Sains Malaysiana 52(7)(2023): 2115-2126
http://doi.org/10.17576/jsm-2023-5207-17

Mechanical Characteristics of Developed Brick from Drinking Water Sludge under Different Firing Temperatures and Rice Husk Ash Contents

(Pencirian Mekanikal Bata yang Dibangunkan daripada Air Minuman Enapcemar Di Bawah Suhu Pembakaran Berbeza dan Kandungan Abu Sekam Padi)

ZULFAHMI ALI RAHMAN*, HAFIS NAZARAH, WAN MOHD RAZI IDRIS & TUKIMAT LIHAN

Department of Earth Science and Environment, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia

Received: 13 February 2023/Accepted: 10 July 2023

ABSTRACT

There is a considerable interest in making alternative bricks using wastes. Firing temperature has been significantly improved the mechanical qualities of bricks. The aim of this study was to investigate into the impact of firing temperature and rice husk ash content on the mechanical properties of drinking water sludge bricks (DWS). Two types of bricks were produced; bricks made of 100% DWS (DWS100) and bricks with 80% DWS and 20% RHA (DWS80). These samples were subjected to different thermal variations of 300 °C and 700 °C for three hours. The unfired brick samples were also prepared for reference. The volume changes of the DWS100 bricks increased as the firing temperature climbed up to 500 °C, before dropped at 700 °C. A similar behaviour was also exhibited by DWS80 bricks, however it shrunk at earlier temperature of 500 °C. At 500 °C and 700 °C, the density of bricks decreased dramatically, with DWS80 bricks consistently being lesser than DWS100 bricks. The water absorption of DWS80 brick began to decrease at 500 °C, a lower temperature than that of DWS100, as the firing temperature climbed. RHA-added bricks (DWS80) were anticipated to absorb more water than DWS100 bricks, but this did not occur. This presumably induced by the constriction of clay mineral structure rather than organic matter removal at high temperature per se. The compressive strength increased with the increase in temperature. It can be inferred that RHA can decrease the compressive strength of RHA-added bricks, despite the fact that a higher fire temperature significantly increased their strength.

Keywords: Brick; compressive strength; drinking water sludge; rice husk ash

ABSTRAK

Terdapat minat yang besar dalam membuat bata alternatif menggunakan bahan buangan. Suhu pembakaran telah meningkatkan kualiti mekanikal batu bata dengan ketara. Matlamat penyelidikan ini adalah untuk mengkaji kesan suhu pembakaran dan kandungan abu sekam padi terhadap sifat mekanikal bata air minuman enapcemar (DWS). Dua jenis bata telah dihasilkan; bata diperbuat daripada 100% DWS (DWS100) dan bata dengan 80% DWS dan 20% RHA (DWS80). Sampel ini tertakluk kepada variasi terma berbeza 300 °C dan 700 °C selama tiga jam. Sampel bata yang tidak dibakar juga disediakan untuk rujukan. Perubahan volum bata DWS100 meningkat apabila suhu pembakaran meningkat sehingga 500 °C, sebelum turun pada 700 °C. Tingkah laku serupa juga ditunjukkan oleh bata DWS80, namun ia mengecut pada suhu awal 500 °C. Pada 500 °C dan 700 °C, ketumpatan bata menurun secara mendadak dengan bata DWS80 secara tekal kurang daripada bata DWS100. Penyerapan air bata DWS80 mula berkurangan pada 500 °C, suhu yang lebih rendah daripada DWS100, apabila suhu pembakaran meningkat. Bata RHA-tambah (DWS80) dijangka menyerap lebih banyak air daripada bata DWS100, tetapi ia tidak berlaku. Ini mungkin disebabkan oleh penyempitan struktur mineral tanah liat dan bukannya penyingkiran bahan organik pada suhu tinggi per se. Kekuatan mampatan meningkat dengan peningkatan suhu. Ia boleh disimpulkan bahawa RHA boleh mengurangkan kekuatan mampatan bata RHA-tambah, walaupun pada hakikatnya suhu api yang lebih tinggi meningkatkan kekuatannya dengan ketara.

Kata kunci: Abu sekam padi; air minuman enapcemar; bata; kekuatan mampatan

Introduction

Bricks have been utilized for building construction for countless centuries. Clay bricks have been made from abundantly accessible mud resources that have been dried under the sun's heat. In ancient Mesopotamia and at Mohenjo-Daro, mud bricks were fired to increase their durability (David 1998). Conventionally, bricks are produced by heating clay to a high temperature, alternatively they can be constructed from Portland cement (OPC) concrete. Each year, the global demand for bricks increases, and over 90% of bricks are produced in Asia. In Malaysia, the demand for bricks has steadily risen, increasing the market price to 4.3% per unit of bricks in 2015, with annual increases anticipated (Ali Rahman et al. 2021). The sole reliance on natural sources has had a negative impact on the landscape and is accompanied by a substantial amount of waste owing to quarrying and excessive energy usage (Zhang 2013). In some countries, a lack of clay has necessitated a reduction in clay-based brick production (Chen et al. 2011; Ling & Teo 2013). The use of sand and OPC has also posed danger to these natural reserves, required a great deal of energy, and produced a significant amount of greenhouse gases.

It is anticipated that the amount of waste generated would increase due to the expanding population's demand for everyday necessities and conveniences. Although waste is abundant, its usage as base/additional materials is still limited. Reusing trash from industrial and agricultural sources appears to be a viable strategy for addressing environmental degradation and the expense of construction (Lamba et al. 2022; Toghroli, Shariati & Sajedi 2018). Bricks are comprised of a considerable number of natural raw materials and are widely utilized in building construction. Therefore, incorporating waste into brick industries might potentially recycle solid wastes into valuable goods (Kumar & Vignesh 2017; Shaqour, Alela & Rsheed 2021). Recycling wastes has many advantages, including energy savings, conservation of natural resources, cost-effectiveness of products, and a decrease in waste disposal (Ali Rahman et al. 2019; Figaredo & Dhanya 2018; McGinnis et al. 2017). Due to their high silica content, which is attributable to their pozolanic activity (Demis, Tapali & Papadakis 2015; Heniegal et al. 2020; Liu et al. 2020), drinking water sludge (DWS) and rice husk ash (RHA) are among the prominent wastes that have been investigated for use in bricks. Rice husk is used as a fuel to generate steam in the parboiling process (Khan et al. 2014) and is produced by paddy rice milling plants in large quantities. It has low bulk density, high silica content, and excellent pozolanic activity. Ash gained from controlled combustion (500 °C-700 °C; 1 hour) largely contains of amorphous silica whose reactivity is attributed to its large surface area (Bhupinder 2018). The use of RHA has decreased $Ca(OH)_2$ in mortar containing RHA, indicating that excellent pozzolanic potential of RHA when used as partial substitute of cement (Amin et al. 2019).

