SUSTAINABLE LIGHTWEIGHT BRICKS WITH FLY ASH, RUBBER POWDER, AND GEOGRID REINFORCEMENT

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The construction sector contributes significantly to environmental degradation due to the extensive use of conventional building materials. Lightweight bricks offer a potential alternative; however, achieving both reduced weight and adequate mechanical performance remains a challenge. The substitution of sand with waste-derived materials provides a sustainable pathway. In this work, fly ash and rubber powder, both industrial by-products, were utilized as fine aggregate replacements in the production of lightweight bricks, combined with geogrid reinforcement to enhance their structural performance. Rubber powder was incorporated at 10%, 20%, and 30% by weight, while geogrid layers were applied in one to three layers. The physical and mechanical properties were evaluated through density, water absorption, macroscopic structure observation, compressive strength, and flexural strength tests. Increasing the rubber powder content effectively reduced the brick density, reaching a minimum of 0.68 g/cm^3 at a 30% replacement level. However, an increase in rubber content led to greater porosity and water absorption, resulting in a reduction in both compressive and flexural strength. Optimum mechanical performance was observed at 10% rubber powder, with compressive and flexural strengths of 2.41 MPa and 1.64 MPa , respectively. The introduction of geogrid reinforcement significantly improved the strength, with three layers achieving compressive and flexural strengths of 6.01 MPa and 3.48 MPa, respectively. The results indicate that combining fly ash, rubber waste, and geogrid reinforcement can effectively produce lightweight, sustainable bricks with enhanced structural performance.

Keywords: mechanical properties; lightweight bricks; fly ash; rubber powder; geogrid

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1. Introduction

The construction industry is one of the largest contributors to global greenhouse gas emissions, with the production processes of building materials, such as fired bricks, being a significant factor. Each kilogram of fired brick produced emits substantial amounts of carbon dioxide, soot, carbon monoxide, and particulate matter, in addition to consuming up to 3.14 J/kg of specific energy [1]. To mitigate these environmental impacts, efforts have focused on identifying alternative building materials that are both environmentally friendly and do not require energy-intensive firing processes [2].

Lightweight bricks (LWB) offer a promising solution for reducing natural resource consumption, carbon emissions, and energy use in the construction industry [3]. Their primary advantages include a lighter weight and larger size compared to conventional bricks, which facilitates faster installation. However, reliance on sand as the primary component in lightweight bricks poses challenges, including suboptimal weight reduction and ecological consequences of sand mining [4]. To address these issues, researchers have investigated the use of alternative materials, such as fly ash, and used rubber powder to replace sand [5, 6].

Fly ash (FA), a byproduct of coal combustion, is often stockpiled or disposed of in landfills, posing risks to air quality and the environment [7]. Its chemical composition, which includes silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), and iron oxide (Fe_2O_3), makes fly ash an ideal binder in mortar mixtures [8]. Similarly, waste rubber from used tires is a growing industrial waste product [9]. For instance, rubber tire production in Indonesia reached 193 million units in 2021, highlighting the increasing volume of scrap tires [10]. These waste materials are difficult to biodegrade, and incineration, a common disposal method, contributes significantly to air pollution [11]. The low specific gravity of waste tires makes them a suitable material for optimizing the weight of lightweight bricks. However, while reducing weight, the incorporation of rubber powder (RP) tends to diminish the mechanical properties of the bricks [12]. To address this limitation, the addition of reinforcements such as geogrids has been proposed as a potential solution.

Geogrids are geosynthetic products designed to reinforce soil and other construction materials. They are elongated polymer sheets with high mechanical strength and a rigid structure, making them ideal for construction applications. Typically made from polyvinyl or polyethylene, geogrids are also lighter than traditional metal reinforcements [13].

