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Valorisation of waste glass in eco-friendly clay brick: Influence on physico-mechanical properties and water absorption

Chew Kai Ying[1], Mohd Fadhil Majnis[2*], Mustaffa Ali Azhar Taib[3], Ayu Haslija Abu Bakar[4], Maliza Ismail Jamail[5]

[1]*Department of Chemical and Petroleum Engineering, Faculty of Engineering, Technology and Built Environment, UCSI University, 56000 Cheras, Kuala Lumpur, Malaysia*
[2]*Faculty of Chemical Engineering, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia*
[3]*Pusat Latihan Teknologi Tinggi (ADTEC) Taiping, 34600 Kamunting, Perak, Malaysia*
[4]*Department of Engineering, Faculty of Engineering and Technology, Sunway University, 47500 Petaling Jaya, Selangor, Malaysia*
[5]*School of Architecture and Built Environment (SABE), Faculty of Engineering, Technology and Built Environment, UCSI University, 56000 Cheras, Kuala Lumpur, Malaysia*

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ABSTRACT

Clay bricks are widely used as building material all around the world. Natural clay is experiencing a constant reduction due to its continual use in the manufacturing of clay bricks. The depletion of clay resources has become a global issue, prompting many countries to limit the use of natural clay. This research study investigates the effect of waste glass addition on the physical-mechanical and water absorption properties of eco-friendly clay bricks, incorporating 0, 5, 10, 15, and 20 wt% of waste glass into the clay. The temperature of 900 °C was used for the firing process of clay bricks. Compressive strength, linear shrinkage, bulk density, apparent porosity and water absorption of the eco-friendly clay bricks were tested. Incorporating 20 wt% waste glass into clay bricks improved mechanical and physical properties: compressive strength (+29.4%), bulk density (+11.3%), apparent porosity (−16.0%), and water absorption (−24.6%). The digital micrographs demonstrated a reduction in the porosity with the addition of waste glass. This study revealed that the addition of waste glass induced the formation of a glass-phase fused bond with the body of clay when subjected to high temperature. Waste glass can be added to clay brick as a partial substitute for natural clay, improving the physical-mechanical and water absorption properties of clay bricks.

[2*]Corresponding author. *E-mail address*: fadhilmajnis@uitm.edu.my
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1. INTRODUCTION

Eco-friendly clay brick refers to an ecological and environmentally friendly version of clay brick. Conventional bricks are usually made up of natural clay minerals, which are non-renewable resources. In general, clay minerals take up hundreds to thousands of years to be generated geologically. Hence, they could be depleted through excessive mining and the consumption of clay minerals. To overcome this issue, an eco-friendly version of clay brick can be manufactured by reducing the natural clay content while maintaining the functionality of clay brick as a construction material.

Bricks are known as one of the oldest construction materials. They are small rectangular blocks used for masonry construction, such as walls and pavements. Bricks can be categorised according to the material, usage and performance. Clay bricks are widely used around the globe owing to their adequate durability, mechanical and thermal performance (Bilgil et al., 2025; Hasan et al., 2021; Syed Minhaj Saleem Kazmi et al., 2018). Usually, the properties of clay bricks depend on various factors like the characteristics of raw materials (Bhoir et al., 2025; Laouidji et al., 2025), brick manufacturing process (Chrachmy et al., 2024; Hanfi et al., 2025; Laouidji et al., 2025) and the firing temperature (Enock Embom et al., 2024; Oyediran et al., 2024). Clay mainly consists of silica and alumina, and the firing process sinters the particles together to form a ceramic bond, giving the bricks their characteristic strength and durability. The sintering process is accomplished by heating silicon dioxide, which exists naturally in clay and shale, to a higher temperature, resulting in its melting. Then, the silica dioxide will develop a bond between adjacent clay or shale particles at the contact point by diffusing across the particle boundaries and forming a solid mass (Hashimoto et al., 2024; Phonphuak et al., 2016).

Owing to the rising population and rapid urbanisation, the demand for construction materials is increasing significantly, causing excessive mining of natural clays. Despite that, the scarcity of natural clays is still growing day by day. So, to limit the usage of natural clay as the primary raw material for brick production, many countries have been searching for alternative materials to incorporate into the clay bricks as additives (Saravanan & Rao, 2023). In recent studies, different waste material was explored and utilised as partial substitutions for clay, such as industrial wastes (Benahsina et al., 2022; Fontana & Mathias, 2025; Zakaria et al., 2023), glass and ceramic wastes (Ajadi, 2024; Khan et al., 2022) and construction and demolition wastes (Pallavi Prasanth Kartha, 2024; Tang et al., 2023). Using waste materials as an alternative source for clay bricks seems promising, given the extremely high global waste generation due to the vast population. Phonphuak et al. (2016) reported that about 38,699 tonnes of solid waste were generated daily by Malaysians. Hence, incorporating waste materials in bricks could reduce the energy consumption for the brick-forming process and reduce the waste products in large quantities, especially at the landfill site, reducing the environmental impact of the waste material.

Burnt clay brick belongs to the wide family of construction materials used to construct the outer and inner walls of buildings. Today, eco-friendly clay bricks incorporated with waste materials have become quite popular within the architecture and construction industries, primarily due to the environmentally friendly factor. More people are becoming aware of the impact of some construction practices on the environment today. Recycling waste material such as glass is a viable solution to be integrated into fired clay bricks, not only to solve environmental problems but also to improve the economic design of buildings and infrastructures (Xin et al., 2021). In addition, incorporating waste glass (WG) into the production of clay bricks enhances their durability, compressive strength, and lightweight properties, while also reducing water absorption. Significantly, these improved physical-mechanical properties of eco-friendly clay bricks make it a more favourable and widely used sustainable material for today's building construction (Syed M. S. Kazmi et al., 2017).

The main applications of the eco-friendly clay bricks produced are for constructing exterior wall brickworks, facing brickworks, short columns, arches, floors, and reinforced brickwork. One of the

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improved qualities of these bricks is weight reduction, which contributes to reducing the dead loads of the overall structure and finally helps in the economic design of the foundations of the buildings (Syed M. S. Kazmi et al., 2017). Besides that, these sustainable materials can withstand different climatic conditions and weather changes, leading to clay bricks being commonly used throughout various continents. In addition, the improved quality of eco-friendly bricks with reduced water absorption increases their usage for both internal and external purposes. Significantly, the enhanced structural quality has made these bricks applicable not only for small structures but also for high-rise structures. Utilisation of glass waste in construction materials helps reduce the volume of waste glass in landfills. Besides that, it decreases the quantity of natural elements required for construction (Ogundairo et al., 2019). Most importantly, the primary reason for using this sustainable material is its enhanced strength and thermal conductivity. Thus, efforts to encourage waste glass in construction materials require prolonged research and development, particularly regarding economic concerns.

