cylindrical samples.

3.3 Third-Point Bending Tests

The beam specimens were tested with a span length of 170 mm. The same procedures were used with cylindrical samples for the drying process of strengthened beam samples in a drying oven. This third-point bending test, in accordance with ASTM C78/C78M-22 [31], was performed via an MTS electromechanical testing machine, and the speed test was set at 0.1 mm/s. Fig. 4c shows the third-point bending test of the sample beams.

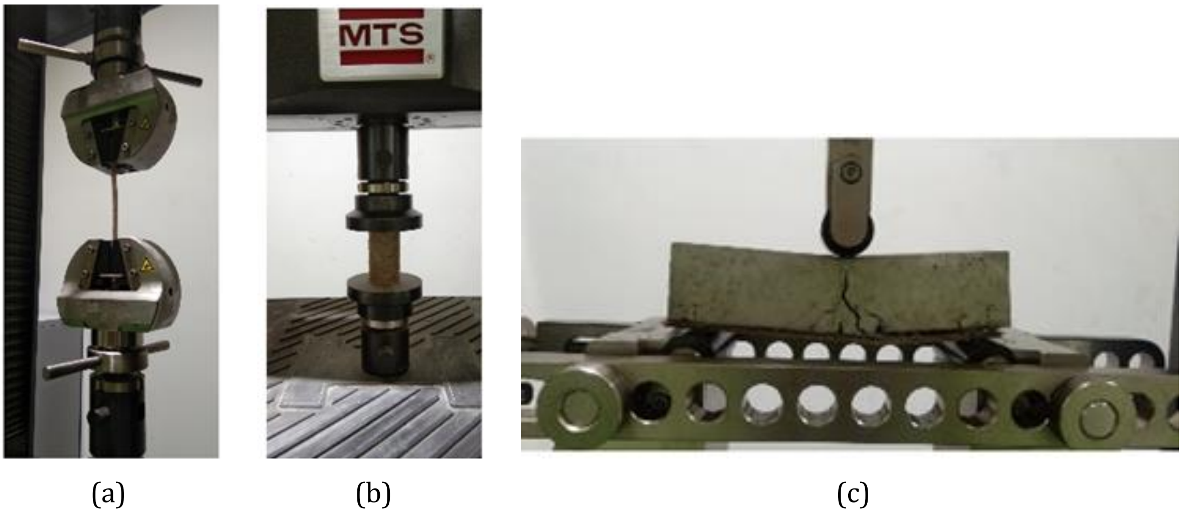

Fig. 4. Experimental setup (a) Tensile test of ramie composites, (b) Compression test of cylindrical samples, and (c) Third-point bending test of beam samples

4. Results and Discussion

4.1 Tensile tests of the RFRP composites

The tensile test of the RFRP composite revealed several key mechanical properties that sustained a maximum load of 851 ± 87.2 N, with a corresponding tensile stress at a maximum of 33.28 ± 4.11 MPa. The Young's modulus was determined to be 1064 ± 91.85 MPa, and the tensile strain at break was recorded as 0.043 ± 0.004, at which point the composite failed due to rupture. The effects of stress and strain on the RFRP composite are shown in Fig. 5. The stress-strain curve exhibited a linear region followed by a gradual nonlinear behavior (or deformation) and an abrupt rupture, indicating brittle fracture characteristics of fiber-matrix composites.