The application of DWS and RHA as potential alternative bricks has been intensively researched (Damanhuri et al. 2020; Herreno et al. 2019). Variations in the ratio of clay to DWS (50-80%) treated at 950 °C and 1100 °C were able to meet the BS 5628:1987 standard (Ramadhan, Fouad & Hassanain 2008). The temperature and sintering of DWS improved the quality of the manufactured brick. Lightweight bricks produced with waste RHA show improvement in compressive strength and water absorption (Janbuala & Wasanapiarnpong 2015; Subashi De Silva & Perera 2018). The RHA presence resulted in a high porosity, however burning increased the compressive strength. The construction of bricks from DWS including a fraction of desert shale and burnt at a high temperature of 1100 °C has affected shrinkage, bulk density, and compressive strength (Mageed, Rizk & Abu-Ali 2011). When firing DWS bricks with varying amounts of RHA (25-75%) at varying temperatures (900-1200 °C), bricks with lower water absorption, but high specific gravity and compressive strength, were produced (Hegazy, Fouad & Hassanain 2012). RHA has also been investigated as a partial cement replacement in concrete bricks. The inclusion of 10% RHA allowed for the attainment of maximum compressive strength, and the curing age can further enhance the strength (Minh & Tram 2017). As the amount of RHA exceeds the optimal level, the strength steadily decreases. The inclusion of RHA can make clay bricks of acceptable quality, but the amount of RHA should not exceed the optimal level to prevent the brick from becoming too brittle and fragile (Huq & Chowdhury 2018). An earlier attempt to manufacture unfired bricks with DWS-incorporated RHA (0, 5, 10, and 20%) produced bricks with low mechanical strength (Ali Rahman et al. 2015). Consequently, the purpose of this study was to investigate the effect of various thermal temperatures (unfired, 300 °C, 500 °C, and 700 °C) and the presence of 20% RHA on selected mechanical properties of bricks manufactured from DWS.

MATERIALS AND METHODS

MATERIALS

The brick samples were produced using DWS as the base material and varying amounts of RHA. DWS was gathered from a treatment water facility at Ijok Selangor, Malaysia. Originally, the DWS sample was partially dried, yellowish to greyish colour, with a fine texture and a high clay and silt content. Bulk samples of DWS were obtained from the site and stored in an airtight plastic container. In the laboratory, DWS was air-dried for one week at room temperature. Aggregates were manually broken to form a fine powder, which was then sieved through a 2 mm sieve. RHA was acquired from a paddy-processing facility in Tanjong Karang, Selangor. It was lightweight and had a black hue. RHA was dried in an oven at 105 °C for 24 h, then left at room temperature before stored in an airtight container. Both prepared DWS and RHA samples were utilized for the fundamental characterization and preparation of the brick samples.

PREPARATION OF BRICK SAMPLES

A previous study demonstrated that the RHA content of unfired bricks affected their mechanical strength. As the compressive strength of unfired bricks increased with increasing RHA content up to 20%, the value was maintained below the clay brick standard (Ali Rahman et al. 2015). To investigate the effect of RHA content on thermal variability, brick samples were prepared with two different ratios of DWS and RHA content: 100% DWS (D100) and 80% DWS and 20% RHA (D80). Brick samples were made using a standard brick mould with dimensions of 215 mm × 102.5 mm × 65 mm (MS 76 1972). Dry DWS was initially weighed and poured into a mixing bowl for D100 bricks. Then, water was added to DWS and mechanically mixed using a mechanical mixer. A similar technique was applied for preparation of D80 bricks where dry DWS and RHA at a ratio of 4:1 was mixed and thoroughly before water was added to the mixture. Mechanical mixing continued until slurry formation. The slurry was slowly poured into a brick mould, and the mixture was gently tapped to allow trapped air bubbles to escape. Wet samples were allowed to dry in the mould at room temperature for one week. The brick samples were then removed from the moulds and dried for an additional two weeks. After a 21-day curing period, the samples of unfired brick were evaluated for each parameter. The fired brick samples were placed in the boiler for three hours of firing at temperatures of 300, 500, and 700 °C. Brick samples were initially heated to 110 °C for one hour before temperatures were gradually increased by 20 °C per minute.

MECHANICAL CHARACTERISTICS

Typically, linear shrinkage, density, water absorption, and compressive strength tests were utilised to determine the mechanical properties of brick samples (British Standard Institution 1985). During drying and firing, bricks undergo an overall reduction in size, resulting in linear shrinkage. Linear shrinkage is essential for determining the amount of firing shrinkage and should not be excessive, as it degrades the quality of bricks. In horizontal, vertical, and lateral rows, each dimension of length, width, and height was measured (12 pieces of bricks). Before conducting measurements, brick samples were laid out on a flat, clean surface. Using six brick samples, the dimensions of individual bricks were also measured. A Vernier calliper and universal inextensible steel tape capable of measuring up to two decimal points were used. The shrinkage linear, L, of the brick dimension is given in Equation (1).

$$Shrinkage\ linear, L = \frac{L_o - L_i}{L_o} \times 100\ \% \qquad (1)$$

where L_o is the original measurement before firing in mm and L_i is the measurement after firing in mm. Based on the measured dimensions, the volume, V, of the brick before and after firing can be calculated. The difference between the original volume, V_o, and the volume after firing or the final volume, Vi, gives the volume change V, as shown in Equation (2).

$$Volume\ change, \Delta V = \frac{V_o - V_i}{V_o} \times 100\%. \qquad (2)$$

The density, D, of a brick is related to its porosity, which affects its water absorption. The density of bricks influences wall weight, and weight variation affects wall structural, acoustic, and thermal design. The density of the brick was calculated using the Archimedes principle, which states that the weight of water displaced is equal to that of the submerged brick. The brick was labelled and dried in an oven overnight to eliminate any remaining moisture. A dried brick was cooled to room temperature and its dry mass, m_d, was determined prior to two hours of immersion in a water tank. The brick sample was then removed from

from the tank, allowed to drain for one minute, and the surface was wiped with a soft cloth to remove excess moisture. The mass of the wet brick, m_1, was measure agaub before it was transferred o a scale submerged in a water tank and its weight while submerged m_2, was measured. This procedure (AS/NSS4456.8 1997,) and the density was calculated using Equations (3) and (4).