Hasan et al. (2021), Mohsin et al. (2023), Phonphuak et al. (2016) and Tripathi & Chauhan (2021) has stated that waste glass is one of the most attractive options to incorporate in bricks due to the availability of waste glass and the mechanical and durability properties of glass itself. Glass as a fragile, inert and amorphous material has been extensively used in the manufacturing of vast products worldwide (Syed Minhaj Saleem Kazmi et al., 2018) and because of the widespread consumption, an enormous amount of waste glass is being produced annually around the world. It has now emerged as a severe environmental problem. Usually, waste glass can be recycled to create new glass. However, according to Ferdous et al. (2021), there are 130 million tons of waste glass generated every year globally, but only 21% of the waste glass generated is recycled. Malaysia's abundant post-consumer soda-lime glass and ball-clay resources make this route attractive for reducing landfill burdens and conserving natural clay while meeting performance needs. Hence, waste glass could be utilised as an additive on clay bricks to minimise the consumption of natural resources, the cost of waste glass disposal, and environmental pollution. It was found that when waste glass was incorporated in a mixture as an additive, it could induce vitrification in clay bricks, producing higher-density and lower water absorption capacity bricks (Crespo-López & Cultrone, 2022; Phonphuak et al., 2016).

Generally, vitrification is the formation of glass through the melting of crystalline silicate compounds and transformation into amorphous compounds associated with glass (Sanito et al., 2022). The strength of the structure and water absorption capacity are affected by the vitrification process. When the clay brick is fired at high temperature with waste glass, the waste glass, an amorphous solid with no fixed shape, is vitrified into molten glass and fills the gaps and pores between the clay particles. After the clay brick is cooled, the liquid glass will bind the other clay particles together and form a rigid structure with higher density, lower porosity and water absorption capacity. However, there is still a need to relate the effect of waste glass on the compressive strength, density, apparent porosity, bulk density, and water absorption of the brick manufactured. This study evaluates Malaysian ball clay with up to 20 wt.% post-consumer soda-lime glass fired at 900 °C, reporting coordinated improvements in shrinkage, density, porosity, water uptake, and strength, confirmed by microscopy. To our knowledge, a Malaysia-focused, microscopy-backed dataset at 900 °C with four independent specimens for each composition (0, 5, 10, 15, and 20 wt.% of waste glass) is scarce.

2. METHODOLOGY

Ball clay was used as the raw material for manufacturing clay brick and purchased from Eda Bey supplier in Ipoh, Perak, Malaysia. The waste glass was utilised as a substitute for ball clay used in the clay brick. Around 10 kg of used waste glass bottles were collected from the local neighbourhood in Taman Panorama Tambun Perdana, Ipoh, Malaysia (geographical coordinate: 4° 34' 8'' North, 101° 8' 19'' East) for this project.

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2.1 Brick specimen preparation

Fig. 1 shows the overall preparation process for the brick specimen. Waste glass bottles were crushed into small pieces of glass using a hammer. Then, the glasses were milled into powder form using a manual Proctor compaction hammer (effective drop mass 2.50 kg; drop height 305 mm; ~30 blows min^{-1}, 25 blows per layer), and a MATEST mechanical sieve shaker (10 min, 600 µm stainless-steel mesh) was used to control the size of the glass powder. The process was repeated several times until all the glass powder collected was smaller than 600 µm.

A wooden brick mould measuring 190 × 90 × 90 mm was constructed from plywood and utilised as the brick mould, as per the BIS (Bureau of Indian Standards) proposal (Siddiquee, n.d.). Then, brick specimens were prepared by mixing the clay and glass powder in various mass ratios. Five brick specimens were prepared with multiple waste glass amounts from 0, 5, 10, 15, and 20 wt.%. The detailed mass composition of each type of brick is shown in Table 1.

After weighing the clay and glass powder according to the mass ratio, the mixture was mixed with 40% water for the clay's weight and continuously mixed until the clay doughs were formed. The clay doughs were placed into the wooden brick mould with the specified dimensions. Excess clay was removed and scraped out of the brick mould, and air bubbles were removed from the mixture to prevent voids from forming on the bricks' surfaces. Afterwards, the shaped brick specimens were removed from the wooden brick mould and dried in the drying oven at 90 °C for 3 days until the bricks were thoroughly dried. Then, the fully dried bricks were sent for the firing process in the furnace at 900 °C for 3 hours. Twenty brick specimens were made in this research for a series of physico-mechanical tests.

Table 1. Mass composition of each type of brick specimen

Type	Waste glass to clay ratio (%)	Dry weight of clay required (g)	Dry weight of glass powder required (g)	Water amount (g)
A (Control)	0	2100	0	840 ± 50
B	5	1995	105	798 ± 50
C	10	1890	210	756 ± 50
D	15	1785	315	714 ± 50
E	20	1680	420	672 ± 50

Source: Authors' own data

Firing refers to the kiln heat-treatment; sintering is the diffusion-bonding mechanism that occurs during firing. In this work, bricks were fired at 900 °C for three hours, which promoted sintering and partial vitrification. Before sending clay bricks for firing, the brick specimens must be thoroughly dried in a drying oven for at least 24 hours. The drying process must be done slowly because when the temperature has reached 100 °C, the water in the bricks will form steam within the clay body. If the drying is too rapid, an explosion may occur. After the brick specimens had completely dried, they were fired in the furnace. When the temperature of the furnace has reached 350 °C, this is the point where the chemically bound water of the clay has driven off. This chemically bound water originates from the molecular structure of the clay, rather than from the water molecules between the clay particles. This process is called dehydration and will last up to 500 °C. At around 573 °C, quartz inversion occurs, where quartz crystals will rearrange themselves into a slightly different order. It is followed by the vitrification process, which involves the hardening, tightening, and partial glassification of clay.

