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Developing and Mechanical Properties of Low Fired and Geopolymer Bricks from Drinking Water Sludge with Different Contents of Added Fly Ash

(Pembangunan dan Sifat Mekanik Bata Suhu Rendah dan Geopolimer daripada Enap Cemar Air Minuman dengan Kandungan Berbeza Nilai Tambah Abu Terbang)

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ABSTRACT

Raw water treatment and coal-based power generation facilities produce a high level of waste to the environment annually. A low recycling scheme has worsened the situation and wastes usually end up in a landfill. Further environmental degradation could be prevented by re-utilising wastes for the production of alternative bricks. Additionally, the development of low-fired brick from wastes can comparatively reduce energy consumption during the firing stage. Geopolymer has successfully replaced ordinary portland cement (OPC) without bargaining its mechanical quality. This study aimed to investigate the effect of fly ash (FA) content and geopolymerization on mechanical characteristics of brick developed from drinking water sludge (DWS). A set of brick samples was fired at 500 °C while another set of samples was prepared under a high alkaline condition to produce geopolymer bricks. Resultantly, both sets of samples demonstrated a decrease in linear shrinkage and increased density with more content of FA. For fired brick samples, the water absorption decreased from 38.6% to 33.3% before rising again at 45% of FA content. However, a continuous decrease was displayed by geopolymer brick as FA increased. The compressive strength of fired bricks showed a decreasing trend as FA content increased and vice versa for the geopolymer brick. The compressive strength of geopolymer bricks increased from 1.22 MPa to 3.63 MPa at 45% of FA content. Comparatively, geopolymer bricks demonstrated higher strength than fired bricks. These results reflect the advantage of the incorporated wastes and geopolymerisation in developing alternative brick for sustainable resources and a better environment.

Keywords: Compressive strength; drinking water sludge; fired brick; fly ash; geopolymer

ABSTRAK

Rawatan air mentah dan kemudahan penjanaan kuasa berasaskan arang batu menghasilkan tahap sisa yang tinggi kepada alam sekitar setiap tahun. Skim kitar semula yang rendah telah memburukkan keadaan dan sisa buangan biasanya berakhir di tapak pelupusan sampah. Kemerosotan alam sekitar selanjutnya boleh dicegah dengan menggunakan semula bahan buangan untuk pengeluaran batu bata alternatif. Selain itu, pembangunan bata berapi rendah daripada bahan buangan secara perbandingan boleh mengurangkan penggunaan tenaga semasa peringkat pembakaran. Geopolimer telah berjaya menggantikan simen portland (OPC) biasa tanpa mempertikaikan kualiti mekanikalnya. Penyelidikan ini bertujuan untuk mengkaji kesan kandungan abu terbang (FA) dan geopolimerisasi terhadap ciri mekanikal bata yang dihasilkan daripada enap cemar air minuman (DWS). Satu set sampel bata dibakar pada suhu 500 °C manakala satu set sampel lagi disediakan dalam keadaan beralkali tinggi untuk menghasilkan bata geopolimer. Hasilnya, kedua-dua set sampel menunjukkan penurunan dalam pengecutan linear dan peningkatan ketumpatan dengan lebih banyak kandungan FA. Bagi sampel bata yang dibakar, penyerapan air menurun daripada 38.6% kepada 33.3% sebelum meningkat semula pada 45% kandungan FA. Walau bagaimanapun, penurunan berterusan ditunjukkan oleh bata geopolimer apabila FA meningkat. Kekuatan mampatan batu bata yang dibakar menunjukkan trend menurun apabila kandungan FA meningkat dan begitu juga sebaliknya untuk bata geopolimer. Kekuatan mampatan bata geopolimer meningkat daripada 1.22 MPa kepada 3.63 MPa pada 45% kandungan FA. Secara perbandingan, bata geopolimer menunjukkan kekuatan yang lebih tinggi daripada bata yang dibakar. Keputusan ini mencerminkan kelebihan sisa yang digabungkan dan geopolimerisasi dalam membangunkan bata alternatif untuk sumber yang mampan dan persekitaran yang lebih baik.

Kata kunci: Abu terbang; bata bakar; enap cemar air minuman; geopolimer; kekuatan mampatan

INTRODUCTION

The demand for construction materials such as sand, lime, brick and cement has risen in Malaysia due to the rapid development of urbanisation schemes. Many construction industries rely largely on raw building materials of limited natural resources. Sand and limestone have to be quarried and this process is associated with noise, air and water pollution, which adversely affects the environment. Main construction materials such as brick and cement are manufactured under high thermal energy and have contributed to greenhouse gases emission (Ling & Teo 2011; Madurwar, Ralegaonkar & Mandavgane 2012). For instance, the cement industry represents 8 % of global CO_2 emitted into the atmosphere (Andrew 2018; Blaszczyski & Król 2017). Conventional fired bricks are also prepared under a high temperature ranging from 1100 °C to 1500 °C to achieve the recommended mechanical standard (Agbede et al. 2016; Karaman, Ersahin & Gunal 2006). As a result, the continuous demand and depletion of natural resources have subsequently affected the cost of the construction sector. Therefore, the utilisation of cheaper alternative resources such as recycling wastes as raw materials for manufacturing brick offers a better approach to waste disposal management and minimises environmental-related problems.

The re-utilisation of drinking water sludge (DWS) and fly ash (FA) could be potential alternative materials for making industrial brick. DWS is a by-product that is generated from a drinking water treatment plant. It begins with the coagulant process that neutralises the charges on particles, followed by the flocculation process. This process enables the particles to bind together and separate from the water. Around half a million tonnes of DWS have been generated in Malaysia and the volume is expected to increase annually (DOE 2013). Meanwhile, fly ash (FA) is produced from the coal-based power generator. It is very fine and dark in colour, consisting of a high amount of Si, Al, Fe and Ca oxides (Joshi & Lohita 1997). It contributes to 7.8 billion tonnes of the annual FA production from the combustion of 780 billion tonnes of coal worldwide (Heidrich, Feuerborn & Weir 2013). Fly ash (FA) is non-plastic that remains stable when used as a foundation structural material (Bhatt et al. 2019). It is also pozzolanic, hence aluminous and siliceous materials can form cement in the presence of water similar to Ordinary Portland Cement (OPC), which is suitable as a prime material in blended cement, mosaic tiles, hollow blocks and has been used in concrete mixes (Rodrigez 2021).