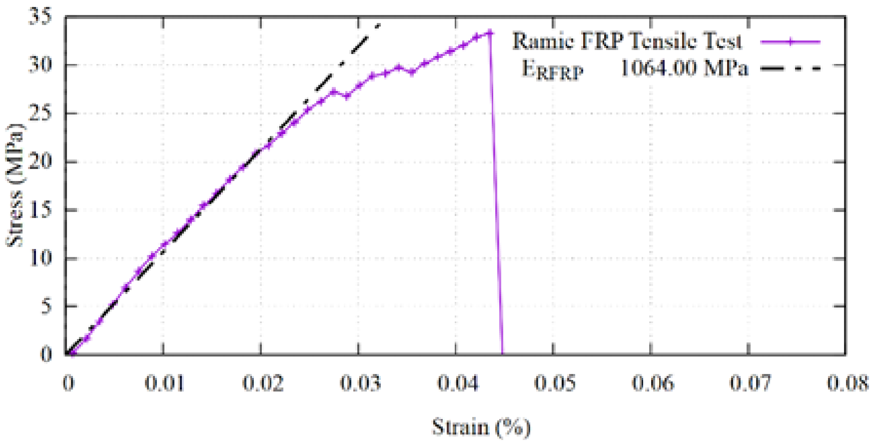

Fig. 5. Stress–strain curve of the RFRP composite

Fig. 6 shows the failure mode observed in the RFRP laminates. All the samples exhibited a characteristic failure pattern, with fractures occurring in the testing region rather than in the grasping area. The failure mechanism corresponds to the angular gauge middle (AGM) type, which originates a crack in a material's weak area, including a fractured fiber end or a matrix flaw [32]. The initial crack propagation in a particular direction is determined by the fiber orientation, the mechanical characteristics of the matrix, and the level of applied stress. If the crack propagates to a critical size, complete material failure will occur.

Fig. 6. Failure modes of RFRP under tensile test

4.2 Compressive Stress–Strain Curves and Strength

The stress–strain curves depicted in Fig. 7 provide a comprehensive understanding of the compressive behavior of the NC (Fig. 7a) and LWC (Fig. 7b) samples. The unstrengthened samples, NC0 and LWC0, exhibit the lowest peak stress and strain values, indicating limited compressive strength and ductility. Compared with the two strengthened samples, the NC0 sample exhibited a peak stress of 15.87 ± 1.20 MPa and a relatively brittle failure mode. The use of a one-layer center strip of RFRP (NC1) resulted in a slight increase in strength (16.96 ± 1.15 MPa) and an increased strain capacity of 28.52% compared to ultimate strain value of unconfined sample (NC0). The use of full jacketing of RFRP (NC2) significantly increased the strength and ultimate strain value, achieving a maximum compressive strength of 23.49 ± 0.85 MPa, which is a 48.02% increase over that of the NC0 sample in strength and an increased ultimate strain of 69.92% compared to NC0.