The integration of fly ash and rubber powder (RP) in lightweight brick manufacturing has demonstrated significant potential for reducing environmental impacts. Fly ash has been shown to produce bricks with low density while meeting compressive strength standards for non-structural applications. Additionally, incorporating low levels of RP (<10% by volume) has been reported to improve the impact resistance of lightweight bricks, despite a reduction in dynamic compressive strength due to its low density [14]. Geogrid reinforcement further enhances the mechanical properties of lightweight bricks, increasing compressive strength by 26% and flexural strength by 39%, while improving load capacity by up to 1.25 times [15].

Previous studies have evaluated the use of rubber powder in cementitious composites and demonstrated that geogrids can mitigate cracking in quasi-brittle materials. However, studies that simultaneously examine the effects of rubber powder substitution and the number of geogrid layers on the physical and mechanical properties of lightweight bricks are limited. Therefore, the relationship among density reduction, water absorption, and load-bearing capacity remains poorly established. This study addresses the gap by partially replacing fine aggregate with rubber powder and systematically adding geogrid layers to lightweight brick configurations. Performance was evaluated through density, water absorption, compressive strength, and flexural strength. Furthermore, the experimental results were correlated with failure patterns to elucidate the mechanisms of reinforcement.

2. Experimental setup

2.1. Materials

This research used Type 1 Portland composite cement from PT Indocement Tunggal Prakarsa and Class C fly ash, obtained from PLTU Tanjung Jati in Jepara, Central Java. The chemical additives included GF 1420 foaming agent, BESTONE 145 concrete hardener, and Polymax 1417 superplasticizer, all supplied by Ztabiler Chemical Concrete. Waste tire powder, specifically 40-mesh SBR (styrene-butadiene) filler, was procured from CV Kramed. Lightweight brick reinforcement was performed using a biaxial geogrid made of polypropylene (PP), sourced from CV Pasti Jaya, Yogyakarta. The complete geogrid specifications are shown in Table 1.

Table 1. Specifications of biaxial geogrid.

Minimum Carbon Black	2%
Ultimate Tensile Strength MD & TD	20kN/m
Peak Strain	13%
Load at 2% Strain	7kN/m
Load at 5% Strain	14kN/m
Aperture Dimensions MD	36 mm
Aperture Dimensions TD	38 mm
Minimum Rib Thickness	1,3 mm

2.2. Lightweight Bricks Preparation

Fine aggregates consisting of fly ash and waste rubber powder were prepared at replacement levels of 10%, 20%, and 30% by weight $(\mathrm{wt})(\mathrm{R}10, \mathrm{R}20$, and R30) and mixed with cement at a 1:1 ratio. In this mix design, rubber powder is added by partially replacing fly ash in the fine aggregate fraction. However, the total amount of fine aggregate (fly ash + rubber powder) is maintained constant in all mix variations. The foaming agent was diluted in a 1:40 ratio of material to water. The concrete hardener and polymer plasticizer were added at 0.5% and 1% by weight of the cement, respectively. The mixture was processed in a 3000 rpm mixer until a dense foam formed, as evidenced by its stability when lifted.

Once the solid foam was prepared, cement and fine aggregates were alternately added, stirred for 5 minutes, and mixed until a homogeneous mixture was achieved. The mixture was then poured into a lightweight brick mold

Table 2. Composition of Lightweight Bricks.

Sample	Material			
	Cement (%wt)	Fly ash (%wt)	Rubber Powder (%wt)	Geogrid
C0	50	50	-	-
R10	50	40	10	-
R20	50	30	20	-
R30	50	20	30	-
R10G1	50	40	10	1
R10G2	50	40	10	2
R10G3	50	40	10	3

measuring 400 mm × 200 mm × 100 mm, which had been pre-coated with a release agent to prevent adhesion. For reinforced specimens, geogrid sheets (400 mm × 100 mm) were installed horizontally within the mold in one, two, or threelayer configurations. A single layer was placed at the mid-thickness (50 mm from the top surface), two layers were placed near the top and bottom regions (25 mm and 75 mm from the top surface), and three layers were placed at the top, middle, and bottom positions (25 mm, 50 mm, and 75 mm from the top surface), resulting in a 25 mm spacing between adjacent layers in the three-layer configuration. After 24 hours, the lightweight bricks were removed from the mold and cured at room temperature for 28 days. The composition with the best mechanical properties was used for samples incorporating geogrid reinforcement. The variations in lightweight brick compositions, including those with rubber powder and reinforcement, are summarized in Table 2.

