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Influence of Recycled Glass Ceramic Waste On Physical and Mechanical Properties of Foamed Concrete

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Abstract: Concrete is the most used man-made material and foamed concrete is a type of concrete widely known with high workability, low density and excellent thermal and sound insulation properties. Its global market has also been predicted to increase. Growing of population and economy, along with urbanization generate wastes which increase yearly. One of the solutions to reduce waste in landfills is by using waste in manufacturing. Glass, classed as a form of ceramic waste (GCW) has been left in the landfills unrecycled due to the challenges it causes. The primary purpose of this research is to find the optimal GCW composition as a quartz sand additive for Foamed Concrete-based Glass Ceramic Waste (FC-GCW) which will reduce the amount of unrecycled GCW that ends up in landfills while producing a sustainable product. The samples were prepared by grinding the GCW and mixing varying percentages of GCW (0, 5, 10, 15, 20, 25, and 30%) with a consistent quantity of cement, quartz sand, water, and foam. Physical (density, water absorption, porosity and Energy Dispersive X-ray (EDX)) test and analysis and mechanical (compressive strength) test were performed on the samples. During physical tests, the density increased as the GCW percentage increased, but water absorption and porosity decreased. FC-GCW 20% had appropriate density, water absorption, and porosity values of 0.887 g/cm3, 22.6 %, and 88.9%, respectively, which demonstrated that the material is lightweight and porous. For EDX analysis between FC-GCW control and FC-GCW 20%, it was found that when GCW was included, the weight percentage of Oxygen and Calcium decreased while the weight percentage of Silica increased, showing GCW increased Silica content, and pozzolanic reaction occurred to from Calcium Silicate Hydrate (C-S-H) gel. For mechanical testing, it was discovered that FC-GCW 20% had the highest average compressive strength of 0.94 MPa and 2.01 MPa for 7 and 28 days, respectively. This research's contribution can be applied to areas where low densities are preferred and low compressive strength is required, such as of road sub-base, fire breaks, raising floor level, void fill, harbour fill, bridge abutments and ground stabilization.

Keywords: foamed concrete, glass ceramic waste, low strength, lightweight, additive

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1. Introduction

Concrete, the most regularly used man-made substance in the world for the previous three centuries, has piqued interest as a means of recycling solid waste products as part of the building sector [1]-[3]. Foamed Concrete (FC) is a form of concrete that has been widely utilized in structural and non-structural construction since the mid-1920s because of its high workability, thermal and sound insulation features, excellent resource and energy economy, low density, and low cost [4]-[6]. The global FC market is predicted to increase at a Compound Annual Growth Rate (CAGR) of 4.4% between 2016 and 2022, reaching $458.1 million by 2022. The Asia Pacific now has the largest foamed concrete market in the world [7]. Because of its textural surface and mono-structural cells, it is frequently used in the domains of thermal insulation, sound absorption, and fire resistance.

FC offers various advantages, making it excellent for filling gaps in subsurface engineering projects, trench restoration, and tunnel rehabilitation. It also has good insulating properties, making it perfect for floor and flat roof thermal and soundproofing insulation. FC is also used in applications such as cavity filling, well backfilling, masonry grouting, pipeline monolithic thermal insulation, monolithic low-rise, and individual house construction, levelling floors, road sub-bases and maintenance, bridge abutments and repairs, and ground stabilization [8]-[13]. Wells (2001) [14] classified the application of FC according to their densities and compressive strength in Table 1.

Increased population, economic growth, and rapid urbanization have all led to the consumption of a vast amount of natural resources and the generation of waste that grows yearly. To safeguard the environment and conserve resources, it is necessary to investigate or develop alternative manufacturing technologies that reduce or eliminate the creation of waste [15]. Because of the benefits of waste prevention, utilization of waste materials, reduction of landfill space, and conservation of natural resources, the use of waste materials in manufacturing is one of the ecologically friendly solutions [2][16]-[20]. Many studies have been conducted to replace raw materials with various industrial wastes such as fly ash [29][21] and recycling waste concretes [22], including glass waste [23]-[27].

Glass or glass ceramic are widely used for its excellent physical and chemical characteristics of transparency, impermeability, mechanical, chemical and thermal resistance [28]. Although glass is classed as a form of ceramic, it differs from other ceramics in a number of ways. When compared to ceramics, it is an amorphous, disordered substance, not a crystalline solid or a liquid with a high silica oxide (SiO^2) content [1], [29], [30] with structural differences on an atomic scale [31], [32]. Glass, like soda-lime, borosilicate, or tempered glass, is inert (non-reactive and non-leaching) and impermeable to liquids and gases. Glass has been shown to be safe in numerous studies and is widely acknowledged as such by governments and legislation. On the other hand, certain varieties of glass may contain poisonous lead or cadmium, which may be present in the lead glass or other glassware with glazes [33], [34].

Around 130 million tonnes (Mta) of glass are produced each year all around the world. Hollow or container glass accounts for the most volume with 63 Mta, or 48%, followed by flat glass (construction and window glass, automotive glass, and others) with 54 Mta, or 42%, tableware with 5%, and all other glass items with 6%. However, glass recycling volumes are estimated to be at 27 Mta globally, accounting for only 21% of total output. Container glass has the highest recycling rates, with an average of 32%, whereas flat glass has only 11%. The rest of the unrecycled glass go to landfills due to variations in colour and compositions, being broken and complex [1], [2], [35].

