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Conversion of auxiliary wastes for production of masonry bricks: towards conservation of natural clay

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ABSTRACT

The concerns about the effect of climate change due to high energy consumption and dwindling natural material for the production of bricks and other construction materials have given rise to this study. To address these concerns, polyethylene terephthalate (PET) waste bricks (PWB) were produced using scrap PET and foundry sand in different proportions of 20%, 30%, and 40% by dry mass of the foundry sand. The durability and strength properties of the fabricated PW bricks exposed to acid attack were investigated and results were compared to conventional clay bricks. The load-bearing capacity of the bricks under compression and tension was also evaluated in compliance with South African National Standard SANS 227. Scanning electron microscopy (SEM) tests were performed to understudy the impact of acid exposure on the microstructure of PW bricks also to track the factors responsible for strength developed in these bricks. The test results revealed that 20% and 30% inclusion of melted PET waste rendered a considerable increase in tensile and compressive strength values to a limiting ratio of 30: 70 blends of plastic and foundry sand, beyond which strength modulus decreased. The tension and compression strength resistance of the PET waste bricks on average recorded an appreciable strength of 1.5 - 2 times higher than that of the commercially fired clay bricks that were used as the control. The exposure to acid attack did not affect the PW bricks whereas, it triggered a decrease in strength when compared with the conventional clay bricks.

Keywords: Masonry bricks, Wastes, Strengths, Conservation, Sustainability.

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1. INTRODUCTION

The ever-increasing generation of wastes and its consequential impacts to the environment are undeniably has become a threat to both human and aquatic lives. The most disposed material in landfills is PET plastic, due to its usage as bottles for beverages and packages for other items that have become part of daily lives. It is estimated that above 480 billion PET bottle units were produced for different uses in 2020 worldwide (Tiseo, 2021). Also, plastics are one of the growing wastes of municipal solid waste (MSW) as PET plastics are found in all major MSW categories. However, PET has become an important commercial polymer with its application spanning fabrics, molded parts for automotive, electronics, packaging, and many more. A higher percentage of plastic waste is deposited in landfills, which causes severe environmental pollution due to its non-biodegradable characteristics (Verma et al., 2016).

Based on the amount of PET waste generated every year, only a fraction of this waste is recycled, while the rest found its way into different water bodies, which in turn contributes to pollution and poisoning of aquatic lives. As a result of these challenges, studies have shown that construction industries are making salient contributions towards the re-use of PET waste (PW) in different forms, such as the aggregate in mortar/concrete mixtures as supported by (Mohammed, 2017; Alfahdawi et al., 2018; Dawood et al., 2021). Hence PET waste has also been understudied by (Benosman et al., 2017; Dębska and Lichołai, 2015) as the binder in mortar/concrete. Whereas in the pavement, the waste plastics have served as an aggregate in binding asphalt (Gürü et al., 2014; Sharma, 2020). Amongst other usages, the PET waste has been included as fiber in soil and concrete reinforcement, as an additive to clay brick (Aneke et al., 2015; Limami et al., 2020), or in other innovative forms such as PET panels, mattresses, and even direct use of PET bottles in non-bearing walls (Chowdhury et al., 2013).

Aneke and Celumusa (2021) supported the utilization of PW as a binder in the production of bricks. In the proposed method, PW was chemically modified by digesting PET molecules with glycol at elevated temperature, which was followed by adding recycled crushed glass. The bricks samples were subjected to strength tests at different temperatures. Findings showed that the produced plastic bricks samples achieved more than 80% of their final strength in one day, which can be counted as an advantage over conventional clay bricks. Findings from another study (Aneke et al., 2021) showed that bricks containing PW binder gave higher compressive and flexural strength compared to those of clay bricks. However, it was reported that PET bricks wall under flexural load at high temperatures, may sustain unreasonably deformations, which need to be avoided.

Wang et al. (2016) introduce a novel approach to producing fly ash bricks through the recycling of fly ash. Their study supported a new kind of technology for brick making by which the use of fly ash content amounted to 50–80%. The high fly ash bricks were produced through proportional dosages of crushed glass which was subjected to a temperature of less than 800°C. Their test revealed that all tested indexes of strength grade, freezing-thawing resisting, and other standards of the bricks complied with the national standards for the building materials industry.