Characterization and Testing

The physical properties of lightweight bricks were characterized through density testing to determine their weight per unit volume, with variations in fine aggregate replacement using rubber powder. The surface porosity of the lightweight bricks was examined microscopically using an Olympus SZX7 Stereo Microscope. Water absorption was measured in accordance with SNI 8640:2018. Specimens were dried to a constant mass and weighed to obtain the dry mass (M_{dry}). The specimens were then immersed in water for 24 hours, removed, and surface-dried to eliminate free water before weighing to obtain the wet mass after immersion (M_{wet}). Water absorption was calculated as:

$$WA(\%) = \frac{M_{wet} - M_{dry}}{M_{dry}} \times 100\% \tag{1}$$

where WA is the water absorption percentage, M_{dry} is the dry mass, and M_{wet} is the mass after immersion.

Compressive strength tests were conducted in accordance with SNI 8640:2018. The compressive test samples, as shown in Fig. 1, were prepared with dimensions of 100 mm × 100mm × 100 mm, and five samples were tested for each variation. The tests were conducted using a SANS-SHT-4166 Universal Testing Machine (UTM) at a loading speed of 0.1MPa/s.

Fig. 1. Compressive strength test samples.

Flexural strength was evaluated using the three-point bending method in accordance with the SNI 03-2823-1992 standard. Three samples from each variation, measuring 240 mm × 80mm × 80 mm, were tested, as shown in Fig. 2. These tests were also conducted on the SANS-SHT-4166 UTM machine at a loading speed of 300 N/min.

Fig. 2. Flexural strength test samples.

3. Result in discussions

3.1. Density

The results of density testing of lightweight bricks with variation of rubber powder additions are shown in Fig. 3. The control sample (C0) has a density of $\mathbf{1.2\ g/cm^3}$, which decreases to 0.98 $\mathrm{g/cm^3}$ in sample **R10** with **10**% rubber powder. Furthermore, increasing the rubber powder content to **20**%(**R20**) resulted in a lower density of about $\mathbf{0.81\ g/cm^3}$. The decrease in density continued until it reached a stable value of 0.73 $\mathrm{g/cm^3}$ in sample R30, which had a 30% rubber powder content. This decrease in density indicates that rubber powder, which has lower density than sand, contributes significantly to the overall weight reduction of lightweight bricks [16]. Partial substitution of fine aggregate with rubber powder effectively produces lightweight bricks with lower density.

Fig. 3 also shows that porosity increases as density decreases, reaching 64.42%, indicating an inverse relationship between these parameters. This trend suggests that as density decreases, the void fraction in the cement matrix rises with increasing rubber content [17]. The results align with previous studies reporting that partially replacing fine mineral particles with crumb rubber can reduce density by up to **42**% under specific mixing conditions [18].

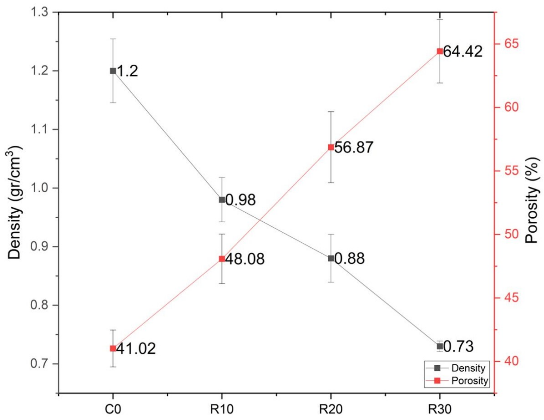


Fig. 3. Density of LWB with rubber powder variation.

