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Compressive Strength and Density in Fresh and Dried Cube Analysis of Autoclaved Aerated Concrete in Cooperating Glass Industrial Waste

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ABSTRACT

In the pursuit of sustainable construction materials, cooperating industrial waste into innovative building solutions has emerged as a promising way. Autoclaved Aerated Concrete (AAC) stands out as one such eco-friendly material renowned for its lightweight and insulating properties. The research highlighted that glass Industrial waste (GIW) had the potential to improve the strength and fire resistance of AAC due to its excellent properties of GIW in terms of physical, mechanical and thermal performances. The possibility of GIW was explored by including it in AAC concrete and analysing the effect of varying additions on the properties of AAC. This fundamental research proposed different percentages of GIW composition (5%, 10%, 15%, 20%, 25% and 35%) as a partial replacement for 70% (Sand+ Gypsum) mixed with different amounts (0.1% and 0.065%) of Aluminium paste. Then, the same percentages of the GIW composition (5%, 10%, 15%, 20%, 25% and 35%) were used as a partial replacement to reduce the silica content of 68% (Sand+ Gypsum) mixed with 0.1% Aluminium paste. All specimens underwent a steam curing process for 12 hours at a temperature of 180°C and a steam pressure of 13 bars in an autoclave machine to produce Autoclaved Aerated Concrete based on Glass Industrial Waste (AAC-GIW). These aspects were crucial in determining the optimum composition of glass waste that could influence the physical, mechanical and thermal properties of AAC-GIW. The optimum composition of GIW, sand, gypsum, lime, cement and aluminium paste as an expanding agent in AAC-GIW were the factors contributing to high strength. The compressive results were analysed in 3 different ratios (Ratio A, Ratio B and Ratio C) for fresh cubes and dried cubes, the work density and dry density. It is revealed that 15% GIW for ratio C is an optimum compressive strength at 2.43 MPa work density of 677 kg/m^3 for fresh cubes as a sand replacement, in dried cube condition, 15% produces the highest compressive strength at 6.64 MPa of 661 kg/m^3 for Ratio B. At different ratios, the most effective GIW content differed, emphasizing the requirement for modifications in AAC-GIW formulations specific to the AAC.

Keywords:
Autoclaved aerated concrete; gypsum; compressive strength; density; glass waste; replacement

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1. Introduction

The Autoclaved Aerated Concrete masonry unit (AAC) represented a concrete block material revolution, transitioning into a lightweight construction material that has been in use since the early 20th century. AAC's composition comprises a mixture of sand, gypsum, cement, limestone, water and an aluminium paste acting as an expansion agent. AAC remains highly significant, finding applications in interior walls, building cladding for low and medium-rise structures, as well as load-bearing and non-load-bearing walls, depending on the structural requirements [1]. The development of AAC can be traced through a series of patents. Initially, Hoffman experimented with and patented the aeration of concrete using carbon dioxide in 1889. Subsequently, Aylsworth and Dyer patented a porous cementitious mixture incorporating calcium hydroxide and aluminium in 1914. In 1923, Axel Eriksson introduced the modern AAC by subjecting his aerated blend of crushed limestone to autoclaving or forced steam curing. These research and development efforts garnered considerable attention, leading to further enhancements in AAC manufacturing. In 1935, the first reinforced AAC components, namely panels and slabs, were created [2].

AAC boasts numerous advantages, including its lightweight nature, portability, excellent insulation against heat and fire and overall durability. Consequently, it quickly gained popularity within the construction industry. Recent industry improvements have further refined AAC's qualities, making it relatively lighter, with lower thermal conductivity, increased heat resistance, reduced shrinkage and quicker construction compared to conventional concrete. Substantial advancements were made by incorporating waste materials as partial substitutes for AAC components, thereby enhancing its physical and mechanical properties while lowering production costs. The development of AAC can be categorized into lime or cement-based processes, contingent on the materials used, such as sand and fly ash [3]. Additionally, AAC development is influenced by the selection of silica or calcareous materials. Aluminium paste is widely used as an air-entraining agent to introduce trapped hollow spaces. Sand, silica fume and slag are increasingly employed as supplementary cementitious materials in AAC formulations, contributing to enhanced density. However, exceeding 30% coal-based ash content can negatively impact AAC strength and reduce absorbent void volume due to hydrogen gas reduction. Variations in ash and silica fume content significantly affect AAC's thermal conductivity [4].

Furthermore, AAC development explores the use of various silica materials for reinforcement by mixing them with other materials containing silica elements like ceramics, glass, quartz and etc. The integration of sustainable materials is closely linked to environmental sustainability. Addressing environmental pollution requires innovative solutions for recycling waste materials and reducing waste disposal concerns to promote sustainable development. Recycling glass waste, rich in silica (SiO_2), can serve as an additive, replacement and reinforcement material in concrete block production [5]. Glass, in conjunction with tires and rubber, ranks as one of the three most commonly disposed-of materials in landfills, with a global recycling rate of approximately 21% [6]. A significant portion of the residual, unnecessary material ends up in landfills, leading to environmental concerns. Consequently, novel approaches are needed to repurpose these landfill waste materials. A comprehensive overview of both global and country-specific waste generation, recycling and landfilling rates is provided to gain insight into the prevailing global waste challenge. The discussion extends to future waste management strategies, potential investment opportunities and avenues for research exploration. Additionally, fresh prospects for recycling glass waste in construction are presented, offering practical and cost-effective solutions to maximize value and ensure its continuous use within a closed-loop system [7].