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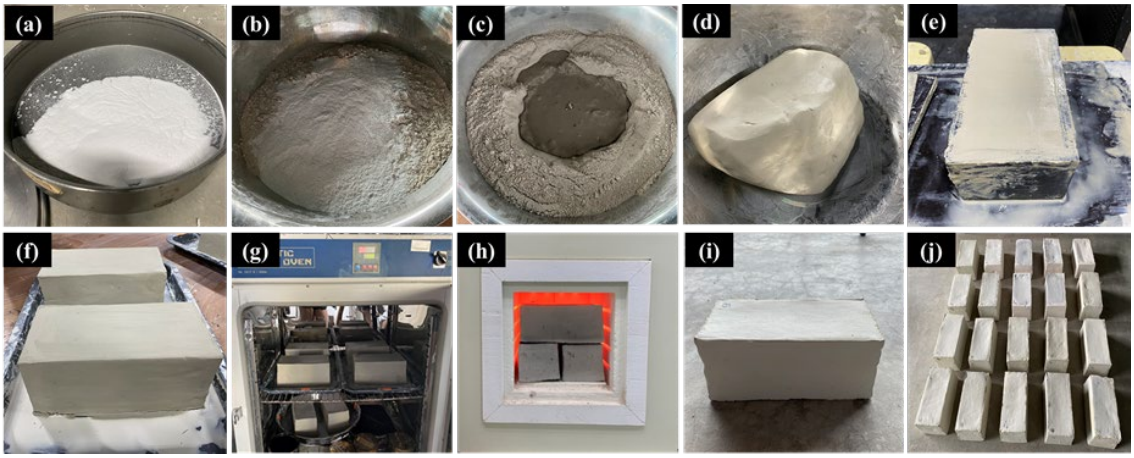

Fig. 1. Clay brick making: (a) Crushing & milling of waste glass; (b) Weighing ball clay and glass powder according to ratio; (c) Adding water into the mixture and mix; (d) Mix until a clay dough has formed; (e) Put into brick mould; (f) Demoulding of brick from brick mould; (g) Drying at 90 °C for at least 24 hours; (h) Firing at 900 °C for 3 hours; (i) cooling process; (j) Total of 20 bricks were made with 4 bricks for each ratio (0, 5, 10, 15, and 20 wt.%)

Source: Authors' own data

2.2 Characterisation of raw materials and brick specimens

The clay particles and glass powder were analysed using an x-ray diffraction (XRD) spectrometer to examine the mineralogy composition of both materials. The composition of the raw materials will contribute to the constituents of the final brick specimens being produced. Each of the constituents will demonstrate different physical and mechanical properties. With the combination of clay and additives, the overall properties and performance of the bricks would change compared to normal clay bricks without additives. The brick specimens were cut into a 10-cent size (~180 mm diameter) using an angle grinder as shown in Fig. 2. Then, the samples underwent XRD analysis for the chemical composition using the X-ray diffractometer (XRD, Rigaku, Ultima IV) using monochromatic Cu-Ka radiation with a wavelength of 1.5406 Å, tested in ADTEC Taiping.

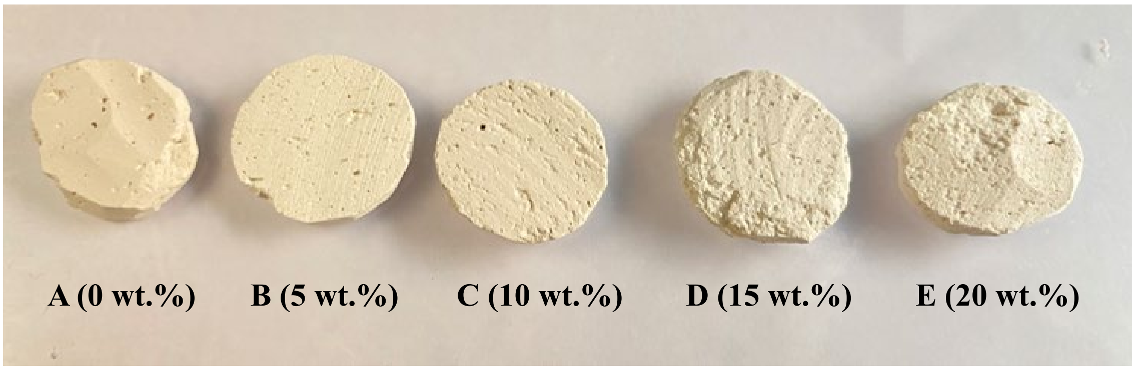

Fig. 2. Optical images of brick specimens with various waste glass amounts for XRD analysis and morphology under a digital microscope

Source: Authors' own data

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2.3 Testing methods

After the firing process, the brick specimens (190 × 90 × 90 mm) were cooled to room temperature to conduct the physical-mechanical performance tests such as shrinkage analysis, compressive strength analysis, bulk density, apparent porosity and water absorption. These properties are considered the most important for clay bricks, as they have a strong correlation with the durability and performance of bricks. Additionally, the properties are correlated and mutually affect each other. For instance, shrinkage and water absorption depend on the porosity of the brick. The bulk density, apparent porosity and water absorption are also interconnected. Unless stated otherwise, all values are mean ± SD based on n = 4 specimens per composition; error bars denote SD.

Linear shrinkage

A brick solid is generally formed by mixing clay or any additive particles with adequate water. When brick is dried and fired at high temperatures, the water contained within the brick evaporates, and the brick particles come closer to each other, causing the brick to reduce in dimensions. Bricks should usually have a shrinkage value below 8% as higher shrinkage will cause cracking and internal fractures in the brick body (Mancuhan et al., 2016). Eq. (1) shows the equation to calculate the percentage of linear shrinkage, S_L.

$$\text{Linear shrinkage, } S_L\ (\%) = (\text{Length before drying and firing} - \text{Length after drying and firing}) / (\text{Length before drying and firing}) \times 100 \quad (1)$$

Bulk density, apparent porosity and water absorption

The bulk density of brick indicates the mass of brick per unit volume, and a greater bulk density means that the brick is heavier while possessing higher strength to withstand greater force. The bulk density is tested according to ASTM C20 (Standard Test Methods for Apparent Porosity, Water Absorption, Apparent Specific Gravity, and Bulk Density of Burned Refractory Brick and Shapes by Boiling Water) (ASTM, 2022).