Glass recycling has a number of issues. In a single-stream recycling system, broken glass can contaminate other recyclables like paper and cardboard, lowering their value. Since the China import ban, recyclers have focused on quality and pollution reduction to maintain the value of their recycled materials. Broken glass is a safety problem for employees, but it may also destroy recycling equipment, raising production costs. It is tough to sort shattered glass, and if it is broken down too finely, it will be too difficult to reprocess. Glass is sent to the dump when recycling businesses find it too difficult or expensive to separate it from the rest of the stream. Because glass is heavy and expensive to transport, some communities are paying to have it properly crushed for building use [2], [36], [37]

Glass waste can be a substitute for sand because it contains amorphous silica, while its high toughness and abrasion resistance properties help as an effective substitution of natural aggregate in cement concrete. However, glass poses risks of high alkalinity and negative effect of expansion caused by alkali-silica reaction (ASR) gels which affect the strength and durability of concrete negatively [2]. Concrete experiences ASR when free silica of certain aggregates reacts with the alkalis in the cement [38]. According to Massekh and Hillal (2022) [39], chemical composition and particle size of glass directly influence the expansion of ASR in foamed concrete. They concluded that the finer the particle size of glass, the lower the ASR expansion value. Guo et al. (2020) [1] found that glass particle size under 0.425 mm did not cause ASR expansion.

2. Literature Review

Schumacher et al. (2020) [23] researched the use of lightweight aggregates in foamed concrete with an open structure and a porous matrix for the improved ratio of compressive strength to dry density. The cement used was rapid hardening ordinary Portland cement CEM I 52.5 R, 0.5% of a polycarboxylate-based superplasticizer, synthetic foaming agent, and different types of lightweight aggregates: pumice (P), expanded clay (EC), foam glass (FG), expanded glass (EG), and expanded perlite (EP). The mixed proportions were designed to achieve good workability and simplicity of the recipes. The ratio of paste/foam was set to 30/70, according to the volume. The production method was mixing cement, water, and superplasticizer initially, adding pre-formed foam using a foam generator and stirring until homogeneous distribution, then adding pre-wetted lightweight aggregates and mixing. The samples were filled into molds without compaction and cured in a climate chamber at 23 ˚C with relative humidity (RH) > 95%. After 24 h, the samples were demoulded and further stored in the climate chamber. Samples containing glass were FG (4-16 mm) and EG (2-4 mm), where 230 kg/m^3 FG was mixed with 675 l/m^3 foamed concrete slurry while 204 kg/m^3 EG was mixed with 644 l/m^3 foamed concrete slurry. It was stated that the dry densities of foamed concrete for samples containing FG and EG were 560 kg/m^3 and 450 kg/m^3 respectively. Compressive strength (150 × 150 × 150 mm) was tested after 28 days of curing. The compressive strength achieved by foamed concrete containing FG and EG was 4.6 MPa and 3.6 MPa respectively, which were the third lowest and the lowest compressive strength achieved among all the samples.

Table 1 - Typical applications of foamed concrete according to dry densities and compressive strength

Application	Dry Density Range (kg/m^3)	Compressive Strength Range (MPa)
Roof insulation screed	400 - 600	1.0 - 2.5
Road sub-base	400 - 1000	1.0 - 3.0
Fire breaks	400 - 1000	1.0 - 3.5
Raising floor level	400 - 1200	1.0 - 4.5
Void fill	400 - 1600	1.0 - 10.0
Harbour fill	400 - 1600	1.0 - 10.0
Bridge abutments	400 - 1650	1.5 - 10.0
Ground stabilization	600 - 1000	2.0 - 5.5
Non-structural walls	800 - 1600	3.0 - 10.0
Decorative panels	1000	3.5 - 5.5
Trench reinstatement	1200	4.5 - 5.5
Floor slabs	1200 - 1600	4.5 - 10.0
Structural walls	1200 - 1600	6.5 - 12.0

Chandni and Anand (2018) [24] studied the utilization of recycled waste as filler in foamed concrete. The materials used were 53 Grade Ordinary Portland Cement, vegetable protein-based liquid foaming agent (pre-formed using foam generator), two types of superplasticizers: Poly Carboxylate Ether (PCE) and Sulphonated Naphthalene Formaldehyde (SNF), and two types of filler: recycled glass powder and recycled thermoplastic powder. Recycled glass powder was crushed waste soda-lime glass from window panels and bottles with particle sizes finer than 0.09 mm. The mix proportion was designed based on volume to obtain a workable mix by varying the water to solids ratio and the foam volume in percentage. Glass filler foamed concrete (GFC) was designed to have densities of 1200 kg/m^3, 1400 kg/m^3 and 1600 kg/m^3 with cement to filler ratio as 1:1 and the actual densities of the mixes produced were ensured to be in the range of ± 50 kg/m^3. Foam density was set to be 40 kg/m^3 and between two ratios of a foaming agent to water which were 1:40 and 1:35, the 1:35 ratio produced a stable intended foam density. The production method was dry mixing of cement and filler, adding and mixing water to the dry mix incrementally to obtain a homogeneous mix, and adding and mixing pre-formed foam to the wet mix until the foam was uniformly distributed with no physical sign on the surface. Mixes with the highest designed densities from each filler type (1600 kg/m^3 for GFC), were selected for the addition of 1.5% by weight of cement of each PCE and SNF at a later stage. For the compressive strength test (50 × 50 × 50 mm), the samples were cast and demoulded after 24 h and then water cured for 7 days and 28 days before testing. The dry densities of the samples were estimated before testing. The sample with the lowest estimated dry density of 1253 kg/m^3 achieved 3.21 MPa and 5.28 MPa after 7 days and 28 days of curing respectively, which were the lowest compressive strength achieved than GFC with higher designed densities.