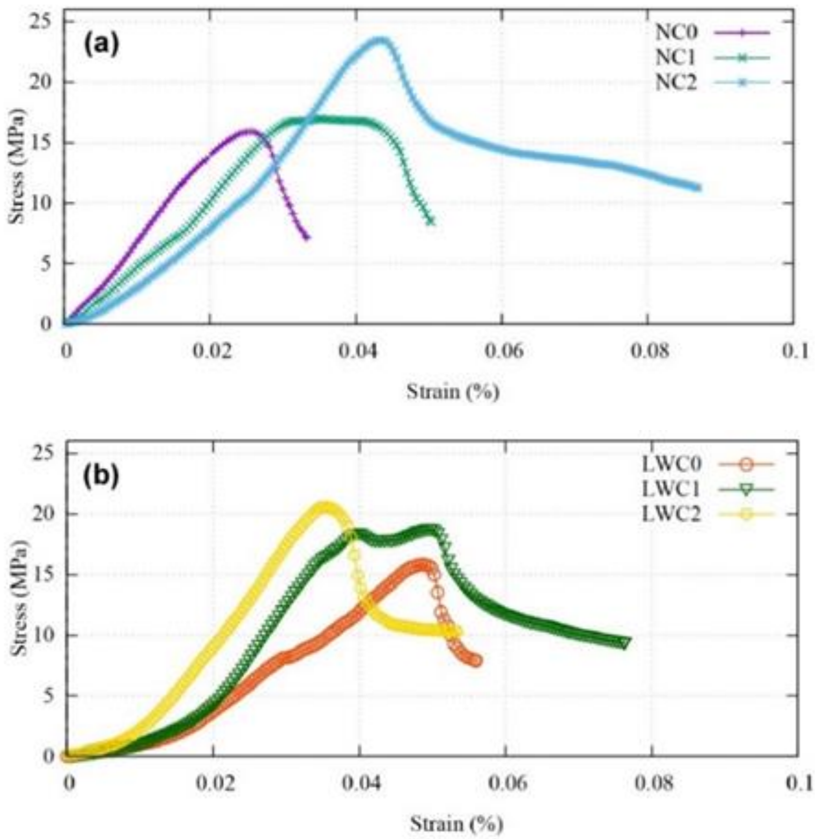

Fig. 7. Stress and strain curves in compression tests: a). normal, b). lightweight concrete

The superior performance of the full jacketing is attributed to more effective lateral expansion, and thus increases toughness. Likewise, the lightweight concrete samples (Fig. 7b) exhibited a consistent pattern. The unconfined sample (LWC0) exhibited a compressive strength of 15.85 ± 0.92 MPa. Following strengthening, LWC1 (center strip) increased to 18.43 ± 1.19 MPa, whereas

LWC2 (full jacketing) reached 20.63 ± 0.80 MPa, reflecting a 30.16% improvement in strength from the unconfined state. Fig. 8 visually confirms these findings by illustrating the relationship between the compressive strength and density across all the samples. Notably, while the normal concrete series had higher densities (~2200–2350 kg/m^3), the lightweight series remained at ~1700 kg/m^3, emphasizing the balance between strength gain and weight efficiency. These findings demonstrate that the use of ramie fibers, which are used for external jacketing in FRP systems, markedly improves the compressive performance of both normal and lightweight concrete. The results of this study are consistent with those of previous studies in which the compressive strength of concrete cylinders confined with NFRP increased by 28–42%, depending on the fiber type [20]. This encompasses not only an increase in the ultimate compressive strength but also significant increases in the strain capacity. This is particularly relevant for using lightweight concrete in structural applications, where the weight of the structure can be reduced without compromising its strength. The RFRP jacketing addresses these limitations by providing additional strength while maintaining structural integrity and offering an environmentally sustainable solution.