Dacuba et al. (2022) reported on the incorporation of coal fly ash (CFA) in fired clay bricks (FCBs), as a clay replacement for cleaner production practices. The CFA-fired clay bricks were fabricated through the incorporation of two CFA, with different content of unburned carbon, FAA (low LOI) and FAB (high LOI) in FCBs. The study reflects that unburned carbon plays an important role in the final properties of FCBs. The thermal decomposition during the firing process promotes an increase in water absorption, decreasing the flexural strength as the porosity increases, although the technical and mechanical properties of samples containing up to 30% FAA and percentages of 20% FAB are acceptable.

Ahmed et al. (2021) supported the fabrication of thermal insulation geopolymer bricks using ferrosilicon slag and alumina waste. A Series of compressive strength, bulk density, cold and boiling water absorption, apparent porosity, thermal conductivity, and Fourier-transform infrared spectroscopy were performed to characterize the properties of the geopolymer bricks. The study indicated that increasing the alumina content enhances the geopolymer properties. This reduces the compressive strength of the fabricated geopolymer bricks. The sample with Si/Al ratio equivalent to 1, exhibited a higher compressive strength of 10.9 MPa than the other Si/Al ratios of 4, 3, 2, and 0.5, and the pristine ferrosilicon slag after 28 days of curing and at 8 M NaOH.

Debska and Licholai (2015) investigated the microstructure and mechanical properties of epoxy bricks containing glycolisates obtained from PW. In their study, a mix of glycolisates and epoxy resin was used as a binder to produce epoxy bricks. Their results showed that the inclusion of 9% PW -based glycolisates resulted in strength gain, which was associated with lower production cost. The effect of PW particles as an aggregate replacement in both unsaturated polymer bricks and epoxy bricks was investigated by Sh et al. (2017). Their findings showed that the replacement of 20% fine aggregate with PW particles led to decreases in specific weight in both epoxy and unsaturated polymer bricks. Meanwhile, the inclusion of PW aggregate in both binder systems yields more ductile material compared to the bricks with no PW in their mixtures. These results agree with the findings by Ali et al. (2021) which suggested that the evaluation of zinc extraction residue as an alternative raw material in the manufacturing of clay-based bricks, contributes to the improvement of product properties and immobilization of heavy metals.

Houssame et al. (2021) proposed an innovative method of producing unfired clay bricks by recycled date pits waste additive as a construction material additive, with multiple waste additive proportions (0%, 1%, 3%, 7%, 15%, and 20%), by weight, in terms of their physicochemical, mechanical, and thermal performances. The incorporation of higher waste additive content in the bricks' composition resulted in the production of more porous samples. The specimens with 20% waste additive percentages, which is the highest evaluated proportion, reflected the highest recorded porosity level of 18.5%, compared to 1.17% of reference samples. This prompted the production of brick samples with a lightweight structure. Their investigation confirmed that waste-based samples of 20% waste additive proportion reflected samples of a 4.02 MPa and 0.98 MPa compressive and flexural strengths, respectively compared to 6.17 MPa and 4.65 MPa of reference samples. The incorporation of waste additives contained in the bricks' matrix reflected enhancements in the specimens' thermal stability. The recorded gains in thermal insulating properties were 37% for thermal conductivity and 21% for specific heat capacity compared to reference samples: as well as 68% and 47% energy savings in terms of thermal cooling and heating loads, respectively, following an energy simulation of a reference house.

In the quest for green-efficient construction materials, scholars like (Aneke and Awuzie, 2018; Aneke and Celumusa, 2021) have published on the part as well as the complete conversion of waste to eco-friendly construction material to mitigate landfill space problems. However, few studies are available in the literature on the strength and microstructure of masonry bricks exposed to acid attack. Therefore, the present study investigated the physicomechanical properties, sustainability, and analytical morphology of sand-plastic bricks exposed to acid attack. As well as the probable utility of foundry sand and melted PET waste combinations for the promotion of sustainable development and eco-conservation of the environment through the production of construction material.