$$Volume, V = (m_1 - m_2) \times 1000 \quad (3)$$

$$Density, D = \frac{m_d}{V} \times 100 \quad (4)$$

The bricks were initially used to determine density before being adapted for measuring water absorption. The bricks were dried at 110 °C for 48 h in a well-ventilated oven. The bricks were then removed and allowed to cool to room temperature for 4 h. Then, the bricks' dry mass, m_d, was determined by weighing them. The pre-weighed bricks were submerged for 24 h in a large tank of water. The bricks were then removed from the tank, and excess water and moisture were removed with a damp cloth. The bricks were reweighted, and the saturated mass, m_{sat}, was recorded. The water absorption, W (%), was determined from the following equation:

$$Water\ absorption, W(\%) = 100\frac{(m_{sat} - m_d)}{m_d} \quad (5)$$

The compressive strength of the bricks was determined by subjecting them to a compressive load until failure. In this study, a compressive Autocon machine with a capacity of 5,000 kN was utilised. The same bricks previously tested for water absorption were used for compressive strength testing, and the bed face of the brick was examined (BS EN 772-1. 2011. The brick was sandwiched between two plywood sheets to reduce friction caused by the surface's irregularities. The plywood should be 10 mm larger in all dimensions than the dimensions of the brick, and each test should use new plywood. The brick sample was then subjected to a constant 15 N/mm^2 loading rate. The loading rate is increased gradually at a rate not exceeding 35 N/mm^2 until half of the anticipated maximum load is reached, and then decreased to 15 N/mm^2 and maintained until failure. When the brick failed, loading was automatically stopped, and the maximum load, F_{max}, was recorded. The bricks' strength and UCS_{max} were calculated by dividing the maximum load by the bed face area, A (i.e., length × width)

$$Maximum\ strength, UCS_{max} = {F_{max}}/{A} \quad (6)$$

Results and Discussion

PROPERTIES OF MATERIAL USED

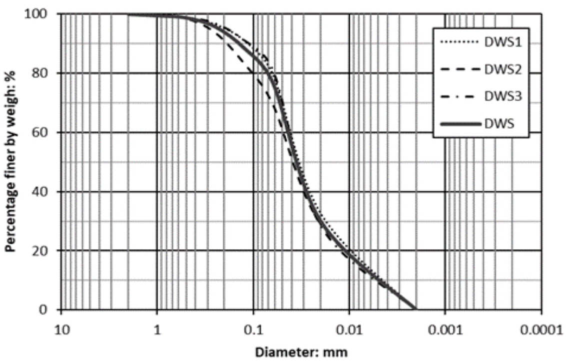
A summary of the basic characteristics of the waste used in this study is shown in Table 1. DWS is classified as acidic with a pH of 4.44, whereas RHA is alkaline with a pH between 8.47 and 8.87 as the temperature increased from 500 °C to 700 °C. The trend of the pH values of both materials was also measured by Ali Rahman et al. (2019). DWS contains less organic matter than RHA, which can be attributed to the flocculation-coagulation of suspended solids in the raw water treatment process. DWS demonstrates a greater specific gravity than RHA. DWS has a specific surface area that is 38.85 m^2/g greater than RHA (24.48 m^2/g). The rustic discoloration observed in DWS is likely a result of iron oxide (Fe_2O_3) traces (Anyokora et al. 2012). The specific surface area of RHA decreased to 20.81 m^2/g and 10.45 m^2/g at higher temperatures. The significant proportion of the DWS consists of clay, followed by silt and sand.

The scanning electron microscopy (SEM) images of the DWS sample show the presence of kaolinite minerals with a flaky morphology and rare instances of quartz minerals (Figure 1(b)). In the SEM image depicted in Figure 1(c), the outer (O) and inner (I) layers of the RHA can be seen clearly. The majority of RHA's components retained their original form after combustion, with only minor structural damage (Xu, Lo & Memon 2012). The exterior layer appeared more rigid and substantial than the interior (I). Its interlayer has a honeycomb-like structure with nanopores ranging in size from several nanometers to several micrometres (Zou & Yang 2019). The SEM image of the 500 °C-fired mixture of DWS and RHA shows the presence of residual RHA (F) and a few larger pores (P) (Figure 1(d)). Figure 2 displays the DWS sample's XRD result. It has a predominant crystalline phase of SiO_2 or quartz, along with moganite and wollastonite. Moganite is composed of SiO_2 and is a polymorph of quartz with a distinct crystal structure. Wollastonite is composed primarily of calcium silicate ($CaSiO_3$), with other elements such as Fe, Mg, Mn, Al, Ca, Na, and Sr also present in its mineral structure. The XRF analysis of DWS showed a high Si content primarily composed of 54.3 wt.% silica, 32.2% alumina, and trace amounts of ferric oxide, K_2O, and TiO_2 (Table 2). Most drinking water treatment plants use alum and/or poly aluminium chloride (PAC) as coagulants, which contributes to the high Al content in drinking water.

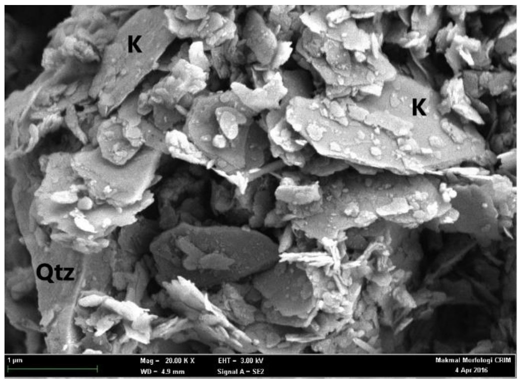
TABLE 1. Summary of the physical and chemical properties of DWS and RHA

Parameters	Drinking Water Treatment Sludge (DWS)	Rice Husk Ash (RHA)		
		Field	500 ˚C	700 ˚C
pH	4.44	8.47	8.66	8.87
Loss of Ignition (%)	6.80	10.78	-	-
Specific gravity	2. 16	1.87	-	-
Specific surface area (m^2/g)	38.85	24.48	20.81	10.45
<u>Particle Size Distribution</u> (%):				
Clay	46.46	-	-	-
Silt	29.85			
Sand	23.69			
<u>Atterberg Limits</u> (%):				
Liquid limit, w_L	61.27	-	-	-
Plastic limit, w_P	50.11			
Plasticity Index, I_P	11.16			

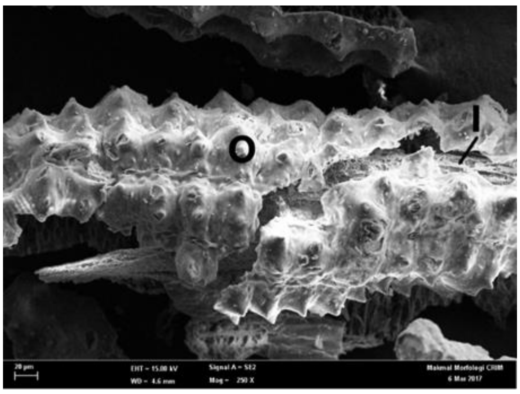
- not available



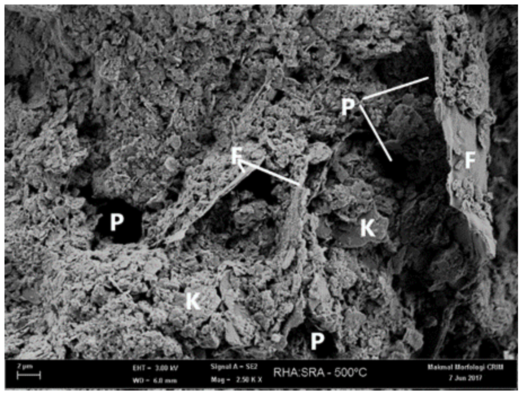
(a)