The brick specimens were dried to a constant mass at a temperature of 105 °C for 24 hours and labelled as 'Dry weight'. Then, the bricks were submerged in water for another 24 hours. Next, the bricks were removed from the water, wiped with a cloth to remove excess water from their surfaces, and then weighed using the digital weighing scale. The reading was recorded as 'Saturated Weight'. Continuously, the suspended weight of the brick in water was measured based on Archimedes' method (Rahman et al., 2023). The weight of bricks when suspended in water was measured using the digital weighing balance with a hook and recorded as 'Suspended weight'. Eq. (2) and (3) were used to calculate the exterior volume and bulk density, respectively.

$$\text{Exterior volume, } V\ (cm^3) = \text{Saturated weight } (W_{sat}) - \text{Suspended weight } (W_s) \quad (2)$$

$$\text{Bulk density } (g/cm^3) = (\text{Dry weight, } D) / (\text{Exterior volume, } V) \quad (3)$$

Apparent porosity is a factor to consider in terms of serviceability and performance. Clay is the most porous sediment, contributing to high porosity for pure clay brick. Hence, clay bricks can absorb and release water easily. Under low temperatures, water is absorbed into the brick body, while at high temperatures, water is released from the brick due to evaporation. However, a high apparent porosity brick is likely susceptible to weathering and chemical attacks. In this research, the apparent porosity of clay brick incorporated with waste glass was investigated to determine waste glass's ability to reduce the porosity of

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clay bricks, thus increasing the brick's serviceability and performance. An apparent porosity test was conducted according to ASTM C20, as outlined in Eq. (4).

$$\text{Apparent porosity (\%)} = (\text{Saturated weight, } W_{sat} - \text{Dry Weight, D}) / (\text{Exterior volume, V}) \times 100 \quad (4)$$

Water absorption is one of the critical parameters to determine the durability property of a brick in terms of the degree of burning, the quality, and the brick's behaviour in weathering (Ikechukwu & Shabangu, 2021). This parameter is critical because brick is a construction material that will be actively exposed to moisture, acids, salts, temperature, and climate changes. Hence, a good quality brick should possess the characteristic that can withstand weathering effects and be durable for an extended period. Clay bricks are composed of clay soil particles, which contain many internal pores that promote the capillary effect and absorb water. Due to its low density, clay soil can retain large amounts of water. The water absorption capacity for clay bricks is recommended to be around 12% and 20% (Fall et al., 2021; Niyomukiza et al., 2022). It is difficult to properly bond the mortar and bricks if a clay brick has either lower or higher water absorption outside the range.

Water absorption analysis for clay bricks was performed following the standard of ASTM C67 (Standard Test Methods for Sampling and Testing Brick and Structural Clay Tile) (ASTM C67, 2001). Before the test, the dry weight of the brick sample was measured and recorded. Brick specimens were soaked in water for 24 hours at room temperature. Then, brick specimens were removed from the water, and excess water was cleaned off the brick surfaces. The weight of the brick is now the saturated weight that was measured. The water absorption for brick was calculated using Eq. (5).

$$\text{Water absorption (\%)} = (\text{Saturated weight, } W_{sat} - \text{Dry weight, D}) / D \times 100 \quad (5)$$

Compressive strength

Compressive strength is one of the critical mechanical properties to investigate for construction materials. Compressive strength testing followed ASTM C67 (Standard Test Methods for Sampling and Testing Brick and Structural Clay Tile). Specimen geometry was 190 × 90 × 90 mm; load was applied at a constant rate of 0.05 MPa s^{-1} (≈ 790 N s^{-1} for the measured bearing area) until failure. Before performing the compressive strength analysis, the length and width of the brick specimens' upper surface and lower surface were measured to calculate the average area. Then, the brick specimens were aligned centrally on the base plate of the concrete test machine, and a uniform incremental load was applied until failure occurred. The indicator reading on the testing machine was raised until a maximum reading was achieved, and then it started to reduce. The maximum value indicates the maximum load that the brick can resist. The formula used to calculate the compressive strength is shown in Eq. (6).

$$\text{Compressive strength, } C = W/A \quad (6)$$

where W is the maximum load applied, and A refers to the cross-sectional area of the cube specimen.

Pore size characterisation of brick specimens

The brick specimens of each waste glass-to-clay ratio were cut into smaller pieces and placed under the MUSTOOL G1200 portable digital microscope (1200× magnification) to observe each brick specimen's structure and pore size.

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3. RESULTS AND DISCUSSION

3.1 Characterisation of raw materials and brick specimens

XRD patterns are characterised by sharp peaks and humps along the graph, where sharp peaks indicate the presence of a crystalline phase or mineral, whereas a hump indicates an amorphous phase. From Fig. 3(a), many sharp peaks indicate that the ball clay consists of kaolinite, $Al_2(Si_2O_5)(OH)_4$ and quartz, SiO_2. The highly crystalline kaolinite area was displayed by narrow and sharp peaks, especially at 2θ of 12.3° and 24.9°, whereas intense quartz peaks can be seen at 20.2° and 26.9°, respectively. Conversely, Fig. 3(b) only shows the halo peak in between 2θ values of 15° and 30°, respectively, due to the distribution of the bond lengths and bond angles, which causes the broadening of the peak. It indicates at least one amorphous phase inside the waste glass sample with short-range order and no crystalline compounds. In Fig. 3(c), the XRD pattern shows a reduction of the crystalline phase, which confirms that most of the crystalline compounds have transformed into a glassy phase and formed a compact clay brick (Gencel et al., 2021; Xin et al., 2023) with the increment of waste glass to clay ratio. It shows a significant change in the clay phase when sintered at 900 °C with higher waste glass content.