The disposal of glass waste represents a pressing environmental issue that is poised to become a global crisis. According to Binici *et al.,* [8], Malaysia generated over 13,800,000 tonnes of solid waste annually, with the figures steadily rising each year. In this context, glass waste accounts for 3.3% of the total solid waste, a surge attributed to human activities and industrial processes. Given the consistent population growth, the volume of glass waste has concurrently expanded. Gokmen *et al.,* [9] stated the recycling rates in Malaysia from 2017 to 2019, revealing that only 1.06% of glass waste was recycled, while other materials such as paper, plastic and metal demonstrated higher recycling rates. To safeguard the environment against glass waste pollution, it is imperative to identify effective solutions for recycling these waste materials and mitigating the waste disposal dilemma to foster sustainable development. This study aims to utilize glass industrial waste (GIW) as a partial replacement for sand in AAC and optimize its physical, mechanical, acoustic and fire resistance properties for wall applications.

2. Literature Review

As indicated by Manaf *et al.,* [10], the government encourages researchers and scientists to explore alternative waste technologies within the construction industry, such as the development of green concrete. In the present market, lightweight concrete, particularly AAC, plays a prominent role. AAC is an easily deployable material and an efficient construction system. It is a precast concrete product crafted from natural raw materials, characterized by its lightweight properties, relatively low density and suitability for fabricating concrete masonry units like wall blocks. AAC, as a green concrete variant, can reduce or partially replace Portland cement and sand, in response to the growing demand for AAC materials. While green concrete comes in various formulations, AAC stands out for its numerous advantages, including its lightweight nature [11], eco-friendliness [12], high porosity as a green building material [13] and its suitability for low-rise construction in seismic-prone regions [14]. Numerous studies have been conducted to enhance AAC by modifying its raw materials, thereby improving product quality, characteristics and cost-effectiveness. Some of these studies have focused on reducing the reliance on sand and cement in AAC production [15], while others have explored AAC compositions based on cement-lime-aluminium [16] or even AAC formulations without aluminium powder and cement [17].

Liew *et al.,* [18] conducted a study in which wood waste fibre and polyester fibre were incorporated to reinforce AAC. This resulted in the production of wood fibre-reinforced AAC (WFAC) and polyester fibre-reinforced AAC (PFAC) by adding varying percentages (0%, 0.1%, 0.2%, 0.3%, 0.4% and 0.5%) of wood and polyester fibres by weight. In both WFAC and PFAC specimens, there was an increase in bulk density and thermal conductivity, accompanied by a decrease in porosity. The mechanical strength of WFAC experienced an increase at a 0.4% fibre content due to the adhesion of wood fibres [18]. In the study by Fiala *et al.,* [19], waste red gypsum (RG) was examined as a replacement for fly ash in AAC. Various proportions of RG (0%, 5%, 10%, 15%, 20%, 25%, 30%, 35% and 40%) were used and the AAC samples were subjected to autoclaving at 200°C and 2 MPa pressure for 8 hours. The results indicated an increase in relative strength due to RG replacement, particularly in the range of 5% to 20%. AAC with 20% RG achieved a density of 617 kg/m3 and a compressive strength of 4.2 MPa, meeting the requirements of grade B06, A3.5 in GB 11968-2019 [19].

Powęzka *et al.,* [20] investigated the use of recycled AAC (AAC-R) as a partial replacement for sand in AAC. AAC-R was employed to replace fine sand at various weight percentages, including 0%, 15%, 20%, 25%, 30%, 35%, 40%, 45% and 50%. The optimal composition with 30% AAC-R replacement exhibited the highest compressive strength (5.85 MPa). Salahaddin *et al.,* [21] explored the utilization of rice husk ash (RHA) as a silica source in AAC by replacing quartz sand. The samples were subjected to different temperatures (152°C, 165°C, 175°C and 192°C) for 6 hours. The results revealed that as the autoclaving temperature decreased from 192°C to 165°C, there was a significant increase in compressive strength by 22% and a reduction in drying shrinkage by 33 %. In Walczak *et al.,* [22] study, waste granite powder was modified as a fine aggregate by incorporating waste polyethylene terephthalate (PET) fibres for reinforcing AAC. Dopamine hydrochloride was used to enhance the interfacial adhesion between the fibres and the AAC matrix. Various ratios (0%, 0.1%, 0.3% and 0.5% by weight) of PET fibre content were added. The results indicated that with 0.1% wt PET fibre, there was a 6.0% increase in compressive strength and a 28.4% increase in flexural strength. Furthermore, the addition of 2 g/L dopamine-modified waste PET fibre led to a significant improvement of 12.7% in compressive strength and 37.2% in flexural strength for the AAC.

3. Methodology

The production of AAC products such as block and panel units involve a five-step process according to different compositions of AAC-GIW as tabulated in Tables 1 - 3.

Figure 1 shows the fabrication process of AAC-GIW involves several steps of mixing, casting, rising, wire cutting and autoclaving. Initially, various raw materials are blended, followed by the addition of aluminium paste as an expansion agent and water, resulting in the formation of a "slurry". The inclusion of aluminium serves to generate hydrogen gas upon its reaction with calcium hydroxide [23]. This hydrogen gas leads to the formation of stable air bubbles within the slurry, introducing higher porosity. Consequently, AAC proves to be a superior concrete material when compared to standard concrete due to its reduced thermal conductivity. The mixed slurry is subsequently poured into a steel box mould, typically filling it to about half to two-thirds of its capacity. A reaction period of several hours allows the mixed slurry to expand, eventually filling the entire mould. Following a pre-curing phase, the slurry solidifies, taking on a "cake" form. This cake is then cut into desired shapes using a cutting wire and subsequently undergoes autoclaving within an autoclave boiler. The autoclaving process typically lasts for 5 to 12 hours at temperatures ranging from 180 to 190°C, all while maintaining a consistent steam pressure of 10 to 12 bar [24]. The strength class of AAC is classified according to ASTM C 1693, falling within the dry density range of 350–850 kg/m3 and exhibiting compressive strengths ranging from 2 to 6 MPa [25].