(b)



(c)



(d)

FIGURE 1. Particle size distribution curves of DWS (a). SEM images of (b) DWS, (c) RHA and (d) a mixture of DWS and RHA. F-fibre; K-kaolinite; Qtz-quartz; P-pore; O-outer part; I-internal part

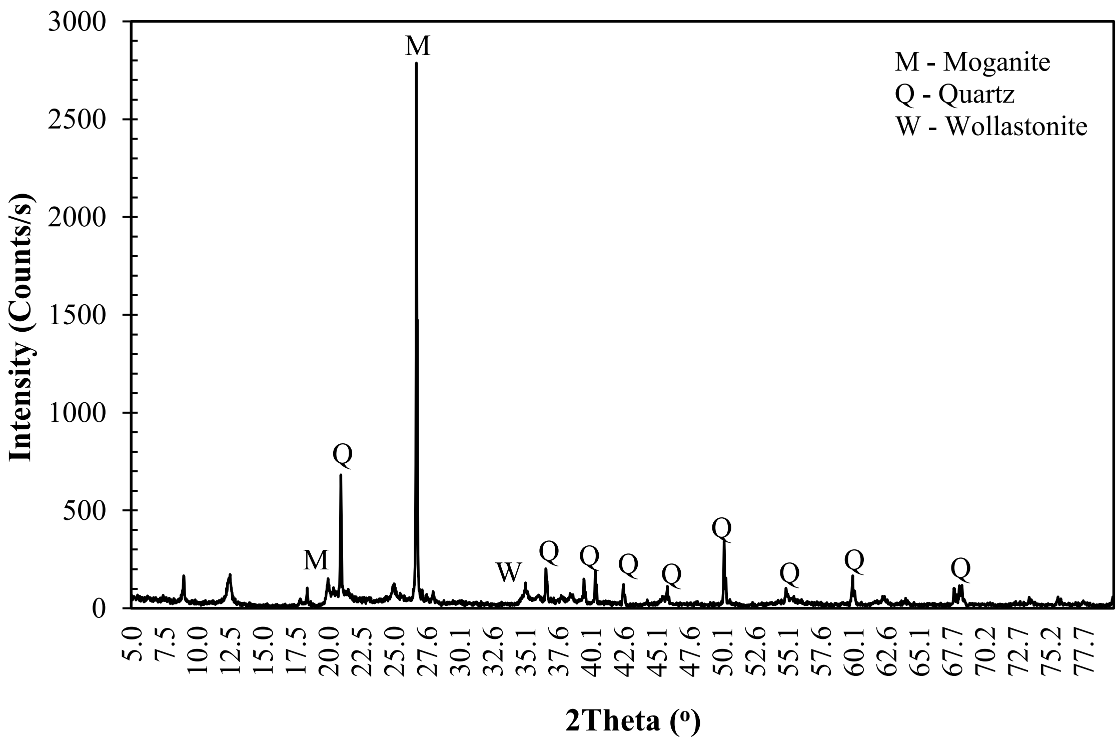


FIGURE 2. The result of XRD analysis of DWS sample

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

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

LINEAR SHRINKAGE

Water is one of the components used to manufacture bricks. The amount of water added varied based on the type of materials used and their plasticity; it helped homogenise the materials and made the brick easier to shape. The drying process causes the brick's volume to decrease due to water evaporation during open-air drying and oven-drying at 110 °C. The presence of RHA in the brick under study and temperature variations both contribute directly to the brick›s volume change (Figure 3). Unfired brick and 300 °C-fired brick exhibited remarkably similar volume changes. As temperature increased to 500 °C, DWS100 brick samples showed higher volume change of 26.7% which later dropped to 23.26% at temperature of 700 °C. As the temperature increased from 500 °C to 700 °C, the volume changes of DWS80 brick samples decreased further. This elucidated the relationship between temperature and the presence of RHA in the bricks. By firing the brick at a high temperature of 500 °C, the brick›s organic material can be destroyed. At this point, the burned organic matters leave spaces that contribute to the brick's increased porosity which end up with low density. Therefore, unfired samples and 300 °C-fired bricks are anticipated to experience a smaller volume change than samples burnt at higher temperatures. The effects of temperature and RHA on the volume change of fired brick have been acknowledged by the previous studies (Khoo, Johari & Ahmad 2013; Sultana et al. 2014). Brick shrinkage may be caused by the combustion of RHA as the temperature rises (Akinshipe & Kornellus 2017). DWS80 bricks exhibited a greater volume change than WDS100 bricks, which can be attributed to the presence of more organic matter in the DWS80 brick's raw materials. This is demonstrated by the fact that the organic content of RHA is approximately twice that of DWS (Table 1). At higher firing temperatures of 700 °C, most of the organic matter was destroyed, causing the final volume to shrink even more (Ali Rahman et al. 2019). The addition of more than 10% RHA associated with higher volumetric shrinkage of fired bricks which related to the inclusion of more amorphous silica, which functions as a filler material in the brick (Sultana et al. 2014).

DENSITY

The density of bricks can vary based on the applied temperature and the raw material used to create them. Because of its low bulk density and high silica content, RHA has been studied for the development of lightweight bricks (Amin et al. 2019; Ling & Teo 2013; Subahshi De Silva & Perera 2018). Figure 4 depicts the effects of temperature variation and RHA content on the density of brick samples. The density of both varieties of bricks decreased as the firing temperature rose. The density of unfired and 300 °C-fired bricks varied marginally. Drastic changes in density were seen at higher firing temperatures from 300 °C to 500 °C for DWS100 and DWS80 bricks, with percentages of reduction of 51.40% and 61.11%, respectively. At a higher temperature, the density reduction percentage was significantly reduced. As the firing temperature increased above 300 °C, a greater reduction was observed. This behaviour was also related to the presence of RHA, as bricks containing RHA had a lower density than bricks without RHA. For unfired and 300 °C-fired bricks, the low specific gravity of RHA explains the low density of bricks containing RHA (Ali Rahman et al. 2015). This is consistent with previous studies (Saleh et al. 2014; Sinuligga, Sirait & Siregar 2018) that examined the effect of RHA on lightweight bricks. The majority of organic material is anticipated to remain stable up to 360 °C. When the temperature reaches 500 °C, organic matter will burn up, leaving voids in the brick samples. Consequently, both types of brick (DWS100 and DWS80) decreased significantly at 500 °C firing temperature compared to the previous temperature. As the temperature increased to 700 °C, there was a negligible change in the brick›s density because most of the organic matter had already been consumed by the fire. The presence of voids has a direct effect on brick density and can consequently alter its water absorption properties (Mageed, Rizk & Abu-Ali 2011; Weng, Lin & Chiang 2003).