The re-utilisation of wastes into alternative products has been encouraged due to limited landfill sites, stringent standards on waste materials and insistence on sustainable practice. The incorporation of wastes as base materials for full or partial replacement of clay or sand may reduce total dependence on natural resources and promote safe waste disposal (Eliche-Quesade et al. 2017; Haniegal et al. 2020). These will improve the environment by minimising issues with waste disposal management and repurposing these wastes into green products. Drinking water sludge contains clay, silt and sand, which can potentially be used as alternative raw material to clay-based products (Oliveira, Sampaio & Holanda 2006). Studies showed that both wastes have been formulated for developing building materials in cement (Aydin et al. 2004; Baricik & Sarier 2014), concrete (Aggarwal, Singh & Aggarwal 2015; Breesem, Faris & Abdel-Magid 2014; Oyejobi, Abdulkadir & Ahmed 2016), and alternative bricks (Anyakora et al. 2012; Haniegal et al. 2020; Mageed, Rizk & Abu-Ali 2011; Tantawy & Mohamed 2017). Fly ash has been used as an additive in a diverse range of ratios between 0% and 70% in unfired (Bikkad et al. 2018; Huy & Phuoc 2017) and fired bricks (Pawar & Garud 2014; Sutcu et al. 2019). Light brick was successfully developed from the combination of fly ash and rice husk ash at the firing temperature between 900 °C and 1100 °C (Chiang et al. 2009). An attempt has also been made to develop light clay brick using wastes from paper mills, orange peels and coconut wastes (Arshad & Pawade 2014). As clay fraction decreased, the compressive strength slightly reduced in both bricks which were incorporated with orange and coconut wastes. The mixture of drinking water sludge (DMS) at different ratios was used to produce clay brick (Fungaro & de Silva 2014; Ramadan, Fouad & Hassanain 2008). Resultantly, the mechanical strength and water absorption increased with the firing temperature. The application of high-firing temperature has increased the cost of production and its implication for the environment such as emission of CO_2 and global warming (Zain et al. 2017). Ali Rahman et al. (2016) showed that the addition of fly ash improved the mechanical strength based on the DWS brick at a lower firing temperature of 500 °C. Further investigation of the effects of fly ash at 20% resulted in lower compressive strength and density, as well as an increase in linear shrinkage (Ali Rahman et al. 2021). However, increasing the firing temperature significantly improved compressive strength when compared to firing at a lower temperature. The utilisation of the geopolymerisation technique to develop a binder can replace the role of OPC and lime, which are largely used in building materials.

Geopolymer can be produced from materials rich in silica and aluminium contents (Rodriguez et al. 2013; Srinivasan & Sivakumar 2013). The strength is provided by the development of a three-dimension amorphous aluminosilicate as a result of the alkaline activation of aluminosilicate at room or higher temperatures (Saravanan, Jeyasehar & Kandasamy 2013). Fly ash is one of the most commonly used aluminosilicates apart from metakaolin (Al Bakri et al. 2011; Elimbi, Tchakoute & Njopwouo 2011). Geopolymer bricks have been studied and this product can potentially substitute conventional bricks (Khater, Ezzat & El Nagar 2016; Muduli, Nayak & Mishira 2014). Several studies demonstrated that the strength of geopolymer brick is better than cement-based products (Mane & Jadhav 2012; Van Jaarsveld, Van Deventer & Lukey 2003; Zhang 2013).

Nevertheless, accumulated evidence suggests data paucity on the development of low-fired and geopolymer bricks that utilise DWS and fly ash. Since most previous studies employed high-firing temperatures ranging from 900 °C to 1100 °C, a lower firing temperature of 500 °C was used in this study. This study also examined the effects of incorporated FA and geopolymerisation on the brick, which was developed from the DWS as a base material. In this study, FA was used as a replacement material for cement at a different ratio between 0% and 45% in the development of DWS brick. Additionally, mechanical characteristics such as linear shrinkage, density, water absorption and compressive strength were investigated in this study. The results were compared between fired brick (non-geopolymer brick) and geopolymer brick.

Materials and Methods

MATERIALS USED

A bulk quantity of drinking water sludge (DWS) and fly ash (FA) was collected, respectively, from one of the drinking water treatment plants (DWTP) and a coal-based electrical power facility in Kapar in Selangor. DWS was partially dry during the collection at the designated disposal site and stored in an air-tight container. The sample was further dried in the laboratory at room temperature for a few weeks. Lumps of samples were broken down and then sieved to obtain a sample size of 2 mm. This sample was restored to the container before being used for analysis and brick sample preparation. Meanwhile, the FA was generally dry, very fine-grained and dark grey. It was carried off in the flue gas and is usually collected by electrostatic precipitators. FA is composed of spherical particulate matter with diameters ranging from 0.1 to >100 μm that is predominately composed of silica, aluminium, iron, calcium and oxygen and some heavy metals, such as arsenic and lead at trace levels (Zierold & Odoh 2020). The collected FA was also stored in a container and further analysed in the laboratory. FA was utilised as an added material at different ratios against the base material of DWS in making the brick sample in this study.

Table 1 depicts the basic characteristics of the collected wastes of DWS and FA. The pH of DWS and FA was 5.76 and 10.1, respectively. The acidity of FA can be attributed to the presence of high content of Si, Ca, and Mg oxides and the type of coal (Micheal 2007). Mean specific gravity, Gs values for DWS was 1.82 slightly lower than FA of 1.99. O ‘Kelly (2008) found that the Gs for DWS were 1.86, slightly higher than the present study. The Gs value for FA could range between 1.6 and 3.1 with a mean value of 2.0 (Awab, Thnanlechumi & Mohd Yusoff 2012; Bhatt et al. 2019). Meanwhile, the loss in the ignition (L.O.I) for DWS was significantly higher than FA (1.14%).