Sharma, Taak, and Bhandari (2021) [25] investigated the influence of ultra-lightweight foamed glass aggregate on the strength aspects of lightweight concrete. The materials used were 43 Grade Ordinary Portland Cement, natural coarse aggregate, sand, and ultra-lightweight foamed glass aggregate. In the research, sand was replaced with foamed glass from 0% to 50% replacement. Three different sizes of foamed glass were used for each percentage, which was large (3-2.5 mm), moderate (2.5-1.25 mm), and small (1.25-0.65 mm). The samples were prepared and cured for 7 and 28 days. Compressive strength was tested and all samples' compressive strength containing foamed glass exceeded the control sample, except a sample containing 10% of large foamed glass replacement. From the result, it can be seen that the smaller the size of foamed glass and the higher the percentage of foamed glass replacement, the higher the compressive strength achieved.

Hameed and Hamada (2020) [26] experimented with using glass and rubber waste as additive sustainable materials to prepare foamed concrete with improved properties. The materials used were Ordinary Portland Cement (Type1), sand, tap water, foam agent (EABSSOC), rubber gloves waste (GV), and glass powder (GP). GP (0.3-1.18 mm) was obtained from flat or window glass and crushed into powder form using the mill. In the study, foamed concrete was produced with 0.8 and 1 wt% of foaming agent variation for each 0.7 and 1 wt% of GP as an additive material. The production method was mixing dry materials (cement, sand, and additive materials) for 2 minutes, adding two-thirds of water to the dry mixture, and mixing for 2 minutes to form a wet mixture while the remaining water was used to produce foam with a foaming agent by hand machine for 4 minutes to form pre-formed foam. The pre-formed foam was then added to the wet mixture and mixing was done for 2 minutes. The wet mixture was cast into pre-oiled molds in three layers, each layer was compacted by the rod. The samples were wet cured at room temperature and demoulded after 24 h, then cured in water and air for 3, 7, 14 and 28 days. Bulk density was tested at the age of 3, 7, 14, and 28 days of curing while compressive strength (50 × 50 ×50 mm) was tested at the age of 7, 14, and 28 days of curing. For samples containing GP cured in water, it was found that bulk density increased when curing age increased, and the sample containing 0.8% foaming agent and 0.7% GP achieved the highest bulk density while the sample containing 1% foaming agent and 0.7% GP achieved the lowest bulk density after 28 days. For samples containing GP cured in air, bulk density decreased when curing age increased, and the sample containing 0.8% foaming agent and 1% GP achieved the highest bulk density while the sample containing 1% foaming agent and 1% GP achieved the lowest density after 28 days. For samples containing GP cured in water, it was found that compressive strength increased with curing age, and the sample containing 0.8% foaming agent and 0.7% GP achieved the highest compressive strength while the sample containing 1% foaming agent and 1% GP achieved the lowest compressive strength after 28 days. For samples containing GP cured in air, it was also found that the compressive strength increased with curing age, and the sample containing 1% foaming agent and 0.7% GP achieved the highest compressive strength while the sample containing 1% foaming agent and 1% GP achieved the lowest compressive strength after 28 days.

Gencel et al. (2022) [27] researched the physico-mechanical, durability, and insulation properties of lightweight foamed concrete containing expanded perlite and glass sand. The materials used were general purpose cement CEM I 42.5 R (EN 197-1), expanded perlite, glass sand (0-2.36 mm) which was obtained from the local company expertizing in window glass mounting, and a synthetic foaming agent containing enzyme-based proteins from Aydos Construction Chemicals-TURKEY. In the research, expanded perlite was replaced with 0, 30, 50, 70, and 100 vol% of the glass sand as fine aggregates, and a foaming agent was used in two volumetric quantities of 50 and 100 kg/m^3. The production method was mixing dry materials initially for 60 s, adding water and continued mixing for another 120 s, then adding foaming agent and continued mixing for another 60 s. The samples were cast and demoulded after 24 h and were cured in water conditions at 20 ˚C until the testing day. Bulk density, water absorption, and porosity (50 × 50 ×50 mm) were tested after 28 days of curing while compressive strength (40 × 40 × 160 mm) was tested after 7, 28, 91, and 120 days of curing. Sample containing glass sand with a bulk density of more than 800 kg/m^3 have the mixed code of G50F100, where expanded perlite was replaced with 50 vol% of glass sand and the foaming agent used was 100 kg/m^3. The bulk density, water absorption, and porosity for G50F100 were 1059 kg/m^3, 31.1%, and 35.95% respectively while the compressive strength for G50F100 after 7 days and 28 days were 0.93 and 1.00 MPa respectively, which was lower than reference sample with 100 kg/m^3 foam.