3.2. Water Absorption

The results of the water absorption test, shown in Fig. 4, indicate that the water absorption value increases with increasing rubber powder weight percentage. The control sample had the lowest water absorption value of 11.13%. At 10% wt rubber powder replacement, the water absorption value increased to 14.22%, then increased to 15.65% at 20% wt replacement, and reached 17.46% at 30% wt replacement. These values are higher than those reported in a previous study, which found a water absorption of 9.60% with 10% wt rubber powder addition [19]. The enhancement is attributed to the higher air content in the concrete matrix, resulting from the formation of voids as the rubber powder content increases [20].

Poor interfacial adhesion allows the formation of more voids and large pores in the lightweight brick, thereby increasing its water absorption capacity while reducing its compressive and flexural strength [21]. The size of rubber particles also plays a significant role. Small particles are more effective in reducing water absorption because the filler effect is able to close the relative pores and reduce the thickness of the capillary wall [22]. In contrast, large particles trap water bubbles due to the non-polar effect, which increases water absorption [23].

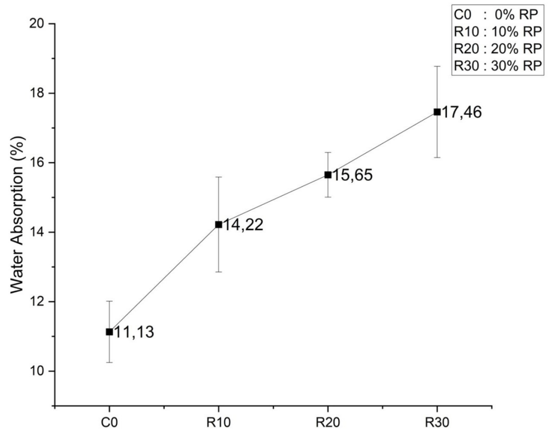


Fig. 4. Water absorption of LWB with rubber powder variation.

3.3. Macroscopic Observation

Figs. 5 and 6 present the macroscopic observations of the porosity structure in lightweight bricks with varying rubber powder content, the cement bond, and geogrid reinforcement. In the control sample (C0), pore sizes are relatively uniform, with diameters below 600μ m. An increase in pore size is observed in R10, while the largest and most irregular pores, reaching 1822.33μ m, are found in R30. The increase in pore size is due to weak interfacial bonds between rubber particles and the cement matrix, which promote the formation of voids in the lightweight brick structure. The phenomenon not only increases water absorption but also decreases density and mechanical strength, since mechanical strength is inversely proportional to porosity and directly proportional to density. The presence of porosity weakens the interfacial transition zone (ITZ) [24], thereby reducing the material's ability to withstand mechanical loads. Geogrid reinforcement exhibits good bonding, as indicated by the presence of cement paste that remains firmly attached to the geogrid surface. It indicates an effective mechanical locking between the cement matrix and the geogrid during hydration. The hollow surface of the geogrid allows the cement paste to fill and adhere to it, producing a strong interfacial transition zone (ITZ). The absence of interface separation further confirms the strong adhesion between the cement paste and the geogrid surface. These characteristics enhance the mechanical strength of geogrid-reinforced lightweight bricks, particularly in resisting flexural cracking and maintaining post-cracking structural integrity. It is consistent with the results obtained in the study [25, 26].

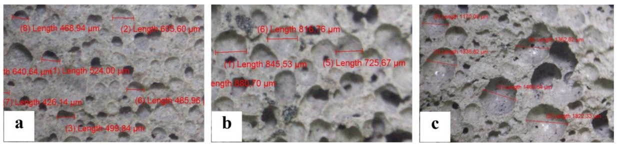


Fig. 5. Macroscopic observations of LWB with rubber powder variation: a) 0% wt, b) 10% wt, and c) 30% wt.