Fly ash is a residue from the combustion of pulverised coal in a coal-fired boiler at high temperatures, thereby destroying organic matter during the process. FA is predominantly spheroid in shape either solid or hollow and amorphous (Bhatt et al. 2019). Silt fraction was the highest, followed by sand and clay in DWS. FA Silt fraction was significantly dominated by silt fraction, accounting for more than 75% whilst clay and sand were 18.05% and 2.11%, respectively. Generally, the particle size in FA varied from less than 1 μm to more than 100 μm (Kosmatka, Kerkhoff & Panarese 2002).

TABLE 1. Basic characteristics of drinking water sludge (DWS) and fly ash (FA)

Parameters	Drinking water sludge, DWS	Fly ash, FA
pH	5.76±0.86	10.10±0.35
Specific gravity	1.82±0.11	1.99±0.13
Loss of Ignition (L.O.I), %	8.42±0.43	1.14±0.06
Clay, %	36.31	18.05
Silt, %	48.44	76.97
Sand, %	15.25	4.98
Max. dry density, ρ_{max} gcm^{-3}	1.32	-
Moisture content, w %	29.00	-

Kaolinite is a clay mineral and its structure is composed of silicate sheets bonded to the aluminium oxide/hydroxide layers. It is dominantly observed with some appearance of quartz minerals (Figure 1(a)). FA grains clearly develop close contact with the clay and quartz minerals in the fired DWS brick sample (Figure 1(b)). The XRD patterns of DWS and FA are illustrated in Figure 2. DWS indicates the presence of the major crystalline phase of quartz (SiO_2) and other minerals of moganite and wollastonite. Moganite is SiO_2 and is considered a polymorph (different crystal structure) of quartz, whereas wollastonite is relatively $CaSiO_3$ but

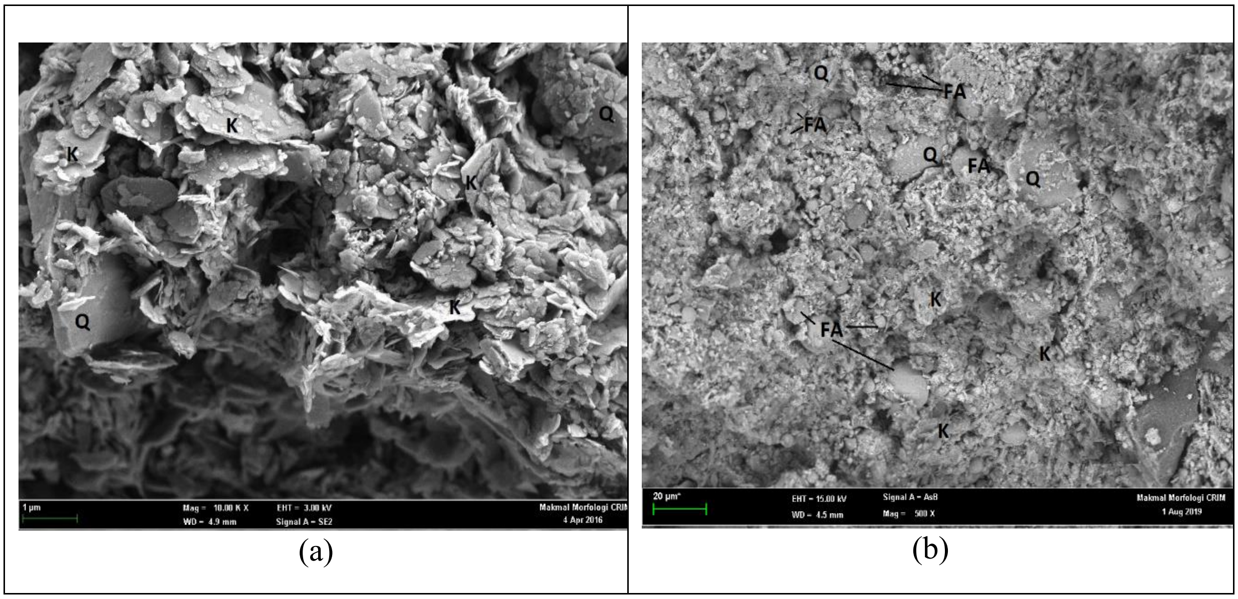

FIGURE 1. Scanning electron microscopic (SEM) images of (a) DWS and (b) of DWS-based brick (FA-fly ash; Q-quartz; K- kaolinite)

other elements such as Fe, Mg, Mn, Al, Ca, Na or Sr are present in its mineral structure (Vista 2000). DWS may exhibit physical and chemical characteristics similar to clay soil (Muhammad Bashar et al. 2016). For the FA, mullite is also present apart from SiO_2 (Figure 2(b)). Mullite is another crystalline specie that is formed during coal combustion, which appears as a product of the reaction between $A_{12}O_3$- and SiO_2- containing materials (Koshy et al. 2021; Schneider, Schreuer & Hildmann 2008).

The chemical composition of DWS and AF was characterised by XRF, and the results are presented in Table 2. DWS is of high Si content and was mainly composed of 54.3 wt.% silica, followed by alumina (32.2 wt.%) and a certain amount of ferric oxide (7.25 wt.%), K_2O (2.7 wt.%) and TiO_2 (1.61 wt.%). A high Al content is associated with the use of alum and poly aluminium chloride (PAC) in the water treatment process. There are also detected a very small amount of other oxides such as Na_2O, MgO, CaO, Cr_2O_3, MnO, NiO and ZrO_2. A high amount of silica and alumina was detected in FA as well as the presence of ferric oxide (7.15 wt%), K_2O (1.86 wt%) and TiO_2 (1.61 wt%).

PREPARATION OF BRICK SAMPLES

In order to investigate the effects of FA addition, two types of samples of fired brick and geopolymer brick were prepared in the laboratory. The first stage was the preparation of brick samples that involved firing at 500 ^oC for 3 hours. Meanwhile, the second set of brick samples known as geopolymer brick samples were prepared under a high alkaline environment.