In the moulding stage, the prepared slurry is poured into half of a polystyrene box with a volume of 0.01589 m^3. To eliminate trapped air within the mixture, the mould is subjected to shaking or vibration for 30 seconds. Subsequently, the mixture undergoes an expansion process, with careful observation of the sample's condition at regular intervals to ensure that the expansion completes and the hardening initiates within a timeframe of 30 to 60 minutes [26,27].

Table 1
Ratio A - Proportion ratio of AAC-GIW

Sample No.	Dry slurry content 70%			30%		
	Sand, S	Gypsum	GIW	Cement, C	Lime, CH	Aluminium, Al
	Weight by weight (%)					
A0 (Control)	67	3	0	18	12	0.1
A5	62	3	5	18	12	0.1
A10	57	3	10	18	12	0.1
A15	52	3	15	18	12	0.1
A20	47	3	20	18	12	0.1
A25	42	3	25	18	12	0.1
A30	37	3	30	18	12	0.1
A35	32	3	35	18	12	0.1

Table 2
Ratio B - Proportion ratio of AAC-GIW

Sample No.	Dry slurry content 70%			30%		
	Sand, S	Gypsum	GIW	Cement, C	Lime, CH	Aluminium, Al
	Weight by weight (%)					
A0 (Control)	67	3	0	18	12	0.065
A5	62	3	5	18	12	0.065
A10	57	3	10	18	12	0.065
A15	52	3	15	18	12	0.065
A20	47	3	20	18	12	0.065
A25	42	3	25	18	12	0.065
A30	37	3	30	18	12	0.065
A35	32	3	35	18	12	0.065

Table 3
Ratio C - Proportion ratio of AAC-GIW

Sample No.	Dry slurry content 68%			32%		
	Sand, S	Gypsum	GIW	Cement, C	Lime, CH	Aluminium, Al
	Weight by weight (%)					
A0 (Control)	65	3	0	19	13	0.1
A5	60	3	5	19	13	0.1
A10	55	3	10	19	13	0.1
A15	50	3	15	19	13	0.1
A20	45	3	20	19	13	0.1
A25	40	3	25	19	13	0.1
A30	35	3	30	19	13	0.1
A35	30	3	35	19	13	0.1

Once the mixed slurry has fully expanded, it is ready for the curing process. The AAC-GIW sample attains an estimated average density of 520 kg/cm^3. In this study, the curing process adheres to the methods and parameters employed within the AAC manufacturing industry. After the samples have foamed and solidified in the moulds, they are left to cure for 24 hours at room temperature. Subsequently, the samples are placed into an autoclaved aerated concrete machine, where they undergo a steam curing process for 12 hours at a temperature of 180°C and steam pressure of 13 bars [28]. During this steam curing process, the polystyrene mould dissolves due to the combination of pressure and heat, resulting in samples that are available without the mould. Following their removal from the autoclave, the samples need to rest at room temperature for 24 hours before they are cut into the desired test specimen shapes. All the specimens are cut using a Vertical Bandsaw machine at Kim Hoe Thye Industries. The machine is equipped with an attached bandsaw blade, specifically the Aurora Grit, which is suitable for cutting concrete. This cutting procedure is performed after allowing the samples to naturally cool for 24 hours at room temperature following the autoclave steam curing process.

Fig. 1. The flow of the fabrication process of AAC-GIW

4. Results and Discussion

4.1 Compressive Strength in Fresh Cube and Dried Cube Analysis

Figure 2 shows that the highest compressive strength ratio A for a fresh AAC-GIW cube was 2.29 MPa. The strength increase is observed with up to 20% AAC-GIW, however a decline occurs when the composition reaches 25%. The compressive strength of AAC increases with the addition of up to 20% GIW. At this stage, the GIW particles help enhance the formation of stable air bubbles and during autoclaving, resulting in improved strength. However, when the GIW content exceeds 20%, the increase content of GIW may disturb the AAC's balanced composition, potentially impeding the development of chemical interaction and air bubbles in AAC slurry. As a result, compressive strength starts to decrease beyond 25%, weakening the AAC matrix that reduce the density and strength [29].

Ratio B demonstrates fluctuating trends with the highest compressive strength observed at 30% AAC-GIW, reaching 3.34 MPa. The variations in strength at different GIW compositions in AAC influence the material's properties. At 0% GIW, the compressive strength is relatively higher at 3.17 MPa, as the increase of GIW allows for an optimum balance among the AAC components, promoting a strong structure. Introducing 5% GIW results in a slight decrease in strength to 2.83 MPa. It is due to early disruptions in the material's chemical interaction from GIW, which has not yet significantly enhanced its strength [30]. When 10% GIW is added, the compressive strength rises to 3.32 MPa, suggesting that GIW gives positively affects the formation of stable air bubbles and crystalline structures during autoclaving, thus improving strength. However, at 15% GIW, strength drops to 2.94 MPa, possibly due to an excess of GIW, which could compromise the AAC matrix's properties, leading to a reduction in strength. At 20% GIW, the strength increases again to 3.27 MPa. This is indicating that this specific proportion creates a balanced composition that optimizes the beneficial effects of GIW on chemical interaction and air bubble formation. The fluctuations in compressive strength highlight a delicate balance between the advantages of GIW in improving chemical interaction and strength and the potential weaknesses of addition GIW, which can weaken the material's properties. The optimum GIW percentage figures to be at 10%.