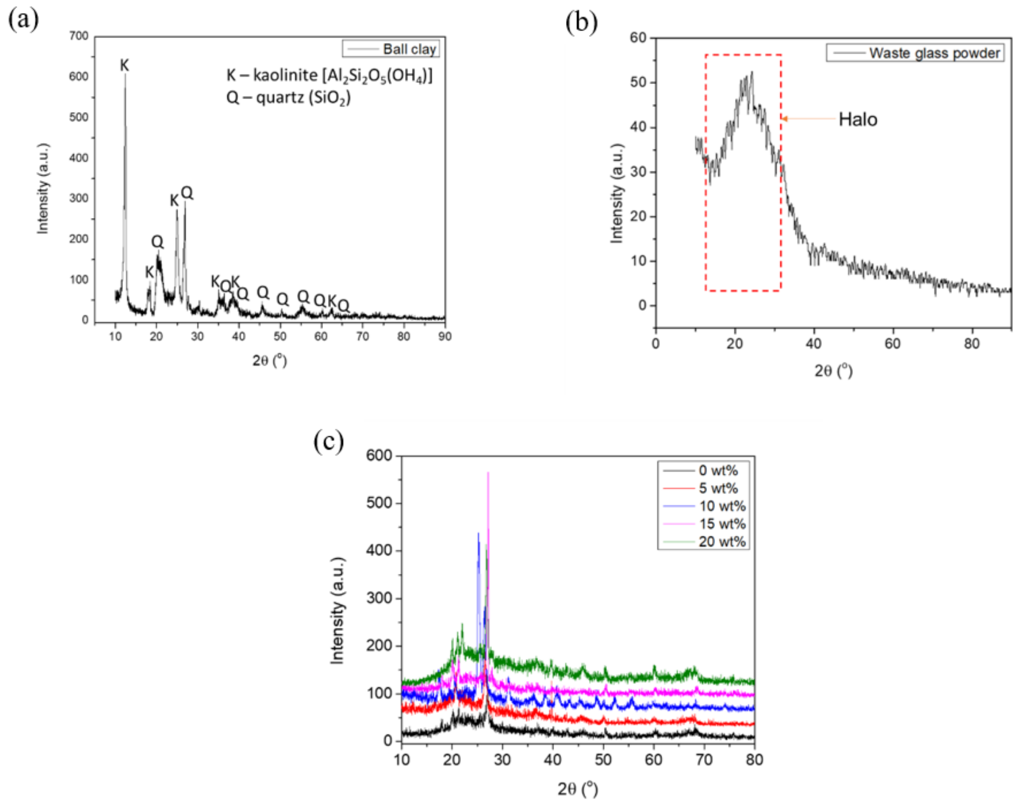

Fig. 3: XRD of (a) ball clay: kaolinite (001) 12.3°, (002) 24.9°; quartz (100) 20.2°, (101) 26.6°; (b) waste glass: broad amorphous halo 15–30°; (c) fired bricks (0–20 wt.% WG): residual quartz (101) 26.6° decreasing with WG and a growing amorphous halo, indicating increased glassy phase

Source: Authors' own data

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3.2 Physical-mechanical properties of brick specimens

Linear shrinkage

Shrinkage is a common phenomenon that occurs in the brick manufacturing industry. The evaporation of water physically and chemically bound within the bricks is due to the loss that occurs during the drying and firing process of clay bricks. Although it is a usual phenomenon, the shrinkage value should not be high, as excessive shrinkage will cause internal compressive stress, resulting in cracks in the clay bricks.

Fig. 4 shows that the linear shrinkage decreases with the increase of waste glass incorporated in the clay bricks. Waste glass acts as a flux during firing, promoting liquid phase formation that fills pores and reduces shrinkage (Xin et al., 2021). Excessive shrinkage generates internal stresses that promote cracking (Makrygiannis et al., 2023; Mancuhan et al., 2016). For the control brick without any waste glass, the linear shrinkage is 8.035%, the highest percentage among all the brick specimens. Whereas the clay brick incorporated with 5 wt.% of waste glass, it has demonstrated a linear shrinkage of 7.642%, followed by 10 wt.% waste glass to clay ratio with a linear shrinkage of 6.879%, 15 wt.% of waste glass addition with shrinkage value of 6.513% and lastly was the highest waste glass to clay ratio of 20 wt.% that obtained the lowest shrinkage value which is 6.169%.

Several reasons can explain the reduction in linear shrinkage with the increase of waste glass. Firstly, when the waste glass-to-clay ratio increases, more glass powders are introduced into the mixture while the amount of clay has reduced. Due to the characteristics of clay particles, which consist of fine particles and have a large surface area with tiny pore size, they have the capacity to retain water. As compared to clay, glass has lower water-retaining capability. Hence, reducing the amount of clay will reduce the maximum amount of water absorbed by the bricks (Crespo-López & Cultrone, 2022; Tripathi & Chauhan, 2021). Then, during the drying and firing process, the amount of water evaporated is the highest in the control brick without glass addition. With the highest waste glass addition, the maximum amount of water absorbed will be less; hence, it demonstrates lower linear shrinkage.

Secondly, because clay has high porosity, clay bricks would also have high porosity. With the addition of glass particles, more glassy phases were available to fill up the pores and make a denser clay brick. Hence, the linear shrinkage will reduce with increased waste glass addition. A previous study by Mao et al. (2018) has also mentioned that the glass phase can fill up pores in clay bricks and produce a denser brick matrix with lesser shrinkage.

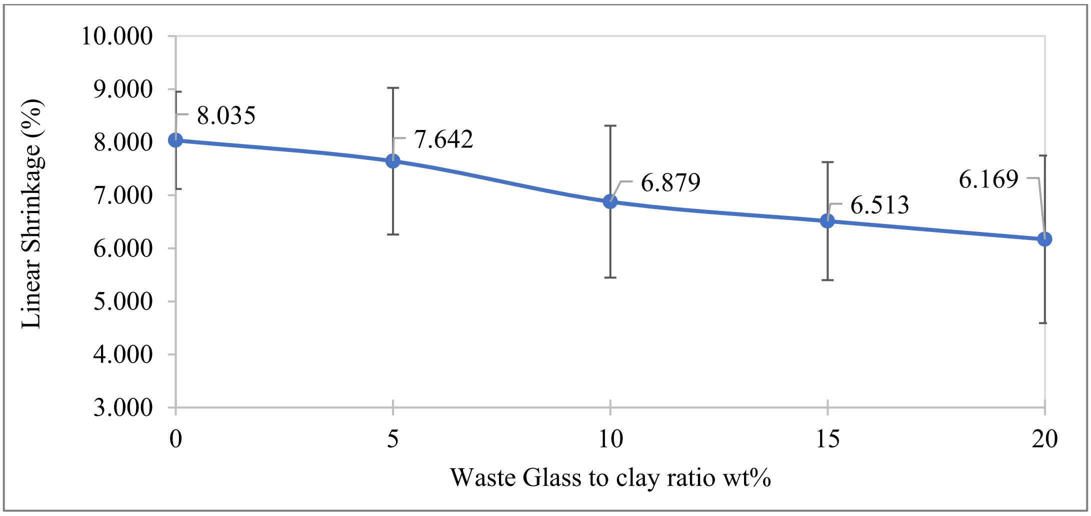

Fig. 4: Linear shrinkage of brick specimens with different waste glass-to-clay ratios (wt.%). Points are means, and error bars indicate ± SD (n = 4)

Source: Authors' own data

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Bulk density

Bulk density is an indicator which shows the compaction of substances within the object matrix. Low bulk density in a clay brick means that the brick matrix is not dense, the brick has high porosity and inter-particle void volume. Bulk density increased monotonically with WG content from 1.236 to 1.375 g cm^{-3}, consistent with densification as softened glass closes interparticle voids at 900 °C. As shown in Fig. 5, the bulk density of brick specimens increases with the increase in the waste glass-to-clay ratio. Adding 5 wt% waste glass increased the clay brick's bulk density from 1.236 to 1.272 g/cm^3. For a waste glass of 10 wt% and 15 wt%, the results showed a gradual increase to 1.288 g/cm^3 and 1.329 g/cm^3, respectively. The clay brick obtained the highest bulk density, which was 1.375 g/cm^3, with the highest waste glass-to-clay ratio.