For the preparation of fired brick, FA was added to DWS at different ratios based on the dried weight of DWS. As described in a previous study, the increasing amount of FA (0, 5, 10 and 20 %) is responsible for the reduction in water absorption and improved density and compressive strength (Ali Rahman et al. 2016). In order

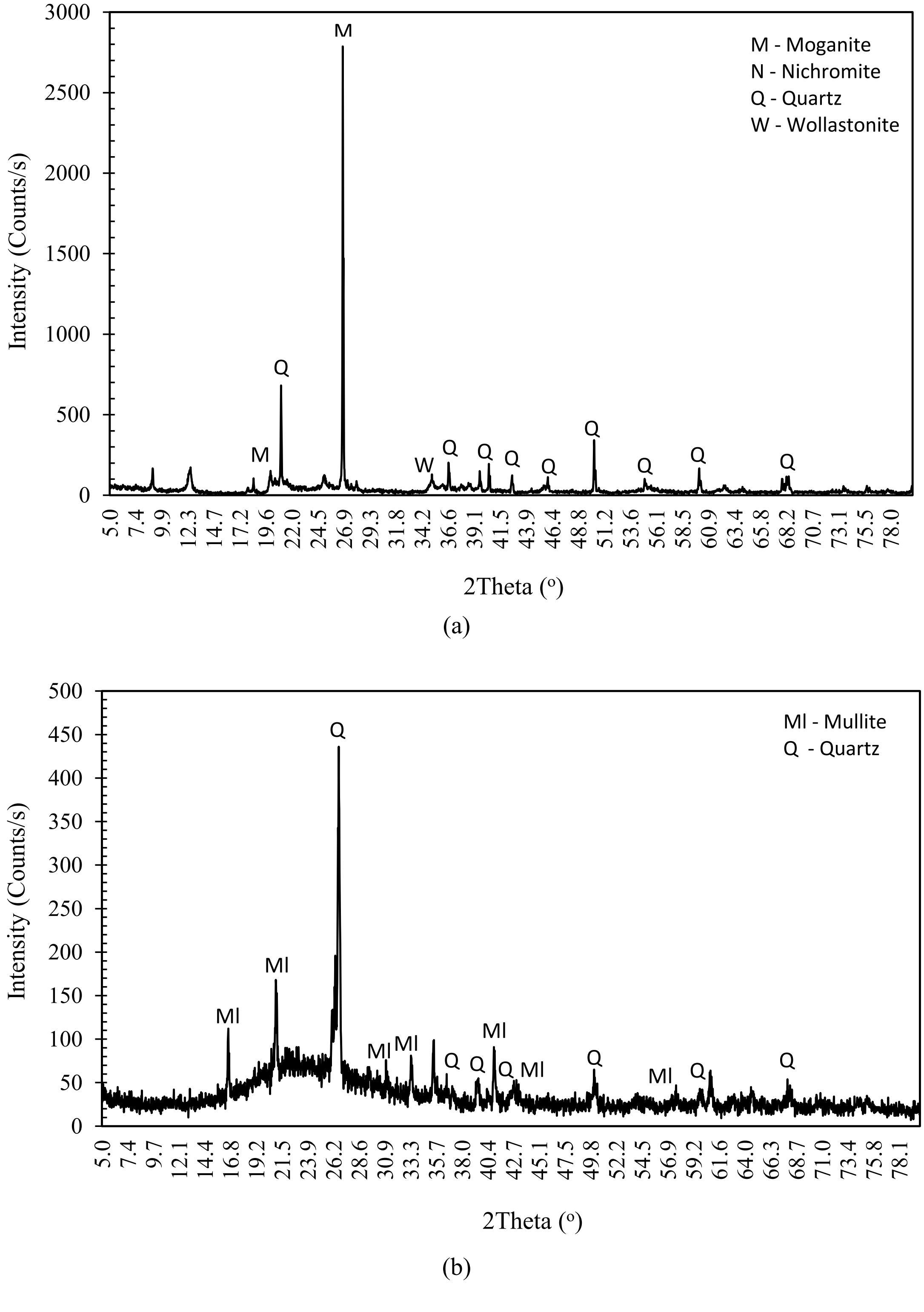

FIGURE 2. XRD patterns of (a) DWS and (b) FA samples

TABLE 2. Quantitative X-ray fluorescence spectral analysis of DWS and FA samples

Compound	Chemical composition (wt.%)											
	Na_2O	MgO	Al_2O_3	SiO_2	K_2O	CaO	TiO_2	Cr_2O_3	MnO	Fe_2O_3	NiO	ZrO_2
DWS	0.19	0.87	32.2	54.3	2.70	0.57	1.61	0.71	0.14	7.25	0.06	0.08
FA	0.60	1.50	25.00	56.20	1.86	0.001	1.61	0.0003	0.16	7.15	0.01	0.08

to examine the effects of FA at higher content, the amount of FA used in this study was 0%, 15%, 30% and 45% of the dry mass of DWS. Several studies have adopted higher FA contents ranging from 0% to 70% to optimise the use of waste in brick products (Bikkad et al. 2018; Huy & Phuoc 2017; Sutcu et al. 2019). Distilled water was added to the mixture and stirred until a uniform thick slurry was achieved. Notably, the amount of water added depends on the amount of FA content. Based on the compaction test, the correlated optimum moisture content, wopt decreased against maximum dry density, ρmax as the content of the added FA was increased relative to the DWS. The slurry was then poured into moulds with a dimension of 215 mm × 102.5 mm × 65 mm. Three layers of slurry were placed and each layer was compacted by 27 blows of a 2.5 kg rammer (British Standard Institution 1990). Thereafter, the samples were allowed to dry under room conditions for several days. Dried samples were extracted from the moulds and transferred carefully into the furnace. At this point, the samples were heated for 24 hours at temperatures ranging from 100 °C to 105 °C to release any moisture present in the brick samples. This method prevents the bricks from cracking when they are fired at higher temperatures in the furnace (Deraman et al. 2018). The firing temperature previously used by Ali Rahman et al. (2016) was employed in this study to examine the effects of higher FA contents on mechanical characteristics. The brick samples were fired for 3 hours at a temperature of 500 °C with an increment rate of 30 °C/minute.

For the preparation of geopolymer brick, a similar ratio of FA was also added as carried out for the fired brick. The alkaline activator solution (AA) used in this stage was 12 M sodium chloride, NaOH. The 12 M of AA solution was prepared by dissolving 480 g solid NaOH in 1 litre of distilled water. After the solution cooled down to room temperature, the AA solution was slowly added to the mixture at a ratio of 1:3 based on the weight and stirred thoroughly for 5 minutes. Then, the mixture was poured into a designated mould and left at room temperature for 2 hours before transferring into the oven at 45 °C for a week. The brick samples were finally removed from the mould and a further drying process was performed in the oven for another week.