Ratio C follows a trend similar to Ratio A, with a 15% AAC-GIW composition achieving the highest strength at 2.64 MPa, which represents the results observed in Ratio A. The variation in AAC-GIW composition ratios suggests that the optimum GIW percentage as a sand replacement in AAC lies between 15% and 20%. The trend in Ratio C, which follows the impact of different GIW percentages on compressive strength in fresh AAC cubes, reveals an interesting pattern. Initially, as GIW is introduced from 0% to 15%, there is a steady increase in compressive strength, rising from 1.83 MPa to 2.64 MPa. This improvement is because of GIW on the AAC material, aiding in the formation of stable air bubbles during the autoclaving process. However, when the GIW content increase 15%, compressive strength begins to reduce. At 20% GIW, strength drops to 2.23 MPa and continues to decrease as the GIW percentage increases to 35%, reaching 1.78 MPa. This reduction in strength may result from the addition of GIW, which could compromise the AAC matrix's properties, weakening the structure. The data from Ratio C indicate that the optimal GIW incorporation for maximum compressive strength in fresh AAC cubes occurs at 15%. Beyond this level, addition GIW gives lower strength of AAC.

Figure 2 demonstrate the compressive strength variations of AAC with different GIW percentages. Ratio A, strength peaks at 2.29 MPa with 0% GIW, increasing up to 20% GIW but declining after 25% due to addition GIW disrupting the chemical interaction of the materials. Ratio B shows fluctuating strength, reaching 3.34 MPa at 30% GIW, with a decrease beyond 15% GIW as addition content weakens the AAC matrix. Ratio C mirrors this trend, with the highest strength of 2.64 MPa at 15% GIW, suggesting an optimal range of 15-20% GIW for AAC performance. Iucolano *et al.,* [31] stated that autoclaving one of the factors in AAC's properties, introduces specific conditions of high temperature and steam pressure that raise the development of its chemical interaction and open pore and closed pore as shown in Figure 6. It is affecting the higher density correlated with lower porosity. This process leads to the formation of stable air bubbles and contributing to the material's strength. Similar finding Lu *et al.,* [32] stated the chemical reaction between materials will increase pore volume in AAC produce lower its density, achieved by higher pore sizes as smaller pore will improve strength between material particles.

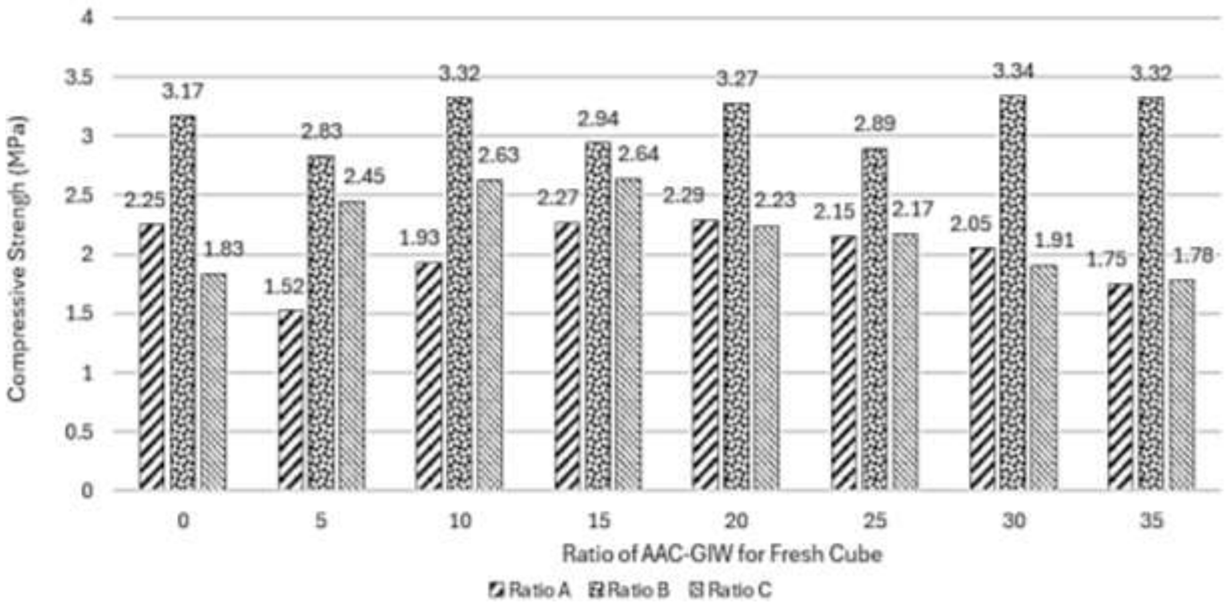

Fig. 2. Compressive strength in a fresh cube of AAC-GIW for (a) Ratio A (b) Ratio B (c) Ratio C

Figure 3 illustrates the trends in Ratio A for dried AAC-GIW cubes with varying proportions of GIW in AAC, revealing a significant pattern in compressive strength. The data indicate that as GIW content increases from 0% to 15%, compressive strength improves significantly, reaching a peak of 4.79 MPa at 15% GIW. However, beyond 15% GIW, the compressive strength shows an irregular trend, with a slight decrease to 4.76 MPa at 20% GIW, still near the maximum strength observed. As GIW content rises to 35%, compressive strength gradually decreases to 3.68 MPa, which may result from uneven distribution leading voids between GIW particles and the AAC matrix and reduced strength. Ratio A suggest an effective range for GIW content in AAC, with 15% GIW achieving the highest compressive strength.