The result has demonstrated that bulk density is proportional to the waste glass-to-clay ratio. This occurrence can be elucidated by the fact that increasing the amount of glass in a brick structure results in more glass particles bonding with the clay bodies. Thus, increasing the weight of clay bricks. Moreover, firing clay bricks will induce vitrification in the brick structure. Vitrification indicates the formation of a glassy phase by transforming crystalline silicate compounds contained in clay into an amorphous phase, a non-crystalline atomic structure like glass. The addition of glass amount will act as a fluxing agent to contribute to the vitrification process by reducing the viscosity of the liquid phase during the firing process (Koca et al., 2012). Then, the melted amorphous glassy phase will close the voids and gaps in the high porosity brick structure, reducing the total volume of clay brick, including the particle volume, inter-particle void volume and internal pore volume. A decrease in total volume will lead to an increase in the bulk density. The results show that adding waste glass content up to 20 wt% can increase the bulk density of clay bricks. Similar results can be observed in the previous studies by Hasan et al. (2021) and Kazmi et al. (2018), after adding waste glass into clay bricks.

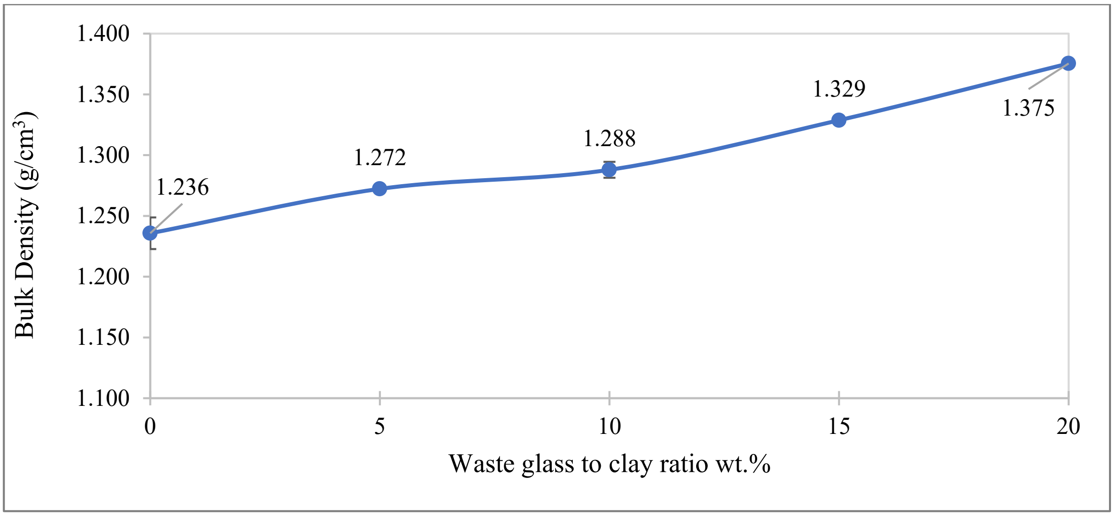

Fig. 5: Bulk density of brick specimens with different waste glass-to-clay ratios (wt.%). Points are means, and error bars indicate ± SD (n = 4)

Source: Authors' own data

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Apparent porosity

An apparent porosity measures the volume of pore spaces over the bricks' total volume occupied. The performance and the quality of the brick depend on the porosity. The pore spaces are associated with the transport of moisture in and out of the brick structure. A lower apparent porosity was desired as high porosity will expose the clay bricks to adverse weathering effects. Fig. 6 shows that the apparent porosity decreases as the waste glass-to-clay ratio increases. The apparent porosity of the control brick has demonstrated a value of 41.333%. After 5 wt.% of waste glass was added, the apparent porosity reduced to 39.986 %. Following the addition of 10 wt.% waste glass, a value of 38.565% was obtained. With a 15 wt.% waste glass addition, the value achieved was 37.17%. Lastly, 34.71% was revealed for the highest percentage of waste glass addition, which was 20 wt.% into the clay brick mixture.

The development of the glass phase can explain this result during the firing process of clay bricks at 900 °C. At high temperatures, the glass particles will fuse with the clay bodies and are associated with the densification of clay bricks. With the increased amount of glass particles, more glass particles can be fused, and more internal pores can be closed, resulting in a lower pore volume as exhibited in the final structure of the brick after the firing process. Furthermore, the increase in waste glass addition induces more vitrification processes of clay bricks. Hence, a reduction of apparent porosity can be observed in this experiment. A similar result was achieved by the previous studies conducted by Phonphuak et al. (2016), where the least porosity of brick specimens was obtained with the highest amount of waste glass added into the clay brick. Also, in the study conducted by Johari et al. (2010), the clay bricks fired at 900 °C have a porosity value of 39%.

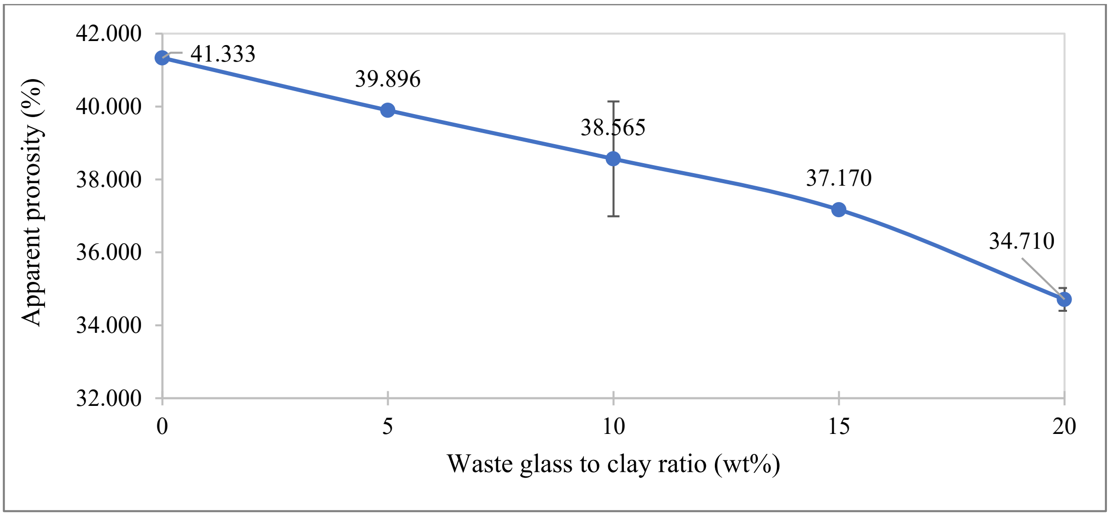

Fig. 6: Apparent porosity of brick specimens with different waste glass-to-clay ratios (wt%). Points are means, and error bars indicate ± SD (n = 4)