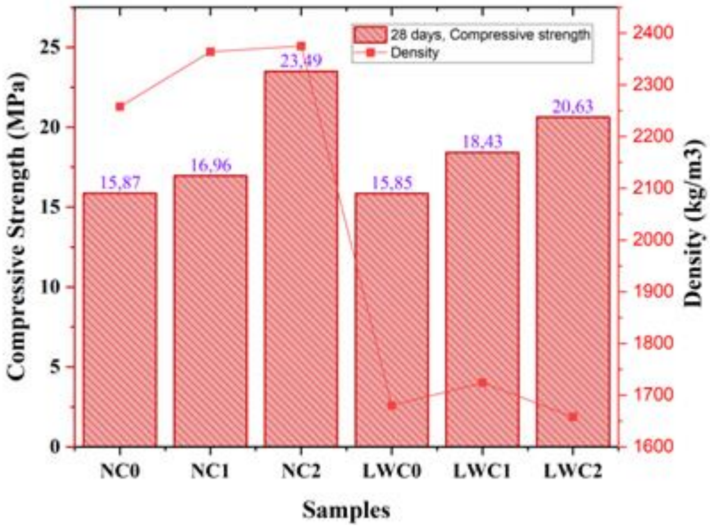

Fig. 8. Compressive strengths of the samples

4.3 Force vs Displacement Curves and Flexural Strength

The force and displacement responses of normal and lightweight concrete beams under third-point bending tests are shown in Fig. 9. The unstrengthened samples (BNC0 and BLWC0) exhibit brittle failure, characterized by abrupt load reductions and limited post-peak deformation, indicating low flexural strength, ductility, and capacity to absorb energy. One layer of RFRP on the BNC1 specimen provides moderate gains in peak force and displacement, while two layers on BNC2 yield the highest post peak force and substantial displacement increase. A similar trend is observed in lightweight concrete beams. The specimen with one layer of RFRP (BLWC1) shows moderate improvement, whereas two layers (BLWC2) significantly raise peak force capacity. The good performance of the two-layer of RFRP is attributed to improve stiffness, more effective crack bridging, and increased load distribution across the section. These findings also suggest that RFRP strengthened normal and lightweight concrete beams effectively inhibit crack propagation and sustain load-bearing capacity, as evidenced by an extended plateau in the post-peak region. This occurrence also indicates the role of fibers in sustaining load following matrix cracking.

Fig. 10 shows the flexural strengths of both the normal and lightweight beam samples in correlation with their densities. Compared with those of BNC2 and BNC0, the flexural strengths of the BNC samples increased from 3.85 ± 0.17 MPa (BNC0) to 4.14 ± 0.23 MPa (BNC1) and 4.18 ± 0.24 MPa (BNC2), corresponding to an increase of up to 8.6%. Due to its greater inherent stiffness and strength of normal concrete, the restricted supplementary effect of the RFRP and its flexural strength increased only slightly (8.6%). For lightweight beams, the flexural strength increased from 3.32 ± 0.15 MPa (BLWC0) to 4.12 ± 0.19 MPa (BLWC1) and 4.16 ± 0.32 MPa (BLWC2), indicating an increase of approximately 25% without a substantial increase in density. In addition to improving strength and ductility, it preserves the low density of lightweight concrete, as shown in Fig. 10. This behavior could be attributed to the increased bond compatibility, stiffness contrast between the fiber and matrix, and the ability of RFRP to bridge cracks more effectively in lightweight concrete under flexural loading. This feature is crucial for structural design in seismic regions, where low mass and high energy dissipation are desired.