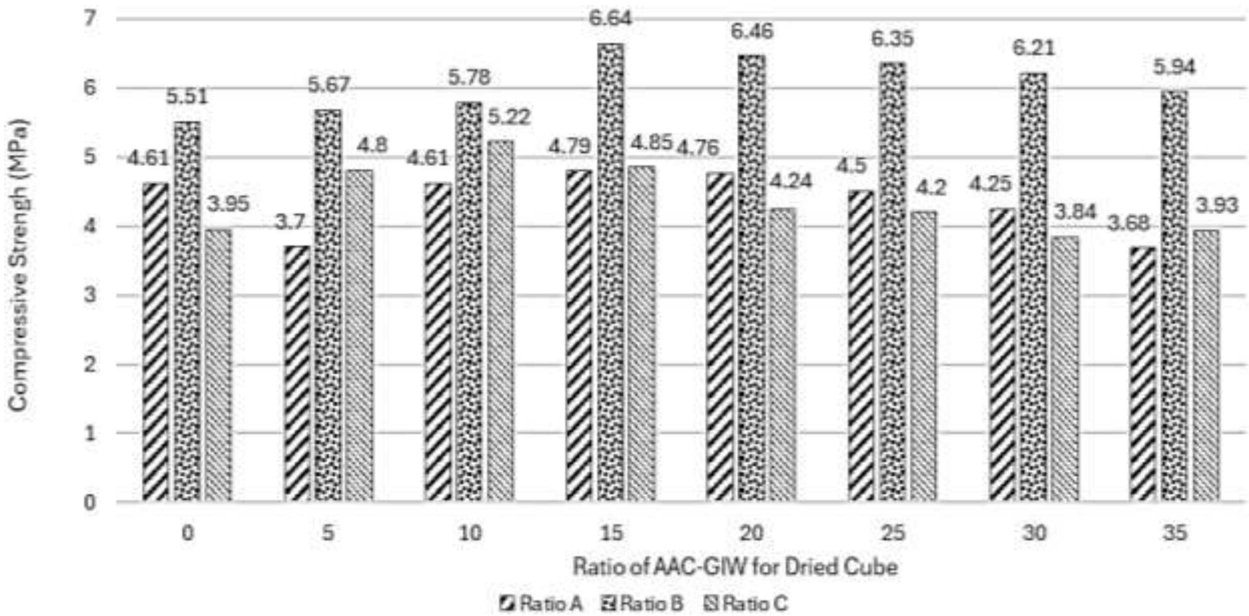

Fig. 3. Compressive strength for a dried cube of AAC-GIW for (a) Ratio C (b) Ratio B (c) Ratio C

Ratio B presents the compression results for Ratio B, delving into the compressive strength of AAC-GIW shows a distinctive pattern characterized by two phases of strength variation. In the first phase, spanning from 0% GIW to 15% GIW, there is a consistent uptick in compressive strength, with values ascending from 5.51 MPa to 6.64 MPa. This incorporation of GIW particles enhances the packing density of AAC, reducing voids and increase strength. The presence of GIW may promotes the formation of stable air bubbles and crystalline structures during autoclaving, leading to strength enhancement. However, the second phase commences at 20% GIW, where the compressive strength initiates a decrease, reaching 6.46 MPa. This decrease persists as the GIW content escalates up to 35%, stabilizing at 5.94 MPa. The variation in the strength trend beyond 15% GIW may be influenced by various factors. The higher GIW content, especially beyond 20%, may introduce difficulties in achieving an optimal mixture that can maintain the interparticle bonds for maximal strength. Mora-Ortiz *et al.,* [33] highlighted that dry AAC exhibits higher compressive strength due to the absence of free water, which can weaken internal bonds and increase susceptibility to failure under load. This aligns with the current study, where drying likely enhances the crystallinity and stability of the AAC matrix, maximizing strength.

Ratio C illustrates the compressive strength results of dried AAC-GIW cubes for Ratio C. These results exhibit a pattern that closely mirrors the trend observed in Ratio A. Initially, there is a noticeable and consistent rise in compressive strength as the proportion of GIW increased. This upward trajectory commences at 0% GIW, where the strength stands at 3.95 MPa and continues until 10% GIW, reaching a peak of 5.22 MPa. This initial strength enhancement can be attributed to the positive influence of GIW on the chemical interaction of AAC. The presence of GIW likely promotes the formation of stable air bubbles and crystalline structures during autoclaving, contributing to the material's overall strength. However, as the GIW content surpasses 10%, the trend undergoes a shift. At 15% GIW, there is a decline in compressive strength to 4.85 MPa and this reduction continues through 30% GIW, where the strength decreases to 3.84 MPa. This decrease in strength can be attributed to various factors, including the potential interference of higher GIW proportions with the structural integrity of the AAC matrix. Interestingly, at 35% GIW, there is a slight resurgence in compressive strength, rising to 3.93 MPa.