Furthermore, the high bond resistance provided by the geogrid ensures even stress distribution across the concrete, slowing crack propagation and increasing the material's post-cracking capacity. As a result, geogrid reinforcement significantly enhances the mechanical performance and durability of lightweight bricks, mitigating the adverse effects of increased porosity caused by the addition of rubber powder.

Fig. 6. Macroscopic observations of geogrid bonding.

3.4. Failure pattern

Observation of the compressive test failure (Fig. 7) reveals that the initial cracks in the lightweight bricks occur at the bottom, due to high compressive stress concentration. These cracks then developed to the center area, which became the focal point of stress concentration due to uneven load distribution. In the unreinforced sample (R10), sudden damage occurred in the center, which is the critical zone. In contrast, in the R10G3 sample, the cracks developed more slowly with a more even stress distribution at the center. The multiple crack pattern observed in R10G3 helps prevent sudden failure, indicating increased deformation capacity and overall durability of the material. The result is in line with the results of research conducted by Al-Hedad and Hadi [27].

In flexural strength failure, the initial crack starts at the lower center, the area of maximum tensile stress. As the load approaches its maximum, the behavior of the cracks shows striking differences. In sample R10, the crack propagated rapidly vertically, indicating a classic flexural failure mode due to the material's lack of cohesive bonding. In contrast, in sample R10G3, cracks developed more slowly and spread gradually, indicating that the geogrid evenly distributed stress throughout the material, slowing crack formation. As the load approached the maximum flexural capacity, the cracks remained concentrated around the center and slowly spread to the reinforcement area. No sudden collapse occurred because the geogrid provided additional structural support, which became more significant as the number of geogrid layers increased [25].

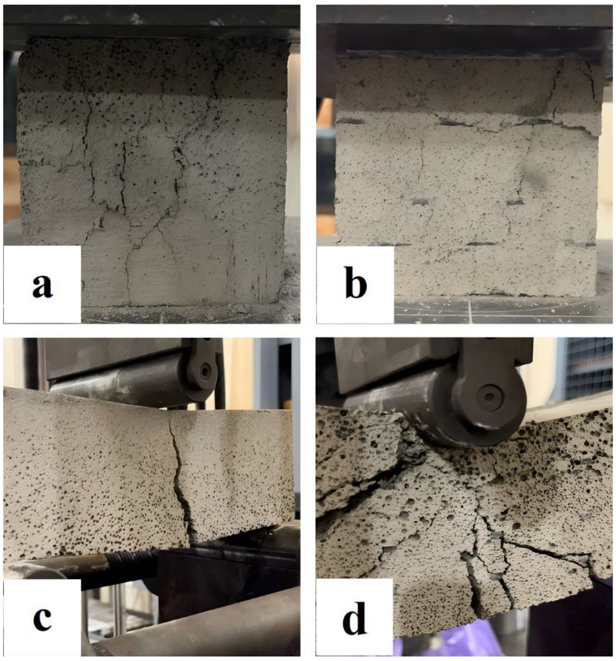


Fig. 7. Observation of failure patterns LWB: **a.** R10 compressive test, **b.** R10G3 compressive test, **c.** R10 flexural test, and **d.** R10G3 flexural test.

3.5. Compressive Strength

Compressive test results (Fig. 8a) indicate that the addition of rubber powder significantly reduces the compressive strength of lightweight bricks. Sample R10, containing 10% rubber powder, recorded a compressive strength of 2.41 MPa , lower than the control sample (3.97 MPa), but the highest among the rubber-modified variations. Increasing the rubber powder content to 20% and 30% further decreased compressive strength to 1.97 MPa and 1.70 MPa , respectively. This reduction correlates with a decrease in density, as rubber powder exhibits weaker mechanical properties compared to sand.