MECHANICAL CHARACTERISTICS OF BRICK

The mechanical characteristics investigated in the bricks comprised the dimensional tolerance, density, D, water absorption, w and unconfined compressive strength (UCS).

LINEAR SHRINKAGE

Variation in brick dimensions should be kept at a minimum without excessive variation (British Standard Institution 1985). A change in the dimension of brick will affect its entire volume. Therefore, this test adopted the dimension tolerance approach which involves the measurement of the length, width and height of each brick. Due to limited samples, 10 bricks were used and the bricks were arranged using a long steel channel to ensure the bricks are formed in a straight line. A flat surface was selected to lay these bricks before an overall measurement was performed on a combined 10 brick samples. The total dimension of each brick was also measured using a steel tape meter. Meanwhile, a vernier calliper was used to measure the dimension of an individual brick to two decimal places (in mm). The linear shrinkage was calculated based on the following equation:

$$L = \frac{L_o - L_f}{L_o} . 100\%$$

where L_o – measurement of each dimension before drying and/or firing, mm; L_f – measurement of dimension after drying and/or firing, mm. From the measurement of each dimension, the volume of the brick sample was calculated and the percentage change in volume due to drying and/or firing processes was further determined between fired and geopolymer bricks. The change in volume, ΔV, was calculated using the following equation:

$$\Delta V = \frac{(V_o - V_f)}{V_o}.100$$

where V_o – volume before dying and/or firing, mm^3; V_f– volume after dying and/or firing, mm^3.

DENSITY

The technique employed to determine the density was based on Archimedes' principle of buoyancy and one of the parameters mentioned in AS/NSS 4456.8: 1997. It stated that an object submerged in liquid experiences a buoyant force, which is equivalent to the force of gravity on the displaced liquid. A total of 10 bricks from the earlier test were also used and labelled with waterproof ink for identification. Then, the brick samples were immersed in a water tank for 2 hours, which were then taken out from the water and allowed to drain quickly in less than a minute. A cloth was used to wipe out any excess water on the brick surfaces. The brick was weighed and the mass was recorded, m_1. The brick was placed in an apparatus to measure its submerged mass, m_2. The apparatus used to measure the submerged mass comprises a water bath with a steel cage, which was connected to a digital weight indicator. One of the samples was placed in the cage while the digital indicator recorded the submerged mass of the brick. The same steps were repeated for all 10 brick samples. Therefore, the volume, V is given by the following equation:

$$V = (m_1 - m_2).1000$$

where V is the volume, mm^3; m_1 is the mass of wet sample in gram; m_2 is the mass of submerged sample in gram. Hence, the density, D can be calculated from:

$$D = \frac{m_d}{V}.1000000$$

where D is the density of sample (kgm^{-3}); m_d is the mass of dry sample in gram; V is the volume of sample, mm^3.

WATER ABSORPTION

The 10 bricks used earlier for density tests were utilised again for the water absorption test. The dry mass, md of the bricks which were recorded earlier in the density test was used in this test. A tank was prepared large enough to accommodate all bricks. Water was added to the level that fully submerged all the bricks for 24 hours. Then, each brick was weighed to record its saturated mass, mw. The water absorption w, in percentage, was calculated using the following equation:

$$w\% = \frac{m_w - m_d}{m_d} \times 100$$

where w is the percentage of water absorption; m_d is the dry mass in gram; m_w is the saturated mass in gram.

COMPRESSIVE STRENGTH

The brick samples were examined for their compressive strength by applying the samples to compression load until a failure was reached. The tests were performed using an Autocon 2000 Universal Testing Machine with a maximum capacity of 2000 kN. The surface of each brick sample was cleaned prior to loading at an applied rate of 7.0 kN/s. The maximum load at failure (N) was recorded and used to determine its compressive strength, τ. Three bricks were used in this test and the compressive strength was calculated from the following equation:

$$Compressive\ strength = \frac{Maximum\ load\ at\ failure\ (N)}{Area\ (m^2)}$$

The determination of water absorption and compressive strength of the studied bricks were based on the methods recommended by BS 3921: British Standard Specifications for Clay Bricks (1985).

RESULTS AND DISCUSSION

LINEAR SHRINKAGE

Brick samples would experience a change in their dimension (length, width and height), thereby resulting in a change in their volume after drying and firing. The mean and linear shrinkage values of each brick dimension are shown in Table 3. The shrinkage patterns in terms of volume change of the fired and geopolymer bricks are depicted in Figure 3.

For the fired bricks, increasing the content of FA has contributed to an increase in the final dimension of the bricks (Table 3). However, the change in each of the measured dimensions between the initial (Lo) and final measurements (Lf) reduced as the FA content was increased from 0% to 45%. A similar pattern was also observed for the geopolymer bricks where each dimension demonstrated increasing values with an increase in the FA content. The change in each dimension between Lo and Lf was reduced for the length, P but increased for the dimension of width, W and height, H of the brick. The measurements for width, W and height, H showed an expansion in each dimension, which is represented by a negative sign (Table 3). The height dimension, H depicted an obvious expansion following the addition of a 15% and 30% FA content for the width dimension, W, respectively. It was also discovered that the change in height is greater than the change in the width dimension.

TABLE 3. Average values of length, width, height and change in each dimension of the studied bricks

Type	FA content (%)	Length, P_f (mm)	Change (%)	Width W_f (mm)	Change (%)	Heigth H_f (mm)	Change (%)
Fired brick	0	204.0±0.8	5.1	98.0±0.8	4.4	63.7±0.9	2.1
	15	204.3±0.9	5.0	98.0±0.8	4.4	64.0±0.8	1.5
	30	207.0±0.5	3.6	100.0±0.8	2.4	64.7±0.5	0.5
	45	209.0±0.5	2.6	100.7±0.5	1.8	65.0±0.8	0.0
Geopolymer brick	0	195.0±0.8	9.3	95.7±0.5	6.7	62.3±0.5	4.1
	15	213.0±0.8	0.9	102.0±0.8	5.0	70.7±0.5	-8.7
	30	214.0±0.8	0.5	104.0±0.8	-1.5	74.3±1.2	-14.4
	45	215.0±0.5	0.2	105.0±0.8	-2.4	75.3±0.8	-15.9

Note: (-) negative sign indicates the expanding of final dimension, L1

The change in volume of the fired bricks showed a decreasing trend from 11.1% to 4.4% as the amount of FA content increased (Figure 3). Meanwhile, the volume change for geopolymer bricks was 18.5% at 0% of the FA content, representing shrinkage in the volume after drying. However, as the FA content reached 15%, the volume of geopolymer bricks began to dilate, representing 7.2% to 18.5% at a FA content of 45%. The expansion of the width and height dimensions (as indicated by the negative sign) of the brick samples when FA content was added is attributed to the dilation of the final volume (Table 3).