Based on the above-mentioned research gap in the literature, it was found that the small size of glass improves compressive strength of concrete. This research studied the physical and mechanical properties of (GCW) from municipal solid waste as additional material with ratio to sand in the production of Foamed Concrete Based Glass Ceramic Waste (FC-GCW). This will contribute to sustainable construction while reducing the amount of glass in landfills.

3. Methodology

3.1 The Preparation of Samples

Crushed GCW was obtained from a recycling company and then ball milled into grain form as shown in Fig. 1. GCW was sieved conforming to BS 410 [40] to obtain particle size less than 0.5 mm to reduce the risk of ASR expansion and to act as filler. Particle size gradation of GCW are shown in Fig. 2. Quartz sand was sieved to obtain particle size ranging from 0.6 mm to 5.0 mm, and the cement used was Holcim's Pozzolanic Cement CEM IV/B (V) 32.5 R while tap water was used for slurry and foam-making. Cement, sand, and GCW were weighed according to the mix design in Table 2.

The design of composition ratio was referred to as an FC product in the market [41] for the control sample and in a recent study of glass waste in concrete as a sand replacement [25] and as additive material [26] for GCW percentage. They used cement, sand, water, and foaming agent only for conventional FC and 5% increment of glass waste, respectively. For this research, GCW was also used in 5% increment based on quartz sand's mass, while quartz sand remained constant which categorized GCW as additive material.

There are three main processes grinding, mixing, and curing process. GCW was obtained from a recycling center, ground into powder using Ball Mill Grinder. The raw materials are weighed using a digital balance. Cement, sand, and water were mixed to form mortar slurry for the control sample while GCW was included for other sample ratios. Foaming agent and water were then mixed and foam was produced using Allefix's 2100W Electric Mixer. The pre-formed foam was then mixed into the mortar slurry to form FC-GCW slurry which was ready to be poured into molds which have been greased beforehand. Fig. 3 illustrated the production process of FC-GCW.

Fig. 1 - GCW in grain form

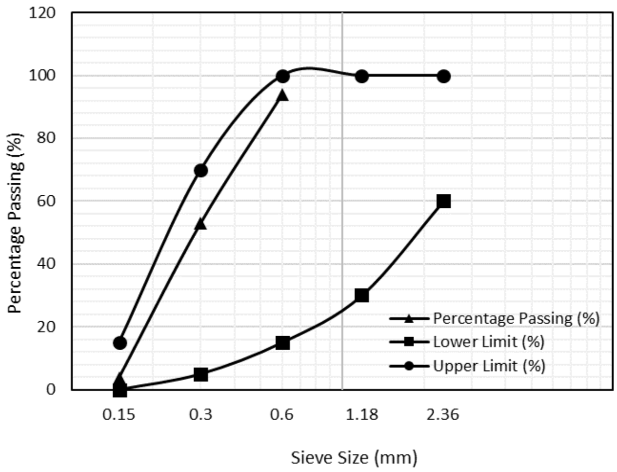

Fig. 2 - The distribution of GCW particles

Table 2 - The ratio of raw materials for producing 1 kg/m^3 of FC-GCW

Mix ID	Glass ceramic waste (kg)	Cement (kg)	Quartz sand (kg)	Water (kg)	Foaming Agent (kg)	Water for Foam Making (kg)
FC-GCW 0% (as a control)	0.0	500.0	300.0	200.0	3	90
FC-GCW 5%	15.0	500.0	300.0	200.0	3	90
FC-GCW 10%	30.0	500.0	300.0	200.0	3	90
FC-GCW 15%	45.0	500.0	300.0	200.0	3	90
FC-GCW 20%	60.0	500.0	300.0	200.0	3	90
FC-GCW 25%	75.0	500.0	300.0	200.0	3	90
FC-GCW 30%	90.0	500.0	300.0	200.0	3	90

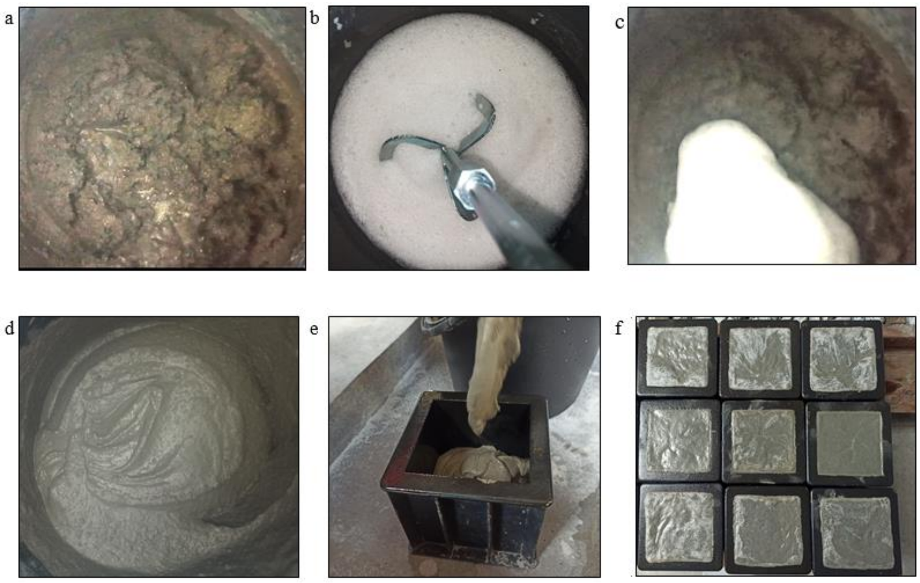

Fig. 3 - The production process of control FC-GCW (a) mixing cement, sand, and water to form mortar slurry; (b) production of foam; (c) adding pre-formed foam into mortar slurry; (d) mixture of FC-GCW slurry; (e) pouring of FC-GCW slurry into pre-greased molds; (f) samples ready for curing