Conversely, as shown in Fig. 8b, adding geogrid layers significantly enhances the compressive strength of lightweight bricks, reaching 6.01 MPa with three layers, an improvement of 149.38% compared to unreinforced bricks. Geogrid reinforcement enhances the interaction between composite elements, ensures even load distribution, and strengthens the material's compressive capacity [28].

The reduction in compressive strength of rubber powder-modified bricks is primarily attributed to the hydrophobic nature of rubber, which is incompatible with the hydrophilic properties of the cement matrix. This incompatibility weakens the interfacial transition zone (ITZ), hinders the interaction between rubber powder and cement, and promotes pore formation, as observed under a microscope. Increased porosity reduces the material's strength, while the low adhesion between rubber powder and cement paste creates weak points where micro-cracks initiate, further decreasing the ability to withstand compressive loads [29]. Additionally, the much lower modulus of elasticity of rubber powder compared to cement contributes to greater deformation under quasi-static loading conditions [30].

Conversely, the addition of geogrids can significantly increase compressive strength by promoting a more even load distribution, particularly in the three-layer configuration. Furthermore, geogrids contribute through confinement and crack-bridging mechanisms that inhibit lateral expansion, delay crack propagation, and help maintain post-crack integrity, allowing the bricks to absorb greater energy before failure. Observation of the failure pattern during the compression test (Fig. 7) shows a more uniform deformation in the geogrid-reinforced samples. This is in line with previous studies that reported an increase in the average tensile capacity of up to 25% in geogrid-reinforced bricks [27]. Thus supporting geogrid reinforcement as an effective approach to improving the compressive performance of lightweight brick.

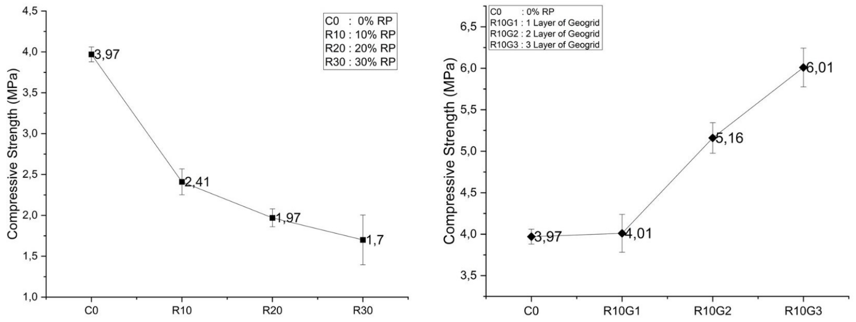
3.6. Flexural Strength

The flexural test results (Fig. 9a) indicate that the addition of rubber powder reduces the flexural strength of lightweight bricks. Sample R10, containing 10% rubber powder, exhibited the highest flexural strength among the rubber-modified variations at 1.65 MPa , but this value was still lower than the control sample (C0) at 1.94 MPa . Increasing the rubber powder content to 20% and 30% further reduced the flexural strength to 1.48 MPa and 1.38 MPa , respectively. This decline is attributed to the weak bond between rubber particles and cement, as well as the increased porosity resulting from the incorporation of rubber powder [31]. In contrast, adding geogrid layers (Fig. 9b) significantly increased the flexural strength of the bricks. Sample R10G1, with one geogrid layer, achieved a flexural strength of 2.21 MPa . This increased to 2.81 MPa in R10G2 with two layers and reached 3.48 MPa in R10G3 with three layers, representing a 119.19% improvement over samples without geogrid reinforcement. These results surpass those of previous studies, which reported up to a 64% increase in flexural strength with geogrid reinforcement [32].