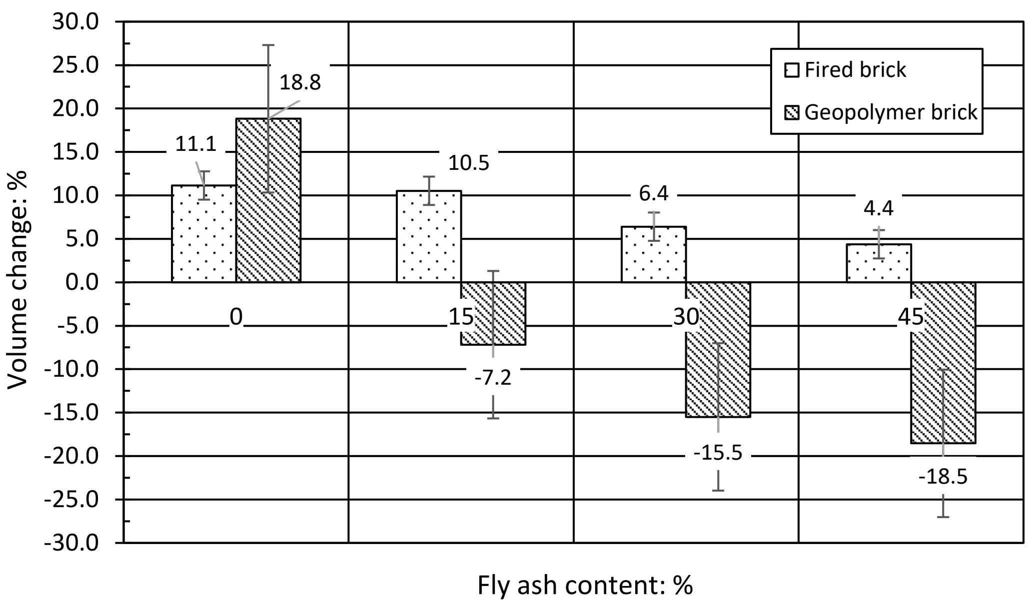

FIGURE 3. Volume change of the fired and geopolymer bricks

The shrinkage in the volume of the fired brick is expected as heat causes the release of water from the layers of the clay mineral, which is primarily kaolinite (Figure 1(a)), during the drying and firing stages (Algamal, Khalil & Saleem 2018; Ali Rahman et al. 2021; Karaman, Ersahin & Gunal 2006; Sarabian-Guarin, Sanchez-Molina & Bermudez-Carrillo 2020). Most of the shrinkage occurred during the drying process. Since the firing temperature of 500 °C was used in this study, further shrinkage would not occur given that the quartz inversion temperature of silica was 573 °C (Karaman, Ersahin & Gunal 2006). Huy and Phuoc (2017) discovered that FA addition resulted in less defect and dimensional change during the drying process of the brick.

DENSITY

The use of different waste combinations and ratios for recycling can alter the mechanical properties such as density. Overall, density reflects the specific gravity of the materials used in the brick. The findings showed that both types of bricks were associated with a small increasing trend of density as the FA content increased (Figure 4). Comparatively, the density of fired brick was slightly lower than that of geopolymer brick. As previously stated, the specific gravity of DWS and FA were 1.82 and 1.99, respectively, and might have contributed to the density of the brick (Table 1). The overall density of brick samples gradually increased as the FA content increased, which can be probably attributed to the formation of denser material. It was clearly seen that spheroidal FA particles can fit between flaky kaolinite mineral spaces, contributing to the compactness of the brick samples (Figure 1(c)). The present result contradicts previous studies on the effect of FA on a fired brick in which the density of the brick decreased as the FA content increased (Jovanovic et al. 2022; Sutcu et al. 2019). The lighter weight of the FA utilised in the latter studies might explain the different results (Abbas et al. 2017; Sukmak et al. 2013; Turkel & Aksin 2012). Resultantly, the density of the brick decreases as the FA content increases. FA also acts as an anti-shrinkage material, preventing brick densification; as FA content increases, bulk density decreases (Choudhary, Koppala & Swamiappan 2015). It was also discovered that the density of fired brick increases as the firing temperature increases, and most previous studies used high temperatures ranging from 900 °C to 1100 °C (Algamal, Khalil & Saleem 2018; Leiva et al. 2016; Sutcu et al. 2019). To date, no study has deployed firing temperatures as low as 500 °C as used in this study, thus comparisons with the current results are difficult.

The geopolymerisation process has contributed to sample densification and increased the ratio of the FA to DWS. Wan Ibrahim et al. (2013) reported that the density of geopolymer brick increased as the ratio of FA to sand increased. The finer particle size of FA contributes to