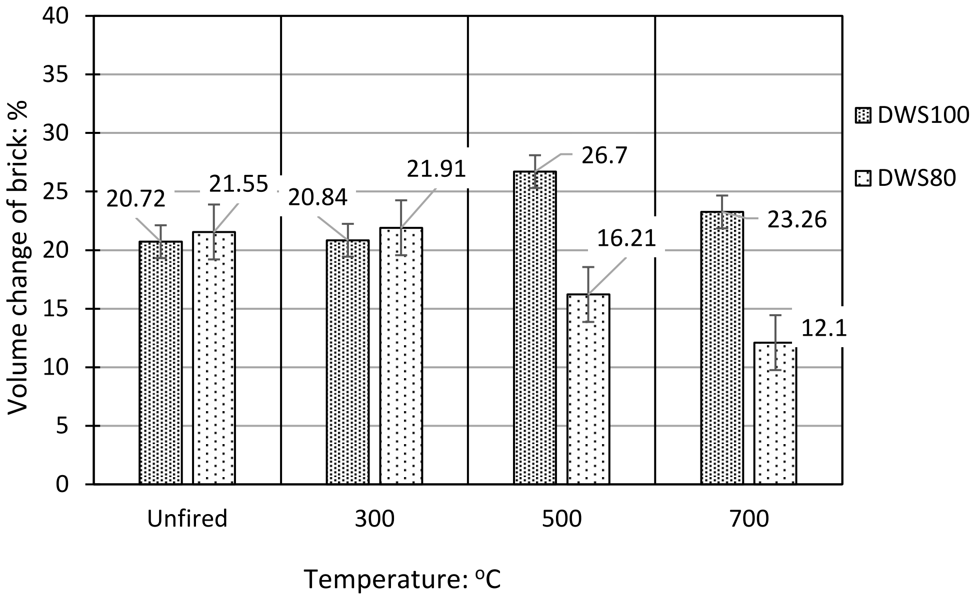


FIGURE 3. Volume change of brick fired at different temperatures with different RHA contents

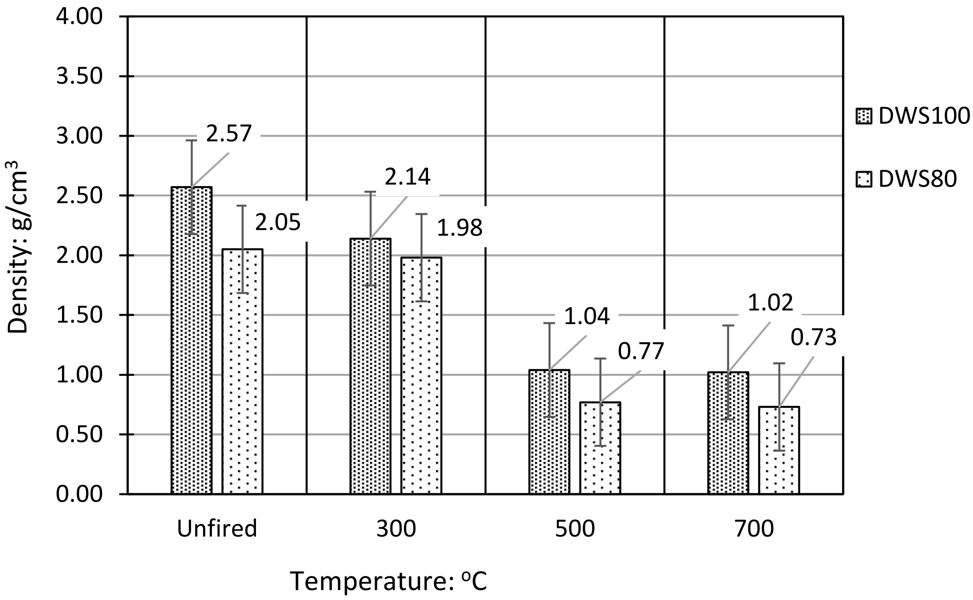


FIGURE 4. Density of bricks fired at different temperatures with different RHA contents

WATER ABSORPTION

This property is related to the apparent porosity of bricks, which is an important parameter for evaluating the water absorption of bricks. Variations in water absorption can impact water-related flaws such as frost action and efflorescence. In addition to allowing salt to penetrate deeper into the brick, water absorption can also allow salt to gradually weaken the brick (AS/NZS 4456.17:2003).

The DWS100 bricks demonstrated a gradual increase in water absorption as the firing temperature reached 500 °C, which then decreased from 65.12% to 54.30% (Figure 5). Similar behaviour is observed for DWS80 bricks as the temperature rises to 300 °C, but it decreases to 51.18% and 48.01%, respectively, at temperatures of 500 °C and 700 °C. For DWS100 bricks, the percentage change in water absorption from unfired to 300 °C-fired bricks was 15.78%, and increased to 31.12% at 500 °C. The percentage change then decreased to 16.62% at 700 °C. The percentage change for the DWS80 bricks from unfired to fired brick at 300 °C was 18.8% and decreased to 8.59% and 6.19% at 500 °C and 700 °C, respectively. The porosity of the brick can directly affect its ability to absorb water. After firing the brick at a high temperature, voids are created due to the combustion of organic matter. At low temperatures, the presence of RHA in DWS80 bricks increased water absorption compared to DWS100 bricks (without RHA) because organic materials can absorb water into the bricks (Figure 5). Once the temperature was raised to 500 °C, most of the organic matter was destroyed, leaving voids in the bricks. When more RHA is added, more voids are created, likely resulting in bricks with greater water absorption (Ali Rahman et al. 2019; Hegazy, Fouad & Hassanain 2012). At 500 °C and 700 °C, it was anticipated that DWS80 would absorb more water than DWS100. However, DWS80 bricks absorb significantly less water than DWS100 bricks. This could be primarily attributed to mineral structure changes caused by clay mineral contraction rather than the influence of organic matter removal per se at elevated temperatures (Krishnan, Jewaratnam & Jewaratnam 2017).