This enhancement compressive strength fresh cube to dry cube density because during the drying process, the moisture present within the AAC matrix evaporates, reducing the internal water content. The removal of free water minimizes internal pore pressure and enhances the stability of the material, which contributes to improved compressive strength. This process also reduces the risk of micro-cracking caused by water expansion during compressive strength test. This observation similar to Shams *et al.,* [34] studied rice husk ash as a silica source for the production AAC implies that beyond a specific material recycling enhance the content stabilizes and the mixture with a balanced composition that improved strength. The findings suggest that the relationship between GIW content and compressive strength between fresh cube and dry cube in AAC is characterized by a composite pattern, encompassing an initial increase, a subsequent decrease and a possible stabilization at higher GIW percentages. This performance behaviour is likely a result of the interactions between GIW and the AAC matrix. To solve the lack of replication of real curing conditions in fresh cube tests, simulate environmental factors such as temperature, humidity and air circulation in controlled curing chambers. Utilize moisture retention methods, like sealed curing or water tanks, to better replicate field curing conditions and improve test accuracy [35].

4.2 Work Density for Fresh Cube and Dry Density for Dried Cube Analysis

Figure 4 illustrates the work density in fresh cubes of AAC-GIW for Ratio A. The results indicate a notable pattern of change in work density as the proportion of GIW within the mixture varies. Initially, with the introduction of GIW, there is a gradual increase in work density, commencing at 0% GIW with a value of 609 kg/m3 and reaching its peak at 25% GIW, measuring 659 kg/m^3. This initial increase in work density is attributed to the inclusion of GIW in the AAC matrix, which likely enhances the compactness and density of the material. The presence of GIW is believed to contribute to more efficient particle packing, resulting in higher work density. However, as the GIW content surpasses 25% and reaches 30% and 35%, a subsequent decrease in work density is observed, eventually stabilizing at 650 kg/m^3. This decline in work density can be attributed to the addition proportion of GIW in the mixture, which may introduce difficulties in achieving an optimal balance of components. Zhang *et al.,* [36] highlights the higher GIW content can potentially disrupt the compactness of the AAC matrix, leading to a reduction in work density. The observed trend in work density reflects the intricate relationship between the GIW content and the compaction characteristics of AAC-GIW. Initially, increasing GIW content enhances work density, but beyond a certain threshold, additional increments in GIW content can result in a decline in work density due to potential mixing challenges and interference with material compaction.

Ratio B in Figure 4 depicts the work density in the fresh cube of AAC-GIW for Ratio B. The observed pattern in work density, influenced by varying proportions of GIW in AAC, reveals a dynamic interplay. At the outset, with 0% GIW content, the work density stands relatively high at 749 kg/m^3. This results from the absence of GIW, which permits an optimal composition and equilibrium among AAC components, facilitating effective compaction and densification. Upon introducing 5% GIW, a slight reduction in work density to 739 kg/m^3 is noted. This dip could be attributed to initial chemical interaction disturbance due to GIW presence, which may not yet significantly contribute to material densification. As the GIW content increases to 10%, work density rises to 757 kg/m^3. This surge can be attributed to GIW's positive influence on stable air bubbles and crystalline structure formation during autoclaving, enhancing material densification. The trend continues with further GIW increments, reaching its zenith at 20% GIW, with work density peaking at 791 kg/m^3. However, at 25% GIW, a slight dip to 756 kg/m^3 occurs, possibly due to addition GIW interfering with AAC matrix compactness. Interestingly, at 30% GIW, a slight upturn in work density to 819 kg/m^3 suggests this specific GIW proportion may lead to an optimized mix maximizing densification. Nonetheless, at 35% GIW, work density drops to 803 kg/m^3, suggesting that addition GIW content could impede material densification. The work density trend in AAC-GIW reflects a delicate balance between GIW's positive densification contributions and the potential drawbacks of addition GIW content hindering material compactness. The optimal GIW percentage seems to be around 20% in this context [37].

Figure 4 for Ratio C shows the work density in the fresh cube of AAC-GIW, exhibiting a trend similar to that observed in Ratio A. The work density varies as the proportion of GIW changes within AAC. With 0% GIW content, the work density is relatively low, registering at 636 kg/m^3. This lower density is attributed to the absence of GIW, allowing for a more porous and less dense AAC composition. Upon the introduction of 5% GIW, there is a discernible increase in work density, reaching 677 kg/m^3. This elevation is a consequence of GIW's influence, promoting densification and reducing porosity within the AAC matrix. However, at 10% GIW, the work density experiences a minor decrease, measuring 674 kg/m^3. This decline could be due to potential interference caused by addition GIW content with the optimal composition necessary for achieving maximum densification. The trend changes again with further increases in GIW content. At 20% GIW, the work density undergoes a significant rise, reaching 704 kg/m^3. This increase is likely a result of GIW's positive impact on compaction and densification of the AAC material. Nevertheless, as the GIW content continues to rise beyond 20%, the work density gradually diminishes. At 35% GIW, the work density stabilizes at 686 kg/m^3. This reduction may be attributed to an addition proportion of GIW in the mix, potentially hindering the compactness of the AAC matrix. The observed work density trend reflects the intricate interplay between GIW proportion and AAC densification properties. Initially, increasing GIW content enhances work density, but further increments beyond a certain threshold may lead to a reduction in work density due to potential mixing challenges and interference with material densification [38].