3.2 The Curing of Samples

For the curing process, the FC-GCW slurry was distributed over the molds for the compressive strength test. Next, the FC slurry was left to cure in the mold for 5 days at room temperature of 27°C ± 0.5 before they were removed and left for air-curing for another 2 and 23 days. Fig. 4 shows the sample of FC-GCW with a different composition ratio of GCW.

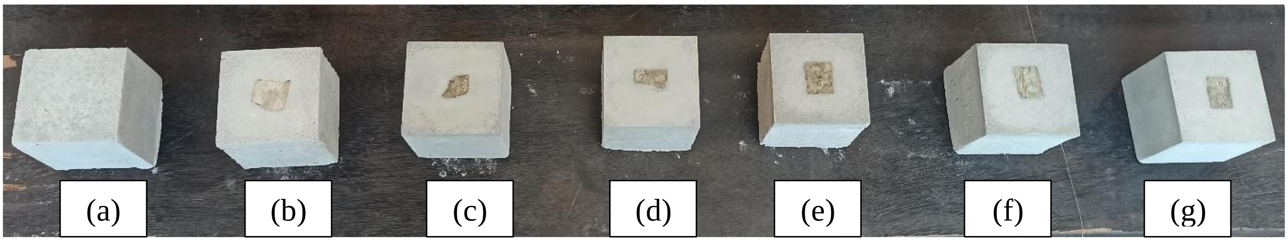

Fig. 4 - The different ratio of GCW in wt% as sand additive in FC-GCW (a) 0; (b) 5; (c) 10; (d) 15; (e) 20; (f) 25 and (g) 30

3.3 The Testing and Analysis of Samples

Test samples for density, water absorption, and porosity were obtained from crushed compressive strength test samples and tested in accordance with ASTM C642 [42]. The test samples were first dried in oven at a temperature of 100°C for 24 h, cooled in dry air to a temperature of 25°C after removal and weighed to determine the dry mass, A. Then, the test samples were immersed in water for 48 h, surface-dried with tissue after removal and weighed to determine mass after immersion, B. After that, the test samples were immersed in water and boiled for 5 h, allowed to cool for 14 h in the water, surface-dried with tissue after removal and suspended by a wire while immersed in water on the balance, the difference of mass before and after immersion was determined to find the apparent mass, C. The density, water absorption and porosity were determined with Eq. 1, Eq. 2 and Eq. 3 respectively. The test setup was as shown in Fig. 5.

$$Density = [\frac{A}{A-C}]\rho \quad (1)$$

$$Water\ absorption, \% = \left[\frac{B-A}{A}\right] \times 100 \quad (2)$$

$$Porosity, \% = [\frac{B-A}{B-c}] \times 100 \quad (3)$$

Where density of water, $\rho = 1$ g/cm³

a b

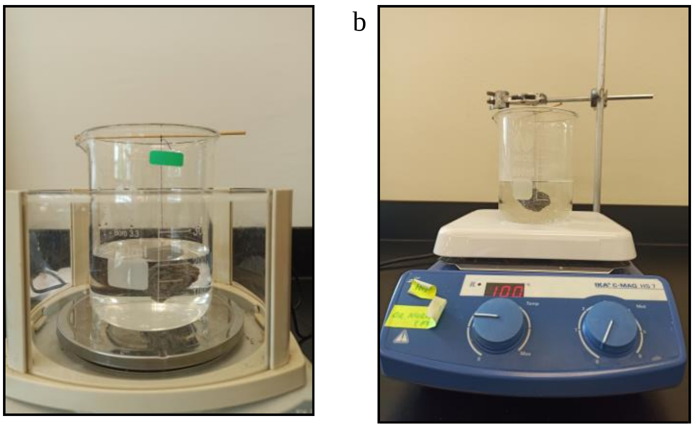

Fig. 5 - The density, water absorption, and porosity test setup (a) density and water absorption were tested without boiling; (b) porosity was tested with boiling

For Energy Dispersive X-ray (EDX) analysis, it was conducted conforming to ASTM E766-14e1 [43]. The test samples were also taken from the crushed compressive strength sample. For this analysis, only test samples for FC-GCW 0% and FC-GCW 20% were analyzed to compare the weight percentage of the elements for analysis of pozzolanic reaction. Fig. 6 displayed the Coxem Scanning Electron Microscope (SEM) in Nano Technology Physics Laboratory in UTHM used to conduct EDX analysis.