COMPRESSIVE STRENGTH

The compressive strength of bricks is a crucial determinant of their potential applications. The maximum stress that a brick can withstand is typically determined by applying stress to the face bed. Figure 6 depicts the compressive strengths of all types of bricks prepared at

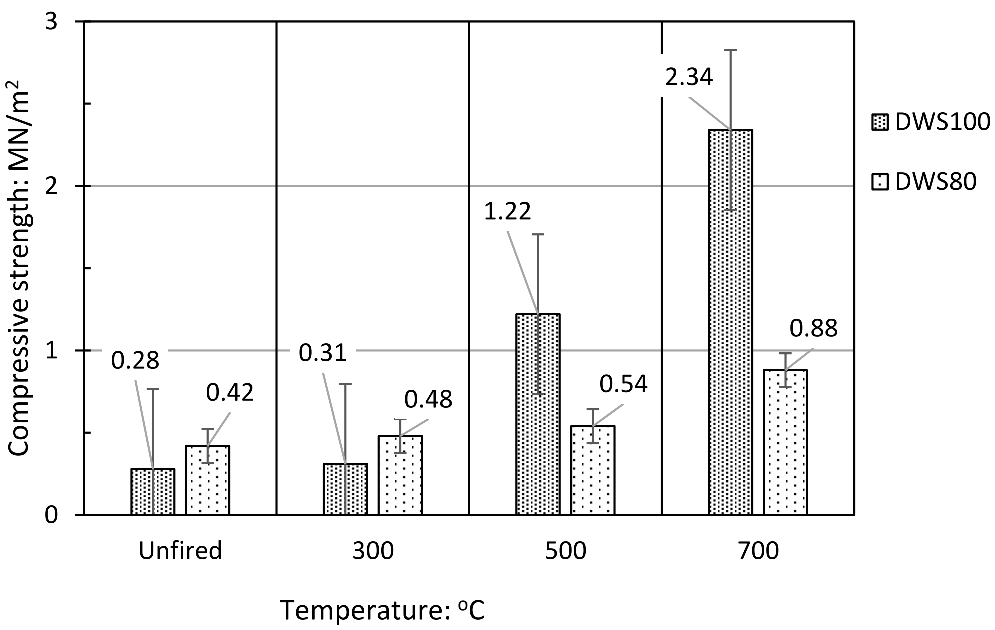


FIGURE 5. Water absorption of brick fired at different temperatures and with different RHA contents

various firing temperatures and RHA compositions. Both bricks' compressive strength increased marginally as the temperature was raised to 300 °C. The compressive strength of DWS100 significantly increased as the temperature was raised to 500 °C and 700 °C, by 174.1% and 234.1%, respectively. At a temperature of 700 °C, the DWS80 increased from 0.42 MN/m^2 to 0.88 MN/m^2 while the DWS80 increased steadily. The percentage changes in compressive strength from unfired to 500 °C and 700 °C were, respectively, 22.2% and 52.0%. These results indicated that the temperature's effect on RHA bricks was significantly lower than that of DWS100 bricks. Several studies demonstrated that the addition of RHA decreased the strength of fired bricks (Huq & Chowdhury 2018; Minh & Tram 2017; Sutas, Mana & Pitak 2012). The presence of aluminium sulphate in DWS, which is commonly used as a flocculant in water treatment plants, has contributed to DWS's high alumina content (Torres, Hernandez & Paredes 2012). Alumina can alter the plasticity of the clay fraction in DWS, resulting in greater clay contraction during the drying process. The coupling effect of high alumina content and temperature resulted in higher strength, associated with the phase change and glassy texture (Sutas, Mana & Pitak 2012). However, at a firing temperature of 850 °C, the DWS brick reached its maximum strength, which then decreased as the firing temperature was increased (Ramadhan, Fouad & Hassanain 2008; Tantawy & Ramadhan 2017). The presence of RHA is associated with the formation of voids, which reduces the bulk density and strength of high-temperature-fired bricks (Subashi De Silva & Perera 2018). As the RHA content has a discernible effect on the compressive strength, the optimal amount of added RHA should be utilised to produce high-quality DWS-containing fired bricks (Hegazy, Fouad & Hassanain 2012; Mohan et al. 2012; Perera et al. 2015). A similar pattern of reduced compressive strength was observed in concrete with added RHA, which was related to high water absorption (Al-Tersawy & El-Sergany 2016). The current study demonstrated conclusively that firing temperature plays a significant role in increasing compressive strength; however, the presence of RHA in the DWS80 brick significantly decreases compressive strength at the corresponding temperature when compared to the DWS100 brick. As a result, the optimal RHA concentration must be determined, as it influences the strength and other mechanical properties.

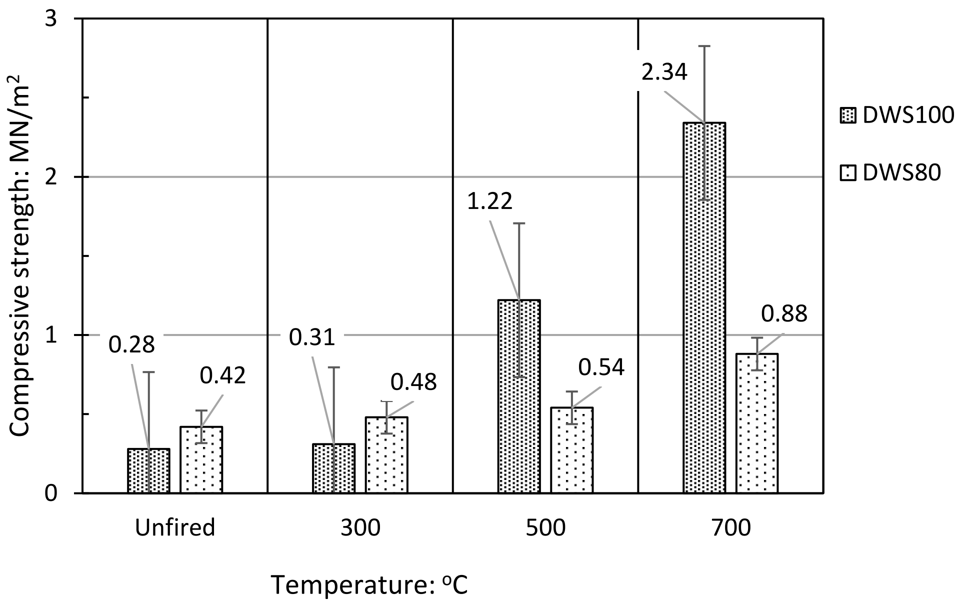


FIGURE 6. Compressive strength of fired brick prepared with different temperatures and RHA contents

CONCLUSIONS

The mechanical properties of bricks made from drinking water sludge (DWS) and rice husk ash (RHA) waste were studied in terms of linear shrinkage, density, and water absorption. The results indicated that variations in firing temperature and the presence of rice husk ash (RHA) had an impact on the bricks under study. The volume change of a DWS100 brick has increased up to 500 °C before decreasing at higher temperatures. In comparison to DWS100, the volume changes of DWS80 bricks began at 500 °C. The high firing temperature and presence of RHA have contributed to the decrease in volume change of bricks containing RHA. As the firing temperature increased, the investigated bricks' density decreased. Density dropped dramatically at 500 °C and 700 °C, with DWS80 bricks always having a lower density value than DWS100 bricks. The water absorption of the investigated bricks steadily increased as the firing temperature rose, with DWS80 and DWS100 bricks beginning to lose water absorption at 500 °C and 700 °C, respectively. It was anticipated that RHA bricks (DWS80) would absorb more water than DWS100 bricks. This behaviour is likely due to the contraction of clay mineral structures rather than the influence of organic matter removal at high temperatures per se. As the firing temperature of both types of bricks was increased, their compressive strength increased. It was hypothesised that the presence of RHA resulted in a decrease in the compressive strength of RHA-added bricks, despite the fact that the bricks' strength was substantially enhanced by the firing temperature. Therefore, the optimal amount of RHA should be utilised; otherwise, RHA can have a negative effect on the quality of bricks.