Source: Authors' own data

Water absorption

Water absorption properties are associated with the durability of clay bricks. Clay bricks with less water absorption capacity are deemed to have better resistance to weathering. In contrast, high water absorption is undesirable as cracks might be formed in the brick body, reducing the clay brick's durability. Based on Fig. 7, lower water absorption indicates better weathering resistance; as waste-glass content increased from

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0 to 20 wt.%, absorption fell from 33.45% (0 wt.%) to 31.356% (5 wt.%), 29.943% (10 wt.%), 27.975% (15 wt.%), and 25.236% (20 wt.%), confirming that waste-glass additions consistently reduce water uptake and should improve durability.

This progressive decline reflects microstructural densification from the viscous flow of softened glass, which reduces pore connectivity. Given the parallel decrease in apparent porosity (~16.0%) and rise in bulk density (+11.3%), densification is the dominant driver, in line with Hasan et al. (2021) and Kazmi et al. (2018), who attributed reduced water uptake primarily to pore closure. Firing at 900 °C causes the waste glass to fuse into a vitreous phase that flows viscously and densifies the brick matrix. This densification closes pores and reduces water absorption. Because glass absorbs less water than clay, substituting 20% waste glass for clay further lowers overall water uptake.

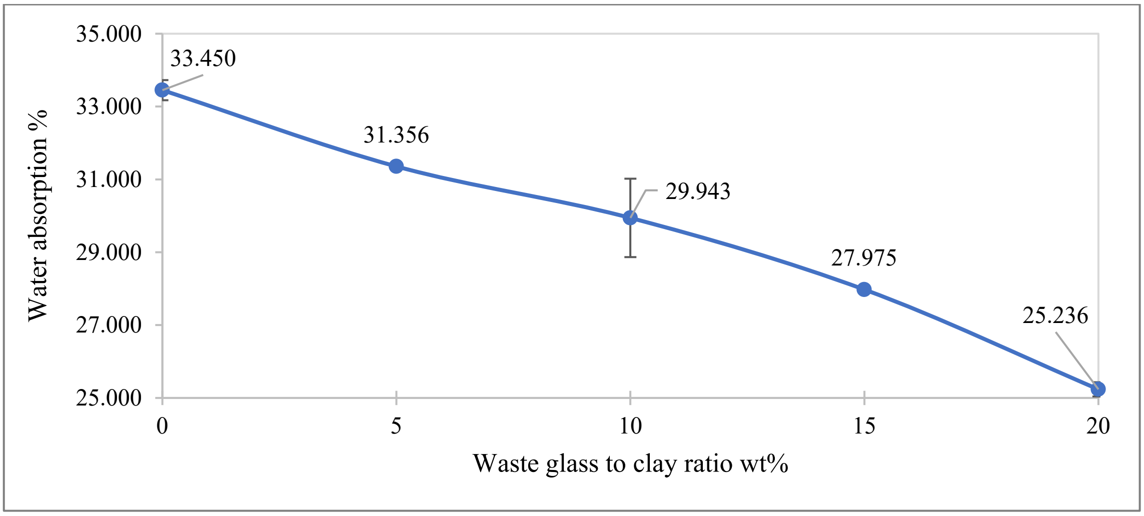

Fig. 7: Water absorption of brick specimens with different waste glass to clay ratio (wt%). Points are means, and error bars indicate ± SD (n = 4)

Source: Authors' own data

Compressive strength

Compressive strength is the most crucial property to determine the quality of building brick, and it can determine how much load can be applied to the clay brick before failure occurs. A higher abrasion resistance can be deduced from a high compressive strength result. The results show that the compressive strength of the clay bricks depends on the addition of waste glass. Fig. 8 shows that the compressive strength increased from 8.12 MPa (0 wt.% WG) to 10.51 MPa (20 wt.% WG), a +29.4% gain, attributable to glass-assisted densification. Further increases in WG may not continue this trend; excessive glassy phases can embrittle the matrix

The obtained result can be explained by the fact that increasing the glass content helps induce vitrification in the internal structure of clay brick during the firing process. During vitrification, the crystalline silicate compounds in clay tend to melt into amorphous, non-crystalline atomic structures correlated with glass (Sanito et al., 2022). The glassy phase then fills up the voids in the brick specimens. Therefore, by increasing the waste glass content, more glassy phases are available during the firing process to close the internal pores of bricks, thus increasing the compressive strength. The increase in compressive strength is related to the reduction in porosity and increase in density, as mentioned in the apparent porosity and bulk density analysis. This result can be supported by the similar trendline observed in the work by

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Phonphuak et al. (2016), where the compressive strength increases when waste glass addition rises from 0 to 10%.

The results indicate that WG additions up to 20 wt.% enhance compressive strength by ~29.4% via microstructural densification. Slightly lower gains than Kazmi et al. (2018) likely reflect the combined effects of specimen geometry (228 × 114 × 76 mm versus 190 × 90 × 90 mm in this work), raw clay mineralogy, and firing schedule, which modulate vitrification extent and stress distribution. Hence, the difference between them could be accepted.