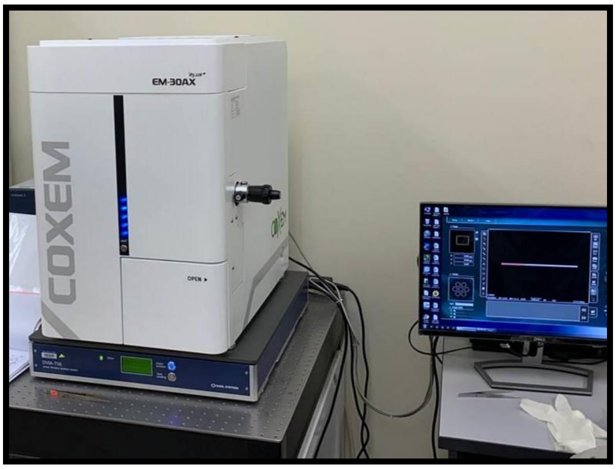

Fig. 6 - The EDX analysis machine setup

For mechanical test, the mold of compressive strength test had dimensions of 100 mm in length, 100 mm in width and 100 mm in height in accordance with BS EN 12390-3:2009 [44] using compressive strength tester machine in Concrete Technology Workshop, UTHM as shown in Fig. 7.

a b

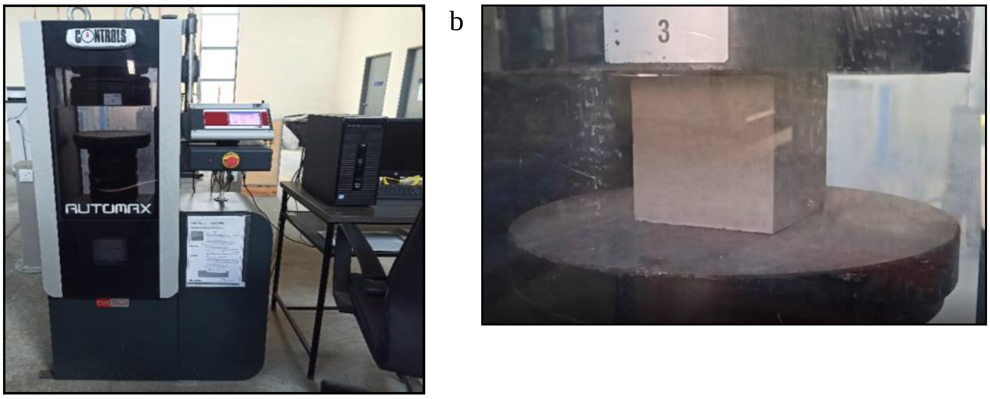

Fig. 7 - The compressive strength test process (a) controls' AUTOMAX super-automatic compact-line compression tester; (b) cube sample of FC-GCW being tested

4. Results and Discussions

4.1 Density, Water Absorption, and Porosity Test and EDX Analysis

The results of the density study were shown in Fig. 8. The graph showed that density increased with increasing GCW percentage. The highest value of density was 0.914 g/cm^3 for FC-GCW 30% followed by FC-GCW 25% at 0.906 g/cm^3, FC-GCW 20% at 0.887 g/cm^3, FC-GCW 15% at 0.872 g/cm^3, FC-GCW 10% at 0.861 g/cm^3, FC-GCW 5% at 0.835 g/cm^3 and the lowest value of density was 0.821 g/cm^3 for FC-GCW 0%. It was observed that the results of water absorption and porosity showed the opposite trend in Fig. 9 and Fig. 10. The water absorption and porosity decreased with the increase of GCW percentage. The highest value of water absorption and porosity was 23.7% and 92.5% for FC-GCW 0%, followed by 23.5% and 91.8% for FC-GCW 5%, 23.1% and 91.2% for FC-GCW 10%, 22.9% and 90.3% for FC-GCW 15%, 22.6% and 88.9% for FC-GCW 20%, 22.2% and 87.4% for FC-GCW 25%, and lastly 22.1% and 86.7% for FC-GCW 30 respectively. It could be concluded that the higher GCW percentage produced higher density and lower water absorption and porosity. The results of EDX analysis were illustrated in Fig. 11 where it could be seen that inclusion of GCW in FC-GCW 20% contained more Silica (Si) and less Calcium (Ca) compared to FC-GCW 0%. The analysis of weight percentage of elements was displayed in Fig. 12, and according to the graph, when GCW was included, the weight of Oxygen (O) and Ca decreased while Si increased.