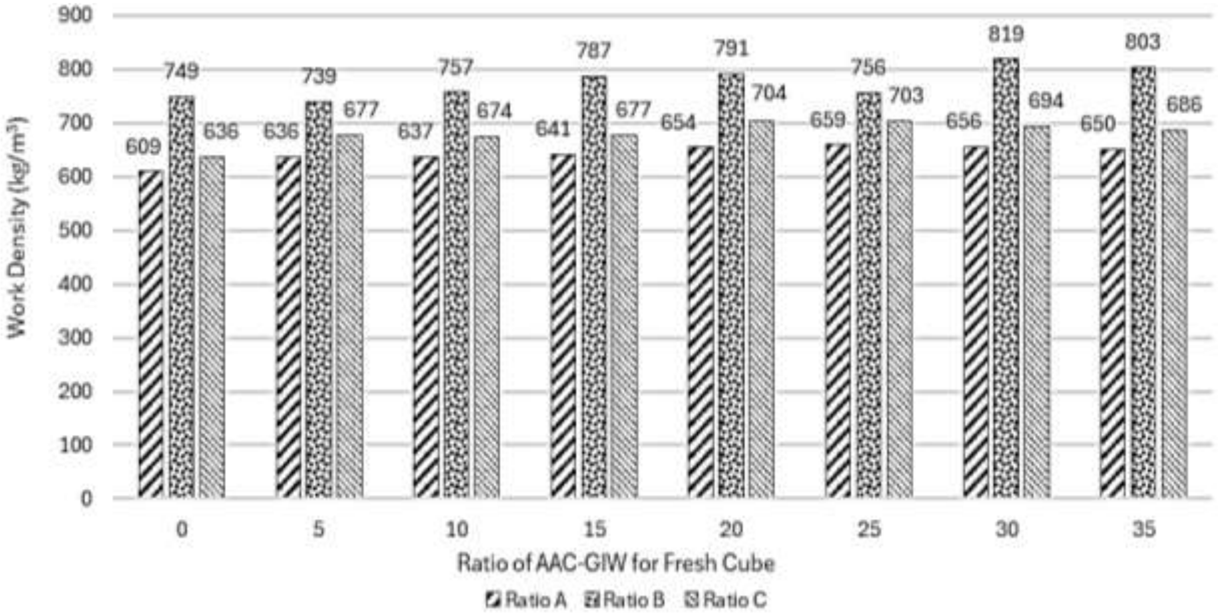

Fig. 4. Work density in a fresh cube of AAC-GIW for (a) Ratio A (b) Ratio B (c) Ratio C

Figure 5 illustrates dry density in a dried cube of AAC-GIW for Ratio A. The results show the trend in dry density in the AAC-GIW mixture, which increases from 0% GIW at 501 kg/m^3 to 25% GIW at 557 kg/m^3 before decreasing at 30% GIW (553 kg/m^3) and 35% GIW (542 kg/m^3), can be explained by considering factors related to compressive strength and density of the properties. The initial increase in dry density can be linked to the positive impact of GIW on compressive strength. As GIW is introduced, it likely contributes to the formation of stable air bubbles and crystalline structures during autoclaving, which enhances the material's strength. Xu *et al.,* [39] stated this increase in strength can lead to denser material. The presence of GIW can influence the chemical interaction of AAC. It may lead to better packing of particles, resulting in increased material density. This improved chemical interaction can be responsible for the higher dry density observed at lower GIW percentages.

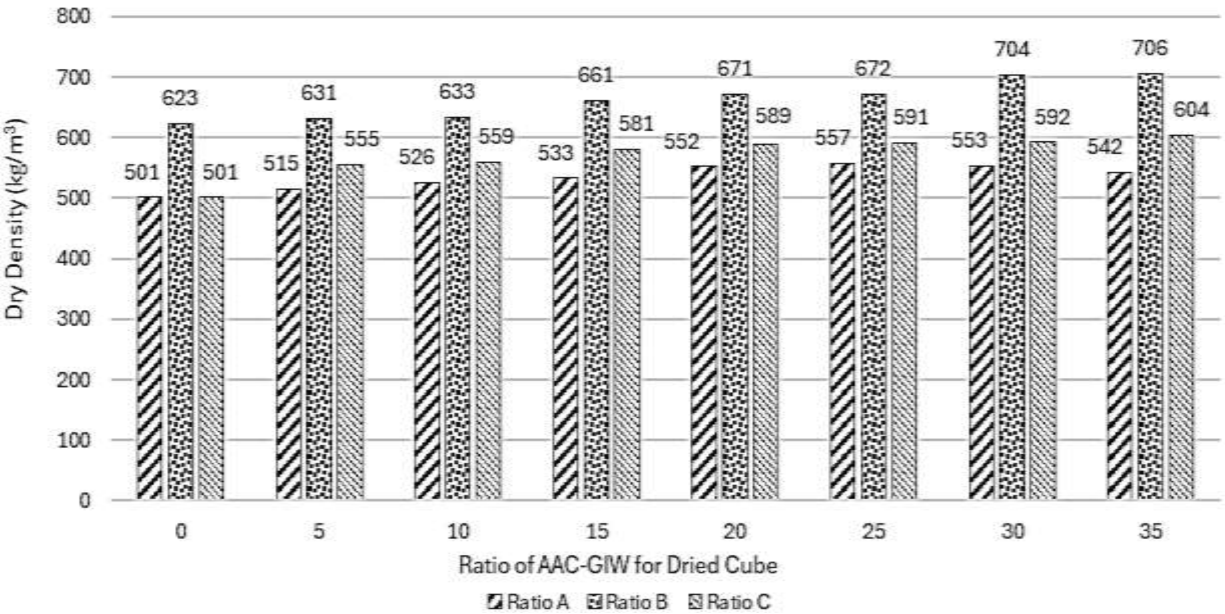

Fig. 5. Dry density for dried cube of AAC-GIW for (a) Ratio A (b) Ratio B (c) Ratio C