2. MATERIALS AND TESTING PROGRAMS

The PET waste used herein was collected from a landfill in Durban South Africa. The PET plastics production depends on its thermal temperature heat, as it may also exist as an amorphous and as semi-crystalline material. The plastic contained bis-B-hydroxyterephthalate as Its monomer and this compound is synthesized by the esterification reaction between terephthalic acid and ethylene glycol having water as a by-product. Thus, it contained hydrocarbons compounds chains having molecules of carbon, hydrogen, and oxygen $(C_{10}H_8O_4)_n$ as presented in Fig. 1. The dry density of the used PET scrap plastic was evaluated to be 921 kg/m^3 according to ASTM D792 (2020) testing protocols. The chemical composition of the PET waste plastic was determined through the X-ray fluorescence (XRF) technique. The testing was achieved by ensuring that the conditions of the experimental setup were strictly adhered to, by using constant radiation that is not capable of reaching the melting heat degree of the plastic.

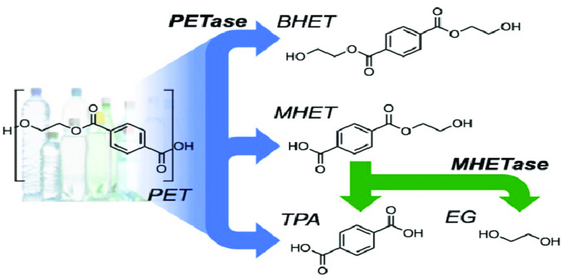

Fig. 1. Molecular of the used scrap PET waste

The foundry sand used here was collected as waste from Joseph Grieveson Ferrous Company in Durban. The sand was passed through an ASTM 2 mm sieve size, having a specific gravity of 2.55. The particle size of sand is important because the amount of open space between the particles influences the strength and microstructure of the bricks. The dominant chemical compositions in the found sand were evaluated to be SiO_2 with a dry mass of 64% and other trace chemical compositions such as Fe_2O_3, Al_2O_3, Cr_2O_3, and CaO making up the remaining 40% of the dry mass. The determination of different chemical compositions with their corresponding percentages was conducted by utilizing an X-ray fluorescence machine that is of Rigaku, Ultima IV, diffractometer with a mounted Goniometer model 2036E201 with Cu Kα radiation (Kα = 1.54056 Å) at an accelerating voltage of 40 kV and a current of 20 mA.

2.1 PET Waste Bricks Preparation

The PET waste was washed using a pressurized water pipe and subsequently air-dried for 3 days in an open space before it was shredded, leaving the waste material in a powder-like form. A Series of design mixes was explored to produce PW bricks (PWB) through a combined mass ratio of 80%: 20%, 70%: 30%, and 60%: 40% by dry mass of the foundry sand and PW. The identities of the produced bricks were formulated based on the ratios of foundry sand and PW for example 80%:20% ratio of foundry sand and plastic waste fabricated brick specimens was tagged PWB-1. Whereas 70%: 30% and 60%: 30% ratios are equivalent to PWB-2 and PWB-3 respectively. The flowchart procedural process followed in this study to fabricate these bricks is presented in Fig. 2. Prior to the scrap PET plastics shredding, the waste material was dried in an open-air place before it was shredded into a tiny particle. The known quantities of the shredded plastic waste were measured, then placed in a steel container, and were taken into a heat-controlled furnace capable of generating up to 1500°C of heat at the rate of 2.0°C/min. The shredded plastic was allowed to melt attaining appropriate consistency with constant stirring using a steel rod. Immediately a viscoelastic consistency was attained, and the measured quantities of foundry sand were gradually added as the composite was manually stirred for 5 minutes until a homogenous composite blend of melted PET waste plastic and foundry sand was achieved. The homogenous composite blend was then cast into a brick mold of 222 x 106 x 73 mm size. The moulds were coated with silicone-based spray to prevent the composite from adhering to the sides of the mold before casting the composite blend. The casted composite blend was compressed using a compressive pressure of 10 MPa to minimize void within the brick matrix before they were allowed to cool at room temperature of 24°C.