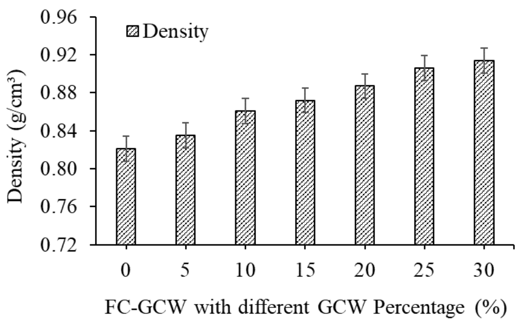

Fig. 8 - The density of FC-GCW with different GCW percentage

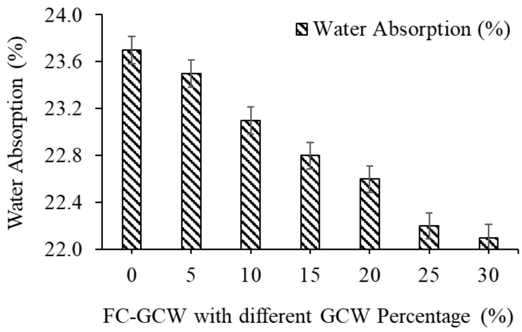

Fig. 9 - The water absorption of FC-GCW with different GCW percentage

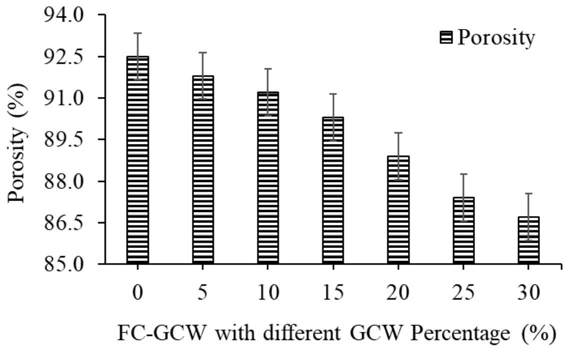

Fig. 10 - The porosity of FC-GCW with different GCW percentage

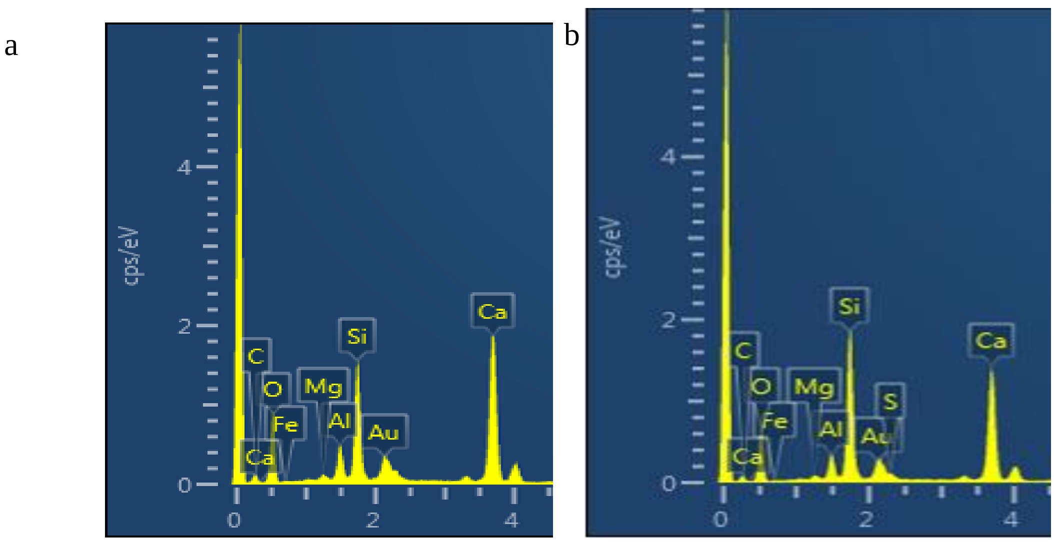

Fig. 11 - The EDX analysis of FC-GCW with different GCW percentage (a) 0%; (b) 20%

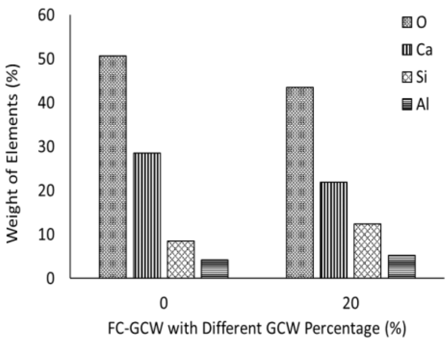

Fig. 12 - The weight percentage of elements with different GCW percentage

According to BS EN 206:2013+A1:2016, 2013 [45], lightweight concrete has a density of not less than 800 kg/m^3 or 0.8 g/cm^3 but not exceeding 2000 kg/m^3 or 2 g/cm^3. Therefore, the samples in this research could be categorized into lightweight concrete. The rising trend in density and declining trend in water absorption and porosity were mostly due to the rise of the fine aggregate total mass. GCW was used as a sand additive in this study. When the proportion of GCW added increased, the overall mass of fine aggregates used increased, increasing the samples' density. Khan et al. (2019) [46] and Bhat and Khan (2020) [47] observed a similar tendency when the mass of recycled glass waste and glass fiber added to the composition ratio was increased. The increased density of FC-GCW implied that there were more GCW particles with low water absorption in the samples. The same conclusion was reached by Khan et al. (2020) [48]. Another cause for the increasing trend of density and declining trend of water absorption and porosity is the filling effect of fine GCW, which filled the voids and increased particle packing, resulting in a dense and less permeable microstructure, particularly at the aggregate-paste interface zone (ITZ). Because of the fineness of the GCW, voids were evenly distributed, regular in shape, and less interconnected. El-Dieb and Kanaan (2018) [49], Schumacher et al. (2020) [23], Chandni and Anand (2018) [24], and Khan et al. (2020) [48] all found the same justification. It is possible that the trend is also due to the pozzolanic reaction increasing as GCW increases, where more Si was available to react with cement (CaOH) to produce the calcium silicate hydrates (C-S-H) gel. The product of this reaction was reduced O and Ca, while Si increased due to Si content from GCW. As a result, the microstructure of the samples got denser. Juan-Valdés et al. (2021) [50] found a similar outcome. Chandni and Anand (2018) [24] stated that pores may merge as a result of the presence of additional voids, resulting in larger, more connected pores. This means that the more voids, the higher the water absorption and porosity. Gencel et al. (2022) [27] previously concluded the same findings.