The density of AAC is closely related to its open pore and closed pore structure as shown in Figure 6. As GIW is added, it may fill some of the voids or pores within the AAC matrix, increasing the material's density. However, at higher GIW percentages, addition pore filling could reach a limit, leading to a reduction in dry density. The interaction between GIW particles and the AAC matrix is significant. At lower GIW percentages, effective chemical interaction can occur, contributing to densification. However, as the GIW content increases, there could be a point at which the interaction becomes less beneficial, potentially resulting in decreased density. The results dry density trend in AAC-GIW are influenced by a complex interplay of factors. The initial increase can be attributed to enhanced compressive strength, improved chemical interaction and efficient density. However, beyond a certain GIW content, factors related to chemical interaction may lead to a reduction in dry density. The optimal GIW proportion for maximizing dry density while maintaining other desired properties would need to be determined through further analysis and experimentation [40].

Fig. 6. Open pores and closed pores of AAC-GIW

Ratio B in Figure 5 illustrates the trend observed in dry density for Ratio B in AAC-GIW. This trend is characterized by a consistent rise in dry density as the proportion of GIW content increases, spanning from 0% GIW at 623 kg/m³ to 35% GIW at 706 kg/m³. This pattern signifies that elevating the GIW content results in a higher dry density within the AAC-GIW material. The underlying reason for this trend can be attributed to the GIW filling effect. When GIW is introduced into the AAC mixture, it serves to occupy the voids and pores present within the material. This filling action contributes to an augmented dry density by diminishing the volume of empty spaces within the material. Additionally, GIW is likely enhancing the compressive strength of AAC-GIW through its pozzolanic properties and its role in generating stable air bubbles during the autoclaving process. This heightened strength translates into denser and more substantial AAC-GIW specimens [41]. Furthermore, the presence of GIW has a positive impact on the compactness of the AAC-GIW matrix, leading to a denser overall structure. Importantly, it's worth noting that even as the dry density increases due to higher GIW content, the AAC-GIW material remains well within the lightweight density range, characterized as being below 800 kg/m³. This indicates that while the dry density rises with increased GIW content, the material retains its sought-after lightweight characteristics. These attributes are highly advantageous for applications that necessitate reduced structural weight, enhanced insulation properties and easy handling. The results trend of escalating dry density with an increase in GIW content in Ratio B is primarily driven by the GIW filling effect, augmented compressive strength and improved material compactness. The increase in dry density does not compromise the material's lightweight nature, rendering AAC-GIW suitable for a broad range of construction and insulation applications [42].

Figure 5 for Ratio C shows dry density in a dried cube of AAC-GIW similar trend with Ratio B. The observed trend of increasing dry density in AAC-GIW from 0% GIW at 501 kg/m³ up to 35% GIW at 604 kg/m³ can be attributed to GIW possesses pozzolanic properties and when introduced into AAC, it can enhance the material's compressive strength. As the GIW content increases, the improved strength can lead to denser AAC-GIW specimens, contributing to the rising dry density. AAC typically has a porous structure that imparts lightweight properties. However, when GIW replaces sand, it fills the voids and pores within the material [43]. This pore-filling effect reduces the overall volume of empty spaces within AAC-GIW, increasing its density. The comparison work density and dry density with the presence of GIW can influence the chemical interaction of AAC-GIW. It may promote the formation of stable air bubbles and improved chemical interaction within the material. These changes result in reduced porosity and contribute to lower density between work and dry density. The interaction between GIW and other AAC elements can enhance the chemical interaction within the material. Improved chemical interaction leads to a denser AAC-GIW structure, further increasing dry density. Despite the rising dry density, all AAC-GIW samples remain within the lightweight concrete category, with densities below 800 kg/m³. This demonstrates that even with the replacement of sand by GIW and the correlated increase in dry density, AAC-GIW maintains its lightweight characteristics. These properties make it suitable for applications where reduced structural weight, improved insulation and relate in any related to desired application for construction materials [44].

5. Conclusions

In conclusion, the compressive strength and dry density trends observed in Autoclaved Aerated Concrete with Glass Industrial Waste (AAC-GIW) highlight the complex interplay of various factors within the material. For compressive strength, in Ratio A, we observed an increase in strength up to 20% GIW due to GIW's positive influence on chemical interaction, particularly the formation of stable air bubbles and crystalline structures. Beyond this point, addition GIW content disrupted the material's integrity, leading to a decline in strength. In Ratio B, the pattern was fluctuating, with optimal strength at 10% GIW, demonstrating the importance of balance in GIW proportions. Ratio C mirrored Ratio A, with a peak strength at 15% GIW. Regarding dry density, all ratios exhibited an increase with increasing GIW content. This trend is attributed to the filling effect of GIW, reducing voids and pores within the material, enhanced compressive strength, improved chemical interaction of materials. Despite this increase, AAC-GIW maintained its lightweight properties below 800 kg/m³, making it suitable for applications requiring reduced structural weight and improved insulation. AAC-GIW significantly impact construction materials by offering a sustainable alternative to traditional concrete. Incorporating glass waste into AAC could reduce raw material costs and lower environmental impact, enhancing both economic and ecological feasibility. The production process could be scaled industrially, through energy requirements for autoclaving and waste recycling processing. Regulatory standards might be adjusted to allow higher percentages of recycled materials in AAC production, supporting circular economy principles while confirming structural properties and safety in construction applications. These findings highlight the importance of determine GIW proportions in AAC-GIW mixtures to optimize both compressive strength and dry density while maintaining lightweight properties.

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