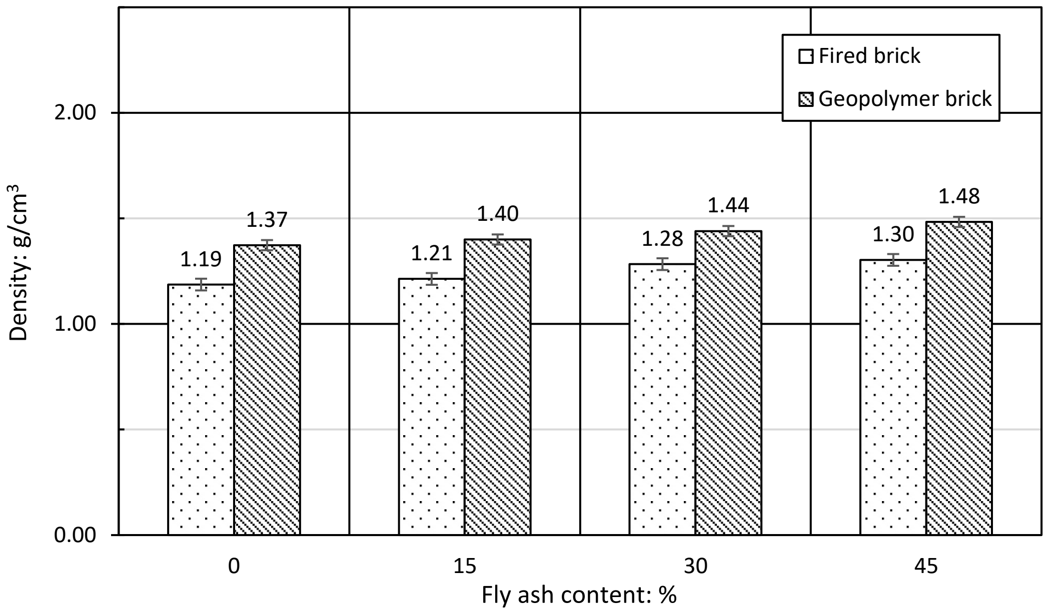

FIGURE 4. Density of the fired and geopolymer bricks

greater compressive strength, which reflects the behaviour of ordinary Portland cement (Deraman et al. 2018). The density of geopolymer bricks based on FA to sand ratio increased as the curing period lengthened, and it is usually higher than that of fired clay and cement bricks (Wan Ibrahim et al. 2014). It was also established that the curing period has a significant impact on the density of the geopolymer brick (Ganesan 2019). According to the European standard EN 771-1(2005), the density of fired clay solid bricks should be between 1.2 g/cm^3 and 1.4 g/cm^3, and almost all of the densities obtained in the currently studied brick were consistent with this standard except for geopolymer brick with 30% and 45% FA contents.

WATER ABSORPTION

Water absorption is an important factor influencing brick durability. Water absorption can be linked to the presence of open pores in a brick sample (Fungaro & da Silva 2014). Rapid deterioration and apparent loss of strength would result from high-water absorption (Ajam et al. 2009). This test was performed on both types of bricks and the results are shown in Figure 5. Water absorption decreased steadily as the FA content increased up to 30% in the fired brick samples. However, when a 45% FA content was added, water absorption increased from 33.3% to 40%. Yadav et al. (2014) reported a similar trend in which water absorption was lowest (19.4%) at 20% FA content before increasing with additional FA content. At 50% FA content, water absorption was slightly increased, ranging from 20.25% to 25.34% (Pawar & Garud 2014). Water absorption in the range of 20 to 30% is considered acceptable in several parts of the world (Abbas et al. 2017; More, Tarade & Anant 2014). These results showed that the water absorption of the investigated geopolymer brick was within the permissible value but not for the low-fired brick.

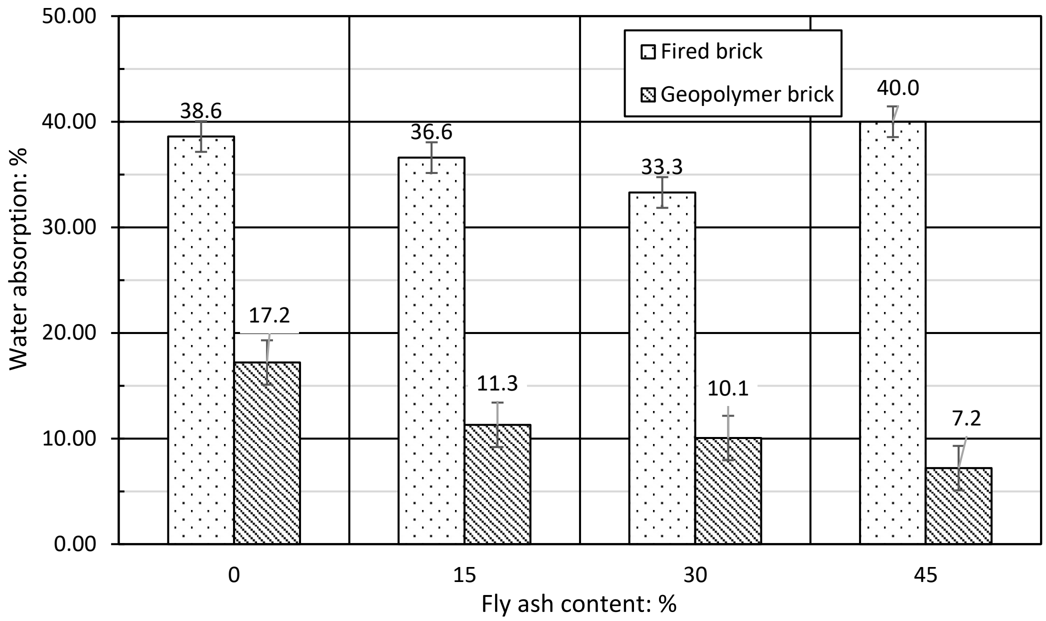

FIGURE 5. Water absorption of the fired and geopolymer bricks

In contrast, the water absorption values for geopolymer brick samples were significantly lower than those for fired-brick samples. As the added FA content increased up to 45%, water absorption decreased from 17.2% to 7.2%. The presence of organic matter in DWS, as indicated by an LOI of 8.42% (Table 1), contributed to higher water absorption in the fired brick. However, densification at the structure level of brick occurred as FA was added, which could be attributed to the gradual decline in the water absorption characteristics. Several studies showed that geopolymer brick of FA content is associated with a low water absorption value (Lavanya et al. 2020). Similar results were stated by Wan Ibrahim et al. (2013) for the geopolymer brick developed from different ratios of FA and sand contents. Besides FA content, higher molarity of alkaline actuator was associated with a decrease in water absorption value of geopolymer brick (Ngo 2020). In another study, the additional FA content in the development of geopolymer concrete brick resulted in a significant increase in water absorption value (Abed & Abed 2019).