4.2 Compressive Strength Test

Fig. 13 depicted the collapse mechanism of FC-GCW which portrayed all four exposed faces are cracked approximately equally. Fig. 14 displayed the compressive strength of samples with different GCW percentages for 7 days and 28 days. FC-GCW with 20% GCW could withstand the maximum force value of 0.94 MPa for 7 days-average compressive strength, followed by a sample with 15% GCW with a value of 0.81 MPa, 25% GCW with a value of 0.79 MPa, 10% GCW with a value of 0.75 MPa, 30% GCW with a value of 0.66 MPa, 5% GCW with a value of 0.63 MPa, and finally 0% GCW with a value of 0.44 MPa. The maximum value for 28 days-average compressive strength was also achieved by FC-GCW with 20% GCW with a value of 2.01 MPa, followed by 1.95 MPa with 25% GCW, 1.92 MPa with 30% GCW, 1.88 MPa with 15% GCW, 1.86 MPa with 10% GCW, 1.85 MPa with 5% GCW, and finally 1.82 MPa with 0% GCW. It was found that the compressive strength test increased with increasing GCW percentage up to 20% GCW, however, the compressive strength started to decrease when more than 20% GCW was added into FC-GCW.

According to EN BS 12390-3:2002 [44], the collapse mechanism of FC-GCW is the satisfactory failure for cube specimens. Compressive strength is primarily determined by the water-to-solids ratio, cement concentration, foam volume, and the type of fillers, according to Chandni and Anand (2018) [24]. Because the cement content and foam volume were held constant in this study, the water-to-solids ratio and the type of fillers had an impact on the compressive strength of FC-GCW. The smaller size of GCW may have contributed to the increase in compressive strength. According to Sharma, Taak, and Bhandari (2021) [25], the smaller the fine aggregate size employed, the higher the compressive strength. The GCW employed in this study was much smaller than quartz sand. According to Balasubramaniam, Gopala Krishna, Saraswathy et. al. (2021) [51] and Juan-Valdés et al. (2021) [50], this contributed to the filling effect of fine GCW, which increased particle packing and filled pores, leading to a dense and less permeable microstructure, especially at the aggregate-paste interface zone (ITZ). It further led to the homogeneous distribution of tiny particles and voids and helped to evenly distribute the load applied to the samples, allowing them to endure greater compressive force. The increasing compressive strength may also be caused by the increasing density. It has been acknowledged by Khan et al. (2019) [39][46], Schumacher et al. (2020) [23] and Song and Lange (2021) [52] that when density increase and porosity decrease, compressive strength increases. The enhanced reaction between silica and the calcium hydroxide $Ca(OH)^2$ given by cement could also be responsible for the rise in compressive strength. When the GCW percentage increased, this resulted in some well-crystallized C-S-H and C-S-H gel on the surface of glass grains. This resulted in FC-GCW having a dense, compact, and uniform microstructure, with more linked particles distributing applied load uniformly. It also strengthened the bond between the cement binder and the tiny aggregate particles, which is in agreement with Tanwar et al. (2021) [53] and Khan et al. (2021) [54].

Fig. 13 - The collapse mechanism of FC-GCW

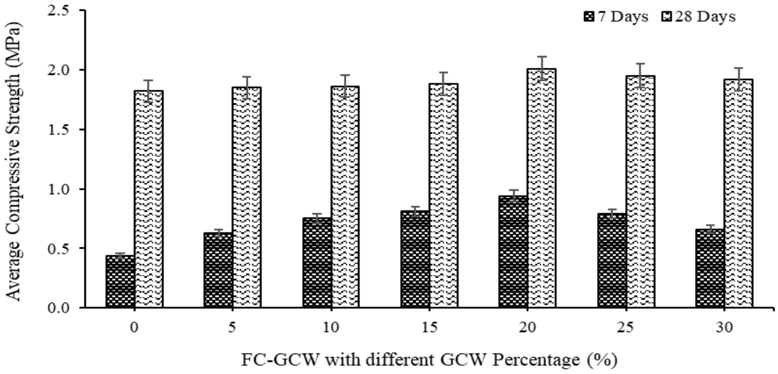

Fig. 14 - The density of FC-GCW with different GCW percentage

5. Conclusion

In a nutshell, FC-GCW with 20% GCW produced the optimum results in terms of physical and mechanical qualities. Physical testing revealed that 20% FC-GCW had appropriate density, water absorption, and porosity values of 0.887 g/cm3, 22.6 %, and 88.9%, respectively, which demonstrated that the material is lightweight. FC-GCW 20 % attained the greatest compressive strength for 7 and 28 days in mechanical testing, with values of 0.94 MPa and 2.01 MPa, respectively. The contribution of this research can be applied to areas where low densities are preferred and low compressive strength is required. Based on Table 1, FC-GCW 20% are suitable for applications of road sub-base, fire breaks, raising floor level, void fill, harbour fill, bridge abutments and ground stabilization. This could assist governments and businesses in reducing pollution caused by land filling and uncontrolled littering around the world. It can also raise economic levels by converting waste into a high-value product and promoting the zero-waste idea.

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