ACKNOWLEDGEMENTS

The authors would like to thank Universiti Kebangsaan Malaysia for financial assistance in supporting this research project under grant code GGP-2020-006. Special thank is also due to the laboratory staffs at the School of Environmental and Natural Resource Sciences, Faculty of Science and Technology, UKM for the sample preparation and testing facilities.

REFERENCES

Ali Rahman, Z., Othman, A.M., Idris, W.M.R. & Lihan, T. 2021. Kesan suhu dan bahan tambah abu terbang terhadap pencirian mekanik bata daripada sisa rawatan air mentah. *Sains Malaysiana* 50(6): 1563-1575. http://dx.doi.org/10.17576/jsm-2021-5006-05

Ali Rahman, Z., Mohd Saleh, N.M., Idris, W.M.R. & Lihan, T. 2019. Thermal effect on mechanical characteristics of drinking water sludge brick incorporated with rice husk ash. *Sains Malaysiana* 48(11): 2541-2549. http://dx.doi.org/10.17576/jsm-2019-4811-24

Ali Rahman, Z., Mat Noradin, M., Abdul Rahim, S., Idris, W.M. R. & Lihan, T. 2015. Some mechanical characteristics of brick developed from drinking water sludge (DWS) and admixture of rice husk ask (RHA). *Proceeds. National Geoscience Conference 2015*. Perdana Hotel, Kota Bharu Kelantan, 31 July - 1 August 2015. pp. 166-168.

Al-Tersawy, S.H. & El-Sergany, F.A. 2016. Reuse of water treatment plant sludge and rice husk ash in concrete production. *International Journal of Engineering Science & Research Technology* 5(12): 138-152. http://dx.doi.org/10.5281/zenodo.192524drinking wat

Amin, M.N., Hissan, S., Shahzada, K., Khan, K. & Bibi, T. 2019. Pozzolanic reactivity and the influence of rice husk ash on early-age autogenous shrinkage of concrete. *Frontier Materials* 6: 150. https://doi.org/10.3389/fmats.2019.00150

Akinshipe, O. & Kornellus, G. 2017. Chemical and thermodynamic processes in clay brick firing technologies and associated atmospheric emissions metrics - A Review. *Journal of Pollution Effects & Control* 5(2): 1-12.

Anyokora, N.V., Ajinomoh, C.S., Ahmed, A.S., Mohammed Dabo, I.A., Ibrahim, J. & Anton, J.B. 2012. Microstructural and chemical characterization of water works sludge for resource utilization. *WEEJS International Journal of Arts and Combined Sciences* 3(1): 1-5.

AS/NZS 4456.8: 1997. *Determining Moisture Content and Dry Density*. Standard Australia and New Zealand.

AS/NZS 4456.17:2003 *Determining Initial Rate of Absorption (Suction)*. Standards Australia and New Zealand.

Bhupinder, S. 2018. 13 - Rice husk ash. In *Waste and Supplementary Cementitious Materials in Concrete. Characterisation, Properties and Applications*, edited by Siddique, R. & Cachim, P. Woodhead Publishing Series in Civil and Structural Engineering. p. 532. https://doi.org/10.1016/C2016-0-04037-8

British Standards Institution. 1985. *British Standard Specification for Clay Bricks.* London, BS 3921.

BS EN 772-1. 2011. *Methods of Test for Masonry Units. Determination of Compressive Strength*. (London: British Standard). pp. 1-18.

Chen, Y., Zhang, Y., Chen, T., Zhao, Y. & Bao, S. 2011. Preparation of eco-friendly construction bricks from hematite tailings. *Construction Building Materials* 25: 2107-2111. http://dx.doi.10.1016/j.conbuildmat.2010.11.025

Damanhuri, A.A.M., Lubis, A.M.H.S., Hariri, A., Herawan, S.G., Roslan, M.H.I. & Hussin, M.S.F. 2020. Mechanical properties of rice husk ash (RHA) brick as partial replacement of clay. The 2[nd] Joint International Conference on Emerging Computing Technology and Sports (JICETS). *Journal of Physics: Conference Series*. IOP Publishing. https://doi.org/10.1088/1742-6596/1529/4/042034

David, R. 1998. *Handbook to Life in Ancient Egypt*. Oxford: University Press.

Demis, S., Tapali, J.G. & Papadakis, V.G. 2015. Plant design and economics of rice husk ash exploitation as a pozzolanic material. *Waste Biomass Valorization* 6(5): 843-853. https://doi.org/10.1007/s12649-015-9412-1

Figaredo, A.T. & Dhanya, M. 2018. Development of sustainable brick materials incorporating agro-wastes: An overview. *International Research Journal of Engineering and Technology* 5(11): 721-726.

Hegazy, B.E.E., Fouad, H.A. & Hassanain, A.M. 2012. Incorporation of water sludge, silica fume, and rice husk ash in brick making. *Advances in Environmental Research* 1: 83-96.

Heniegal, A.M., Ramadan, M.A., Naguib, A. & Agwa, I.S. 2020. Study on properties of clay brick incorporating sludge of water treatment plant and agriculture waste. *Case Studies in Construction Materials* 13: 1-13. https://doi.org/10.1016/j.cscm.2020.e00397

Herreño, L.C.F., Solano, D.M.V., Sarabia, K.D.R., Pérez, J.O.C. & Quintero, A.A.M. 2019. Drinking water treatment sludge as a partial substitute for clays in non-structural brick production. The 6[th] International Meeting of Technological Innovation (6[th] IMTI). *Journal of Physics: Conference Series*. IOP Publishing. https://doi.org/10.1088/1742-6596/1409/1/012013

Huq, R.S. & Chowdhury, F. 2018. Use of rice husk ash as substitute to make clay bricks. *International Journal of Innovative Research in Science, Engineering and Technology* 7(10): 10236-10243.