The clay bricks used in this investigation were supplied by Corobrik in Durban South Africa. The supplied clay bricks could be classified as well-burnt with good texture and color bearing the same dimension as the PW bricks produced in this study. Some samples of the clay bricks were obtained from all sides using a hammer and chisel to eliminate any form of result discrepancies that might occur from the XRF test. Subsequently, the samples of the clay brick were dried in an oven for 24hours at 110°C, before it was finely milled to a fine powder before the XRF analysis commenced. Table 1 present the chemical compositions of the materials used in this study.

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2.2 Unconfined Compressive Strength (UCS) Test

The compression test was carried out on both the clay and PW composite bricks to determine the strength properties of the specimens. The specimens were tested following the ASTM D2166 at a displacement rate of 0.5 mm/min. An equilibrium period of two days was allowed after the production of the PW bricks before compressive strength was conducted using an average of 2 bricks and the mean value of the tested bricked was recorded as the final value. The stress-strain deformation values were automatically obtained from an electronic data logger upon the test completion.

2.3 Modulus of Rupture

The modulus of rupture was conducted on the bricks in accordance with ASTM C583-15 (2021). The bricks were tested such that the span in between the supports was less than 40 mm of the brick's actual length. The load applied was administered at a rate of 1.25 mm/min in the direction of the brick's depth at the mid-span. A steel surface of 6 mm thickness and 40 mm width was placed at the top of the brick in the direction of the applied load. After the bricks specimen was fractured the distance between the line of fracture and nearest support was measured, and the modulus of rapture was thereafter computed using Equation 1.

$$\sigma_R = \frac{PL}{bd^2} \quad (1)$$

where R is the modulus of rapture, P is the applied force, L is equal to the length of the brick on the tension face, and b and d are equivalent to the average width and depth of the bricks, respectively.

2.4 Durability Test

The durability test of any construction material is very important because it evaluates the performance of materials for any given conditions. Both the PWB and clay bricks were subjected to durability testing following the ASTM D559 / D559M (2015) standard method. The bricks were completely immersed in solutions containing different tetraoxosulphate vi acids (H_2SO_4) concentrations for 90 days as presented in Fig. 3. Different concentrations of 2.30E-08M, 5.20E-07M, 3.60E-05M, and 4.60E-03M were chosen to evaluate the acid durability of both the clay and PW bricks. The dry densities of the bricks were obtained before and after the soaking process to determine mass lost particles disintegration. After the 90 days soaking was completed, the bricks were removed from the acid basin using a pair of big tweezers, following the cleaning up, of the bricks. After measuring the weight of the bricks, it was placed on a surface to enable the drying process for 48 h after which the absorption rate capacity was measured. Subsequently, the soaked bricks were subjected to compressive and tensile strength resistance to measure the effect of acidic soaking on the bricks under severe acidic environmental conditions. This test was done to determine the durability and effects of soaking on the strengths of the bricks in an acidic environment.

Different quantities of water were used for H_2SO_4 concentration adjustment as the brick composites were submerged into each concentration for 90 days as shown in Table 2. The submerged bricks were left to dry for 24 h after 90 days of the equilibrium time were reached and subsequently tested for tensile and compressive strength resistance following the standard protocol mentioned in sections 2.2 and 2.3, respectively.