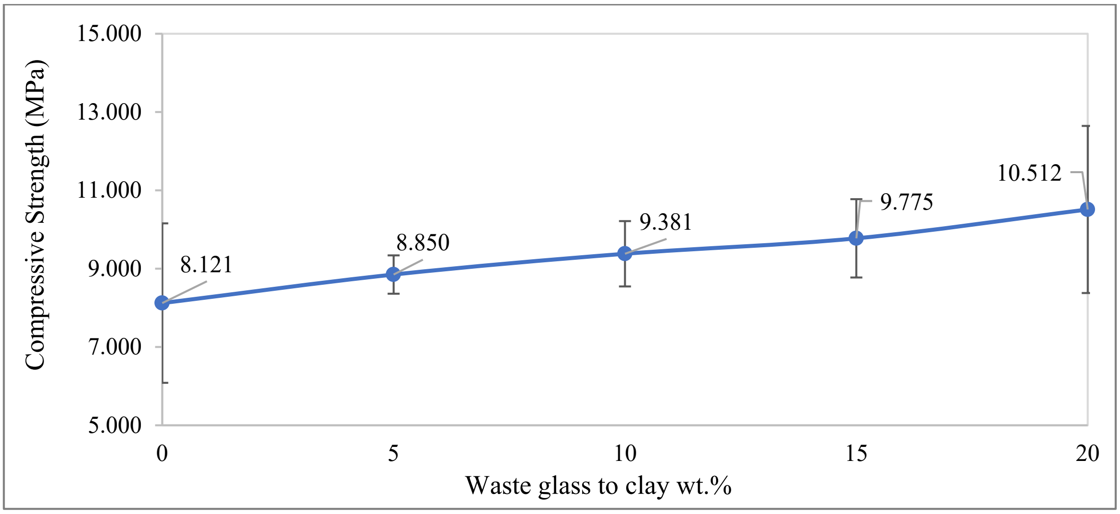

Fig. 8: Compressive strength of brick specimens with different waste glass to clay ratio (wt.%). Points are means, and error bars indicate ± SD (n = 4)

Source: Authors' own data

Pore structure analysis on brick specimens

Fig. 9 shows the images of clay brick specimens with varying waste glass-to-clay ratios. It has been demonstrated that increasing the waste glass to clay ratio results in clay brick specimens with a denser brick matrix, characterised by reduced porosity and smaller pores, as shown in Fig. 9(e). At 0 wt.% WG (Fig. 9a), large, interconnected pores are observed, while at 20 wt.% WG (Fig. 9e), pores are smaller and less frequent, confirming improved densification. Fig. 9(b), (c), and (d) show that the number of pores has reduced with the higher waste glass to clay ratio. Fig. 9 shows progressive pore-size reduction and fewer open pores with increasing WG, consistent with a denser matrix and with the observed drop in water absorption and rise in strength. Future work should quantify pore-size distributions (e.g., image analysis). At 900 °C, soda-lime glass softens and flows into interparticle voids, reducing open porosity and forming a denser matrix. These results agree with the SEM images analysed by Xin et al. (2023), which indicate that the bricks are denser with increasing glass composition. Similar pore-closing effects of waste glass in fired ceramics have been reported (Crespo-López & Cultrone, 2022; Gencel et al., 2021; Xin et al., 2023).

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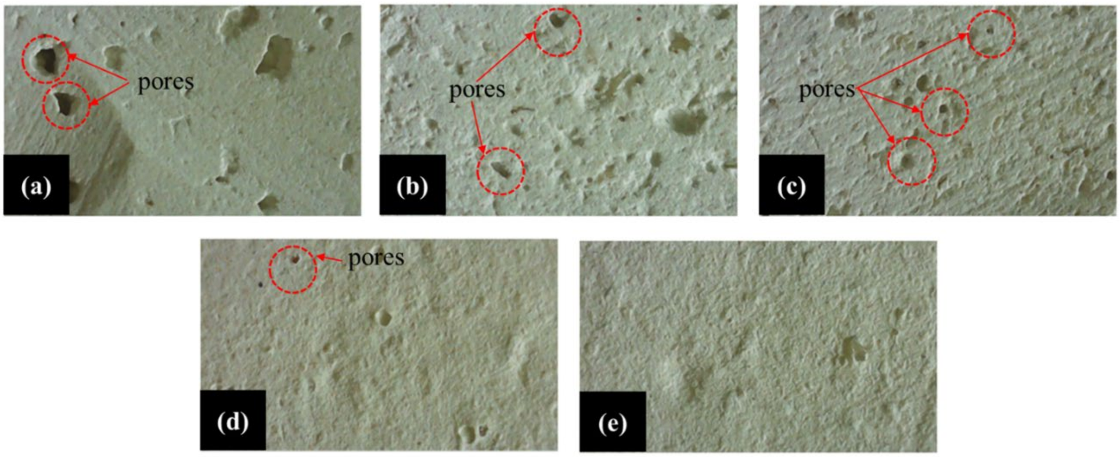

Fig. 9: Optical micrograph of specimens (a) 0 wt.% WG;(b) 5 wt.% WG;(c) 10 wt.% WG; (d) 15 wt.% WG, and (e) 20 wt.% WG

Source: Authors' own data

4. CONCLUSIONS

Eco-friendly clay bricks incorporating 0, 5, 10, 15 and 20 wt.% of waste glass to the clay were prepared and analysed. All brick specimens were characterised by their mineralogical composition using the X-ray diffractometer technique. The pore size of bricks was characterised using a portable digital microscope. Moreover, the effect of different waste glass-to-clay ratios on the physical-mechanical properties was also analysed throughout the research. The XRD pattern shows a reduction of the crystalline phase, which confirms that most crystalline compounds have transformed into a glassy phase and formed a compact clay brick. The micrograph shows that the number of pores has reduced with the higher waste glass-to-clay ratio, which confirms that the transformation of the glassy phase causes the closing up of internal pores in the brick structure during the firing process of clay bricks at 900 °C. It is feasible to incorporate waste glass as a substitute for clay in manufacturing clay bricks. The clay brick with a 20% waste glass to clay ratio is the best quality of brick among the other ratios, as it can achieve the lowest linear shrinkage, highest bulk density with the lowest apparent porosity, the lowest water absorption, and the highest compressive strength compared to other bricks. Variability in waste-glass composition, kiln uniformity at scale, and long-term durability (freeze–thaw, sulfate, alkali-silica) were not assessed and warrant future work. Nonetheless, using 15–20 wt.% WG can lower clay consumption and landfill load with minimal processing beyond crushing/sieving, supporting near-term pilot-scale trials in Malaysia.

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CONFLICT OF INTEREST STATEMENT

The authors agree that this research was conducted in the absence of any self-benefits, commercial or financial conflicts and declare the absence of conflicting interests.

AUTHORS' CONTRIBUTIONS

Chew Kai Ying: Conceptualisation, methodology, formal analysis, investigation, visualisation and writing-original draft; **Mohd Fadhil Majnis**: Conceptualisation, supervision, formal analysis and validation; **Mustaffa Ali Azhar Taib**: Conceptualisation, resources, formal analysis, and validation; **Ayu Haslija Abu Bakar**: Writing- review and editing, and validation; **Maliza Ismail Jamail**: Writing- review and editing.

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