Janbuala, S. & Wasanapiarnpong, T. 2015. Effect of rice husk and rice husk ash on properties of lightweight clay bricks. *Key Engineering Materials* 659: 74-79. http://dx.doi.10.4028/www.scientific.net/KEM.659.74

Khan, M.N.N., Jamil, M., Kaish, A.B.M.A. & Zain, M.F.M. 2014. An overview on manufacturing of rice husk ash as supplementary cementitious material. *Australian Journal of Basic and Applied Sciences* 8(19): 176-181.

Khoo, Y.C., Johari, I. & Ahmad, Z.A. 2013. Influence of rice husk ash on the engineering properties of fired clay bricks. *Advanced Materials Research* 795: 14-18.

Kumar, L.V. & Vignesh, B.J. 2017. Experimental investigation on replacement of bagasse ash in bricks. *International Journal of Innovative Research in Science, Engineering and Technology* 6(5): 8303-8309.

Krishnan, P., Jewaratnam, J. & Jewaratnam, J. 2017. Recovery of water treatment residue into clay bricks. *Chemical Engineering Transaction* 56: 1837-1842. http://doi.10.3303/CET1756307

Lamba, P., Kaur, D.P., Raj, S. & Sorout, J. 2022. Recycling/reuse of plastic waste as construction material for sustainable development: A review. *Environmental Science and Pollution Research* 29: 86156-86179.

Ling, I.H. & Teo, D.C.L. 2013. EPS RHA concrete bricks - A new building material. *Jordan Journal of Civil Engineering* 7(4): 361-370.

Liu, Y., Zhuge, Y., Chow, C.W., Keegan, A., Li, D., Pham, P.N., Huang, J. & Siddique, R. 2020. Properties and microstructure of concrete blocks incorporating drinking water treatment sludge exposed to early-age carbonation curing. *Journal of Cleaner Production* 261: 121257. https://doi.org/10.1016/j.jclepro.2020.121257

Mageed, A.A., Rizk, S.A. & Abu-Ali, H. 2011. Utilization of water treatment plants sludge ash in brick making. *Journal of Engineering Sciences* 39(1): 195-206.

McGinnis, M.J., Davis, M., de la Rosa, A., Weldon, B.D. & Kurama, Y.C. 2017. Quantified sustainability of recycled concrete aggregates. *Magazine of Concrete Research* 69(23): 1203-1211. https://doi.org/10.1680/jmacr.16.00338

Minh, L.T. & Tram, N.X.T. 2017. Utilization of rice husk ash as partial replacement with cement for production of concrete brick. *MATEC Web of Conferences* 97: 01121. http://dx.doi.101.1051/matecconf/20179701121

Mohan, N.V., Satyanarayama, P.V.V. & Rao, K.S. 2012. Performance of rice husk ash bricks. *International Journal of Engineering Research and Applications* 2(5): 1906-1910.

MS 76. 1972. *Specification for Bricks and Blocks of Fired Brick Earth, Clay or Shale (Selangor: Malaysian Standard)*. pp 1-74.

Perera, B.V.A., Madushanka, K.G.S., Subashi De Silva, G.H.M.J. & De Silva, G.S.Y. 2015. Effect of rice husk ash on structural properties of fired clay brick. *6th International Conference on Structural Engineering and Construction Management.* Kandy, Sri Lanka, 11th-13th December.

Ramadhan, M.O., Fouad, H.A. & Hassanain, A.M. 2008. Reuse of water treatment plant sludge in brick manufacturing. *Journal of Applied Sciences Research* 4(10): 1223-1229.

Saleh, A.M., Rahmat, M.T., Mohd Yusoff, F.N. & Eddirizal, N.E. 2014. Utilization of palm oil fuel ash and rice husks in unfired bricks for sustainable construction materials development. *MATEC Web of Conferences* 15: 01032. http://dx.doi.10.1051/matecconf/20141501032

Salehi, M.H., Hashemi Beni, O., Beigi Harchegani, H., Esfandiarpour Borujeni, I. & Motaghian, H.R. 2011. Refining soil organic matter determination by loss-on-ignition. *Pedosphere* 21(4): 473-482. http://dx.doi.org/10.1016/S1002-0160(11)60149-5

Shaqour, E.N., Alela, A.H.A. & Rsheed, A.A. 2021. Improved fired clay brick compressive strength by recycling wastes of blacksmiths' workshops. *Journal of Engineering and Applied Science* 68(5): 1-14.

Sinuligga, K., Sirait, M. & Siregar, A.M. 2018. Addition of nano particles effect of rice husk ash as a mixture on the bricks strength. *The 8th International Conference on Theoretical and Applied. Journal of Physics: Conference Series*. IOP Publishing. https://doi/10.1088/1742-6596/1120/1/012090

Subashi De Silva, G.H.M.J. & Perera, B.V.A. 2018. Effect of waste rice husk ash (RHA) on structural, thermal and acoustic properties of fired clay bricks. *Journal of Building Engineering* 18: 252-259.

Sultana, M.S., Hossain, M.I., Rahman, M.A. & Khan, M.H. 2014. Influence of rice husk ash and fly ash on properties of red clay. *Journal of Scientific Research* 6(3): 421-430.

Sutas, J., Mana, A. & Pitak, L. 2012. Effect of rice husk and rice husk ash to properties of bricks. *Procedia Engineering* 32: 1061-1067. http://dx.doi.org/10.1016/j.proeng.2012.02.055

Tantawy, M.A. & Ramadan, S.A.M. 2017. Middle Eocene clay from Goset Abu Khashier: Geological assessment and utilization with drinking water treatment sludge in brick manufacture. *Applied Clay Science* 138: 114-124. http://dx.doi.org/10.1016/j.clay.2017.01.005

Toghroli, A., Shariati, M. & Sajedi, F. 2018. A review on pavement porous concrete using recycled waste materials. *Smart Structure and Systems* 22: 433-440. https://dx.doi.org/10.12989/SSS.2018. 22.4.433

Torres, P., Hernandez, D. & Paredes, D. 2012. Productive use of sludge from a drinking water treatment plant for manufacturing ceramic bricks. *Revista Ingeniería de Construcción*, 27(3): 145-154. http://dx.doi.org/10.4067/S0718-50732012000300003

Weng, C.H., Lin, D.F. & Chiang, P.C. 2003. Utilization of sludge as brick materials. *Advances in Environmental Research* 7(3): 679-685.

Xu, W., Lo, T.Y. & Memon, S.A. 2012. Microstructure and reactivity of rich husk ash. *Construction and Building Materials* 29: 541-547.

Zhang, L. 2013. Production of bricks from waste materials - A review. *Construction and Building Materials* 47: 643-655. http://dx.doi.org/10.1016/j.conbuildmat.2013.05.043

Zou, Y. & Yang, T. 2019. Rice husk ash and their applications. In *Rice Bran and Rice Bran Oil. Chemistry, Processing and Utilization*, edited by Cheong, L.Z. & Xu, X. London: Elsevier Inc. pp. 207-246.

*Corresponding author; email: zarah1970@ukm.edu.my