COMPRESSIVE STRENGTH

Compressive strength is an important characteristic given that bricks must be made up of sufficiently strong materials to support load, and its load bearing capacity is typically evaluated using the compressive strength test. A specific range of compressive strength is appropriate for certain engineering applications and to ensure the engineering quality of building materials (Ramadan, Fouad & Hassanain 2008; Torres, Hernández & Paredes 2012). Figure 6 depicts the results of the compressive strength tests performed on the investigated bricks. The compressive strength of the fired brick was highest at 0% FA content (2.03 MPa) but decreased as the added FA increased to 45%. In contrast, the compressive strength of geopolymer brick was slightly lower (1.22 MPa) than that of fired brick at 0% FA content, but increased steadily from 2.33 MPa (15%) FA content to 3.63 MPa at 45% FA content. The result suggests that the presence of FA increased the strength of the geopolymer brick. The compressive strength difference between fired and geopolymer bricks at the highest FA content was 2.75 MPa, which represents a 312% difference for the same amount of FA content.

The firing temperature has a significant impact on the quality of brick in terms of compressive strength (Ali Rahman et al. 2021; Zhang 2013). However, the presence of certain material may change its optimum strength as a result of a physical reaction caused by temperature. Adopting a higher amount of FA has resulted in a disadvantage for fired clay brick evident by the decrease in the compressive strength from 4.35 N/mm^2 to 0.83 N/mm^2 when the FA content exceeded 15% (Pawar & Garud 2014). Yadav et al. (2014) discovered a similar decreasing trend in compressive strength (from 6.4 MPa to 1.2 MPa) in DWS fired brick following the addition of 20% FA. Despite using high firing temperatures of 1000 °C, they discovered that the compressive strength of fired brick was reduced by more than 80%. Meanwhile, Leiva et al. (2016) reported that increasing the firing temperature to 1000 °C improved compressive strength compared to 800 °C and 900 °C, which was associated with a decreasing trend with added FA content. The use of a lower firing temperature in the present study resulted in a lower compressive strength in comparison to a normal firing temperature. The presence of organic matter in the raw material might impact the mechanical

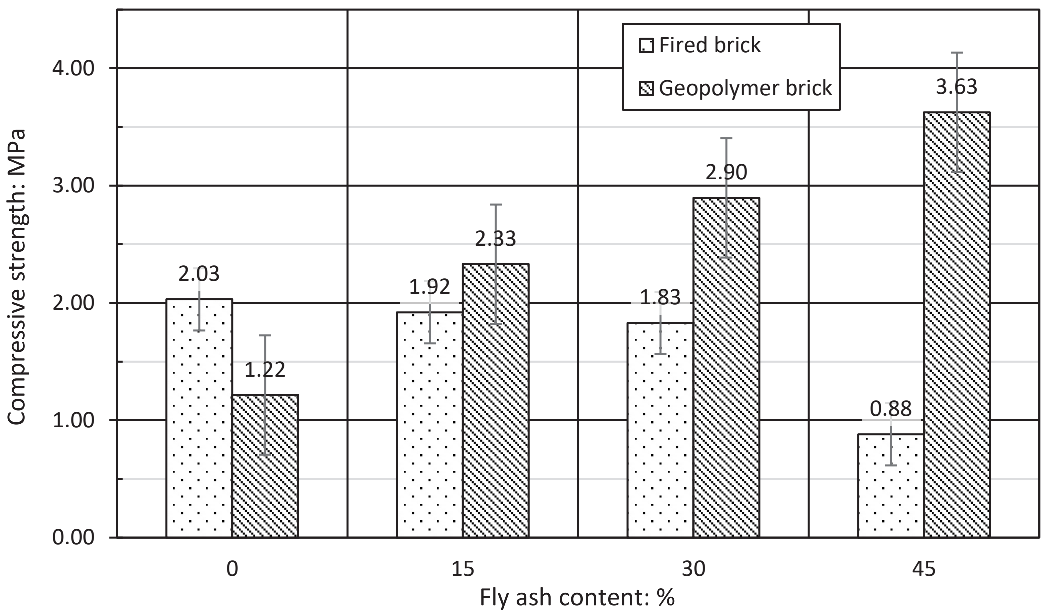

FIGURE 6. Compressive strength of the fired and geopolymer bricks

properties of the fired brick. The combustion of organic matter during the firing process results in porous bricks with lower mechanical strength (Ukwata & Mohejerani 2017). However, the compressive strength did not reflect the water absorption of the studied fired brick, which might be related to the porous state of the brick.

The addition of FA can improve the compressive strength of the brick. Kockal et al. (2019) discovered that the compressive strength increased as the FA content increased to 50% silica fume. Geopolymer bricks have significantly higher compressive strength than clay and cement bricks (Wan Ibrahim et al. 2013). Deraman et al. (2018) found that using a higher fly ash ratio increased the compressive strength of geopolymer bricks mixed with FA and bottom ash. This indicated that fineness is also important given that FA has a high surface area, which allows more silica and alumina to dissolve, thereby increasing the compressive strength. Microscopic examination showed flocculence from the active substance in FA, which serves as a critical component in cementing materials (Yang et al. 2020). While the remaining materials do not chemically react, they become filler material and the skeleton of the geopolymer sample.

Conclusions

In this study, geopolymer and low-fired bricks from DWS were developed, and the effects of added FA ranging from 0% to 45% of the contents on some mechanical properties of these bricks were investigated. The following conclusions can be drawn based on the findings of this study: The final dimension of low fired and geopolymer bricks increased as the FA content increased. The change in each dimension of length, width and height decreased for low-fired brick and opposite for width and height for geopolymer brick. In the geopolymer brick, there was an obvious expansion of the height dimension, H, at 15% of FA and 30% of the width dimension, W. The density of the brick increased steadily as the amount of added FA increased, which can be attributed to the higher specific gravity of FA compared to DWS. Comparatively, the geopolymer brick had a higher density value than the fired brick. Fired brick absorbed far more water than geopolymer brick. With the exception of the highest FA content of 45%, the fired brick depicted a decreasing trend similar to geopolymer brick. The water absorption value of the investigated geopolymer brick was within the allowable range but not for the low-fired brick. Geopolymer brick clearly had higher compressive strength than the fired brick. The compressive strength of geopolymer brick increased as the FA content increased and vice versa for the fired brick.

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