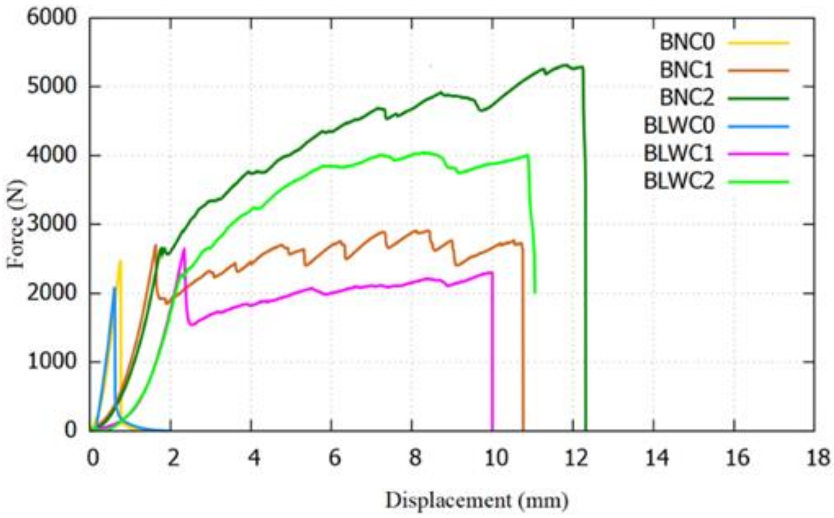

Fig. 9. Force vs. displacement curves of normal and lightweight concrete samples

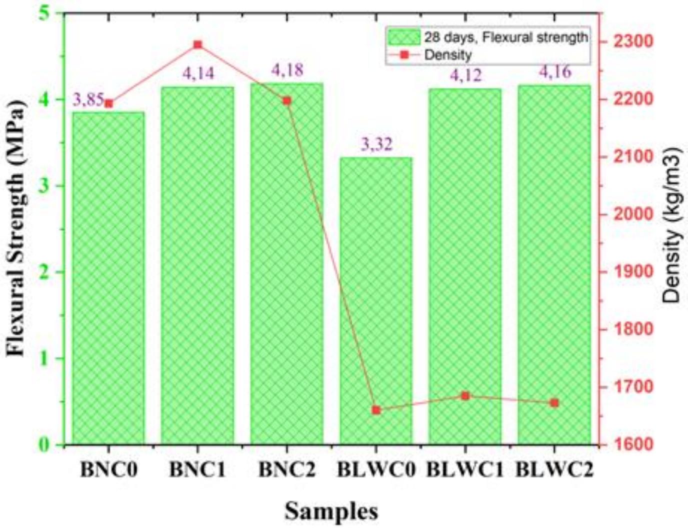

Fig. 10. Flexural strength of the samples

4.4 Failure Modes

The failure modes of the unconfined and RFRP-confined concrete cylinders in the NC and LWC series are illustrated in Fig. 11. The unconfined samples, NC0 and LWC0, displayed classic brittle failure, characterized by vertical cracking and crushing at the top edges. These cracks propagated rapidly after the peak load, confirming the typical brittle nature of plain concrete. In contrast, specimens with center strip RFRP confinement (NC1 and LWC1) exhibited partial crack control, characterized by vertical cracks, but less fragmentation and crushing at the top (NC1) and bottom (LWC1) edges. The RFPP strips around the midsection effectively delayed failure, particularly at the center of the samples, allowing them to retain their integrity longer under axial loading. The effect of RFRP was even more pronounced in specimens with full jacketing (NC2 and LWC2) confinement method. This method provided the greatest confinement, producing evenly distributed cracks and a more intact shape post-failure, suggesting enhanced strength and ductility.

Damage after the peak load was reached was observed in the overlapping RFRP section by debonding between confined layers. Overall, these findings align with previous studies, which have reported that natural fiber-confined concrete results in reduced crack width, produces more controlled failure patterns [20], and that full confinement restrains lateral expansion and delays crack propagation [22].

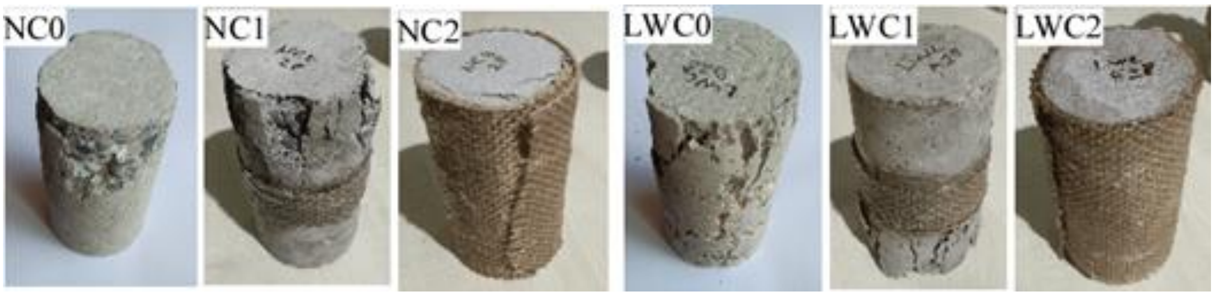

Fig. 11. Failure modes of unreinforced and strengthened NC and LWC cylinder samples

Fig. 12 shows the failure patterns of unstrengthened and RFRP-strengthened beams. The description of the beam failure modes is based on qualitative observations, as crack widths and propagation rates were not measured. The unstrengthened beams, BNC0 and BLWC0, exhibited a single crack at mid-span, typical of flexural failure under third-point loading. The cracks spread considerably through the depth of the beam, indicating brittle fracture of the samples. Compared with the unstrengthened samples, the single layers of the RFRP-strengthened samples (BNC1 and BLWC1) demonstrated more controlled cracking behavior. While major cracks still formed at the expected location, they appeared narrower and accompanied by distributed small cracks, especially at the RFRP-concrete interface. The presence of the RFRP laminate improved the load redistribution and crack-bridging capacity. In the concrete beams with two layers of RFRP (BNC2 and BLWC2), the failure modes were notably more constrained. The cracks were slightly narrower and more tortuous, indicating enhanced capacity and energy dissipation. On the other hand, the reduction in crack width and propagation confirms the effectiveness of multilayered fiber reinforcement in resisting tensile stresses. Previous investigations have documented these types of failure modes in natural FRP-strengthened concrete beams [3,33].