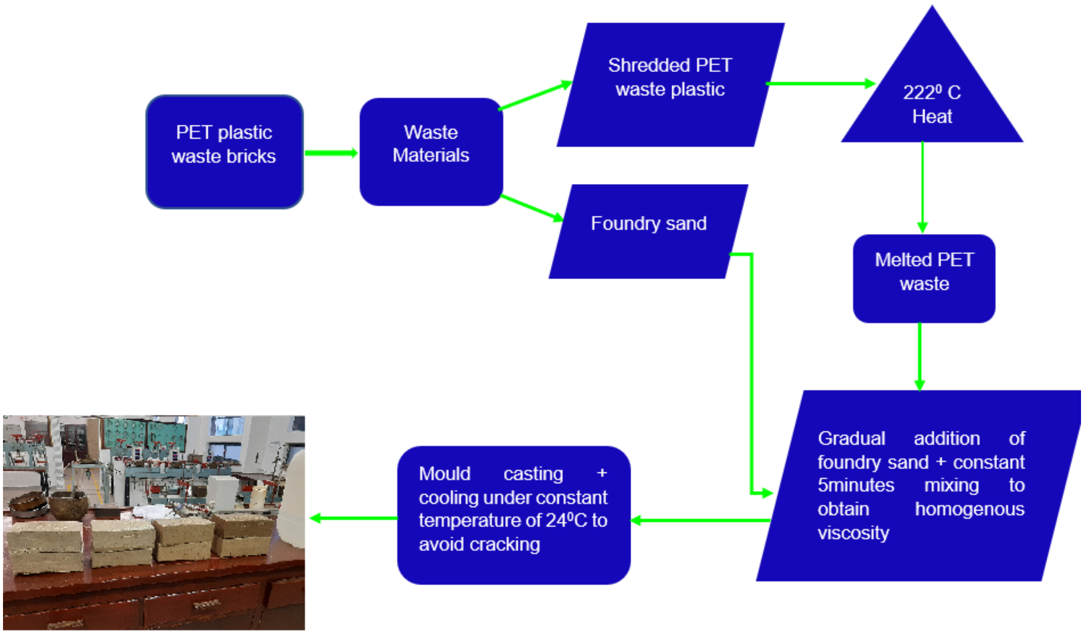

Fig. 2. Flow chart diagram of PW bricks making

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Table 1. Chemical composition of the materials used

Materials	Chemical compositions (%)				
Foundry Sand	SiO_2 -70	Al_2O_3 -16	Fe_2O_3 -10	COa - 2%	Other - 6
Clay Bricks	SiO_2 -60	Al_2O_3 -23	Fe2O3 - 6	COa - 3%	Other - 8
PET waste	$C_8H_6O_4$-58	$HOCH_2CH_2OH$- 8	>	>	Other - 8

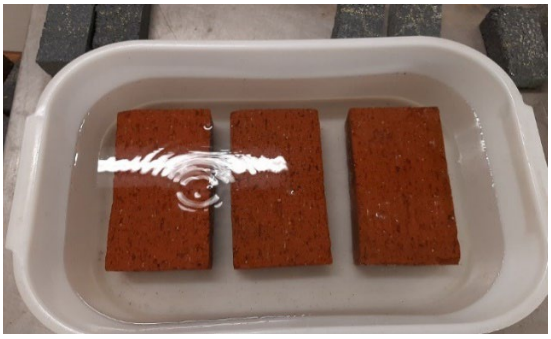


Fig. 3. Durability test setup for clay and PW-bricks

Table 2. Properties of immersion solutions and duration

Series	Molarities (M)	H_3O^+	pH	Time exposure (Days)
1	2.30E-05	2.30×10^{-5}	4.64	90
2	5.20E-04	5.20×10^{-4}	3.28	90
3	3.60E-03	3.60×10^{-3}	2.44	90
4	4.60E-02	4.60×10^{-2}	1.34	90

2.5 Scanning Electron Microscopy (SEM)

The microstructural analysis of the investigated bricks was conducted using SEM apparatus VEGA3 TESCAN-6480 operated at 20 kV following ASTM E986-04 (2017). The samples of the bricks were carefully prepared to obtain the required information on the brick's microstructure. The sample's size, shape, state, and conductive properties were considered before sample preparation. The analytical microstructure of the bricks was performed through polarized light microscopy in thin films with transmitted light. Through this process, SEM determined the primary elemental composition for all the bricks as well as the elemental compound associations of clay PET waste. Mayor, minor, and signs of minerals´ crystalline phases were also presented. It was noted that the microscope's detection capacity is as much as 1 μm from the sample surface, to enable the convenience of identifying unknown particulates as well as studying the interaction between substances and substrates. It is worthy to mention that the aspect ratio of the tested bricks was not within the scope of this study.