The reduction in flexural strength with increasing rubber powder content is similar to the decrease in compressive strength. It is primarily caused by the incompatibility between the hydrophobic rubber powder and the hydrophilic cement matrix, which creates a weak interfacial transition zone (ITZ). Additionally, the fine particle size of rubber powder accelerates crack propagation under loading, further diminishing the material's resistance to external forces. The low elastic modulus of rubber compared to the sand it replaces also contributes to reduced density and stiffness, leading to a linear decrease in flexural strength. These findings confirm that rubber powder does not significantly enhance the overall stiffness of lightweight bricks. While rubber powder offers potential benefits in waste recycling and weight optimization, its adverse effects on mechanical properties must be mitigated to enable broader applications.

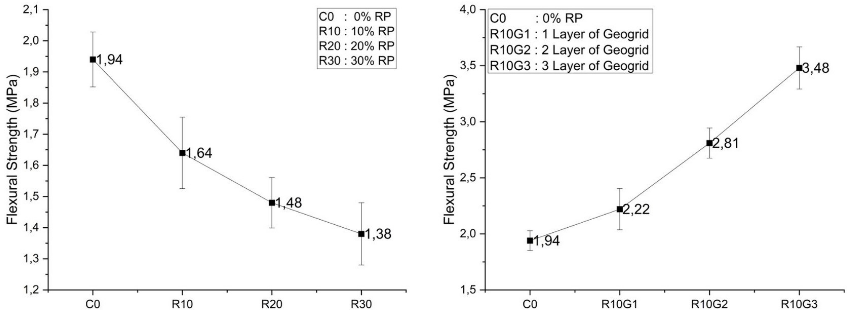
The improvement in flexural strength through geogrid reinforcement is attributed to the even distribution of loads, which reduces stress concentrations and enhances resistance to failure under repeated loading conditions [33]. Geogrids also increase energy absorption before failure, as evidenced by the absence of slippage between the geogrid and the lightweight brick matrix, indicating a strong bond. Sample R10G3, with three geogrid layers, demonstrates an optimal configuration for resisting flexural loads. This is further supported by crack pattern observations (Fig. 7d), which reveal better load distribution in geogrid-reinforced samples compared to those without reinforcement.

An increase in flexural strength with additional geogrid layers is supported by findings that geogrids enhance the deformation capacity of materials by improving ductility [34]. The strategic placement of geogrids, particularly in the upper and lower thirds of the brick's depth, effectively resists crack propagation and enhances durability [35]. The added ductility also delays the onset of complete failure, improving the overall structural performance of lightweight bricks [36]. With the three-layer geogrid configuration (R10G3), lightweight bricks exhibit not only higher



a) b)

Fig. 8. Compressive strength of LWB: a) rubber powder, b) geogrid layers.



a) b)

Fig. 9. Compressive strength of LWB: a) rubber powder, b) geogrid layers.

flexural strength but also improved resistance to cracking and deformation, making this approach an effective solution to mitigate the adverse effects of rubber powder addition.

4. Conclusions

Replacing fine aggregate with rubber powder significantly affected the physical and mechanical properties of the lightweight bricks. A **30**% replacement produced the lowest density ($0.68\ \mathrm{g/cm^3}$), which is attributed to the lower specific gravity of the rubber powder compared to that of the sand. The 10wt.% replacement yielded the lowest water absorption (**13**.**75**%), whereas replacement levels above **10**wt.% increased the entrapped air content and promoted a more porous matrix. The highest compressive and flexural strengths, 2.41 MPa and 1.64 MPa , respectively, were also achieved at a 10wt.% rubber powder content. This trend indicates that higher rubber contents tend to weaken the loadbearing skeleton, primarily due to poor interfacial bonding between rubber particles and the cementitious matrix.

Geogrid reinforcement enhanced the mechanical response of the lightweight bricks, as indicated by higher compressive and flexural strengths with increasing geogrid layer count.

The best performance was achieved with three layers, yielding compressive and flexural strengths of 6.01 MPa and 3.48 MPa, respectively. This improvement is attributed to the geogrids' ability to distribute stress, bridge cracks, and enhance post-cracking integrity, thereby increasing energy absorption and delaying collapse.

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