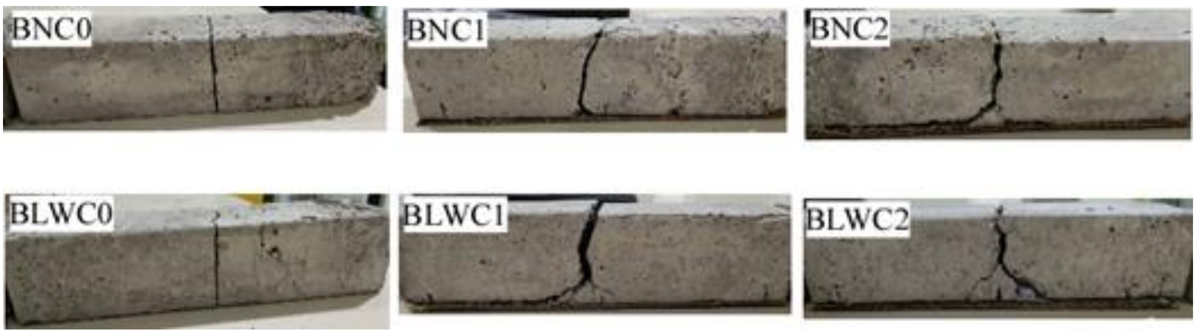

Fig. 12. Failure modes of the unstrengthened and strengthened beam samples

5. Conclusions

The mechanical of RFRP composite, normal and lightweight concrete strengthened with RFRP were investigated. The following conclusions were drawn in accordance with the experimental results:

- The tensile test of RFRP composite obtained several results such as 33.28 ± 4.11 MPa of tensile strength, 1064 ± 91.85 MPa of Young's modulus, and exhibited a characteristic failure pattern with fractures occurring in the testing rather than in the grasping area.
- The RFRP strengthening significantly enhanced both compressive and flexural performance. Compared with their unconfined counterparts, full jacketing with RFRP increased the compressive strength of cylindrical samples by up to 47.9% in normal concrete and 30.2% in lightweight concrete. The flexural strength of the beam samples

also increased, with BNC2 and BLWC2 exhibiting the greatest improvements of 8.6% and 25.3%, respectively.

- The stress–strain curves revealed that RFRP confinement increased both the peak stress and ultimate strain, particularly in the NC2 and LWC2 samples. Likewise, the load–displacement curves of the beam samples demonstrated increased load-bearing capacity and postpeak ductility with increasing layers of RFRP.
- Although the normal concrete samples exhibited greater overall strength due to greater density, the application of RFRP in lightweight concrete effectively closed the strength gap without significantly increasing the weight. This demonstrates the potential of the RFRP to decouple strength enhancement from density increase, making it highly advantageous for lightweight and sustainable construction.
- The failure mode shifted from brittle splitting or sudden crushing in the unconfined samples to more ductile and progressive response in the RFRP-confined samples. This behavior was reflected in the lengthened plateau region of the force-displacement curves, indicating enhanced energy absorption capacity. RFRP jacketing effectively bridged cracks and delayed their propagation, resulting in improved ultimate strain capacity and enhanced energy damping.
- The RFRP shows potential for retrofitting applications, particularly in normal and lightweight concrete, due to its ability to enhance strength and ductility. However, further studies are needed to address limitations associated with durability, long-term performance, and cost-effectiveness. Future research should investigate environmental exposure, economic feasibility, and full-scale structural applications to ensure its effectiveness for practical adoption in construction.

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