3. RESULTS INTERPRETATION

3.1 UCS and MOR Results

The compressive and tensile strength of brick is an important parameter for the structural design of masonry structures. Fig. 4 demonstrates the compression and tension strength resistance after 2 days of the production process. Generally, an increase in compressive strength of a brick unit will virtually contribute to an increase in the masonry assemblage compressive strength and flexural elastic modulus. The test results marked a difference in the observed strength between the PWB and fired clay bricks. It was noted that the strength of the produced bricks is 33.12 MPa, 36.18.01 MPa, and 28.40 MPa for PWB-1, PWB-2, and PWB-3, respectively, compared to fired clay bricks that recorded an average compressive strength of 13.81 MPa. The results indicated that the PW bricks are times greater than the clay bricks. The strength of the PW bricks complies with the South African standard specification for burnt clay masonry units (SANS 227, 2007) requires that the nominal compressive strength for face bricks be not less than 17.0 MPa, with individual strengths greater than 12.5 MPa, for burnt clay brick with a loadbearing capacity of retaining walls and story buildings. In furtherance, the densities of 1784, 1887, 1828, and 1894 kg/m^3 for PWB-1, PWB-2, PWB-3, and clay bricks, respectively.

It was noted that the PW and clay bricks meet the standard requirement recommended by SANS for retaining structures using bricks. The high strength in PWB could be attributed to the viscoelastic properties of the PET under melting temperature, as well as the percentage of foundry sand. The effect of foundry sand and the plastic ratio on the density and strength of the bricks reduces porosity and increases density, as increasing the amount of foundry increased the compressive and tensile strength for additions up to 70% of the dry mass of the foundry sand (Kazmi et al., 2016). It is also worthy to mention that the tension resistance of PWB-3 which contains 40% of PET plastic is higher compared to the rest of the bricks. The high tensile value rendered by this brick is mobilized by the ductile and viscoelasticity of characteristic of the PET plastic. Generally, it is noted that PWBs gave 57% higher compressive strength, on average, compared to those of clay-fired bricks used herein.

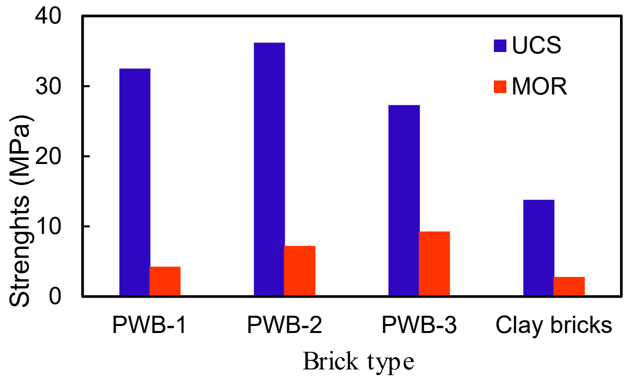


Fig. 4. The strengths of the investigated unsoaked bricks

3.2 Effect of Acid Solution on the Compressive and MOR of Bricks

The performance assessment of PWB and clay bricks subjected to the acidic soaking solutions of different concentrations are presented in Fig. 5a and b. Overall, the PWBs survived the 90-day acidic soaking irrespective of the solution concentration. It was noted that the PW bricks did not render any changes in the strengths during the completion of 90 days of acidic soaking. Whereas significant decreases in strength were observed on clay bricks due to the long-term acidic soaking. It is worthy to mention that the clay bricks particularly the ones soaked in 2.30E-08 M and 5.20E-07 M of sulphuric acid solution lost up to 12.1% grams of their initial mass, as it resulted in a significant loss in strength. The drop in the legend was that of clay bricks corresponding to the concentration of the acid solution as demonstrated in the curve. The adsorption of the acid solution in the pore spaces of the bricks triggered the replacement of exchangeable cations by protons which was mobilized by the interaction between the fired clay bricks and the acid solution. The absorption of the acid solution caused the proton to diffuse with the voids of the bricks leading to a chemical reaction that aids the decrease in alkalinity of the bricks leaving them venerable to low compression strength. In furtherance, the internal hydration of calcium silicate and the calcium aluminate hydration lost their stability and accelerated their hydrolysis, destroying the internal microstructure of the clay bricks leading to low compressive strengths as reported elsewhere by (Eyssautier-Chuine et al., 2016; Wang et al., 2016). The moisture absorption capacity of the PWBs is very low compared to fired clay bricks. The less acid absorption by the PW brick contributed to a higher strength increase as mobilized by the hydrophobic characteristic of melted PET plastic in the bricks. The indicated viscoelastic properties of the PW bricks have direct proportionality to the percentage of melted PET contained in the bricks to the corresponding sand proportions which caused the high resilience to dampness portrayed by the produced bricks.

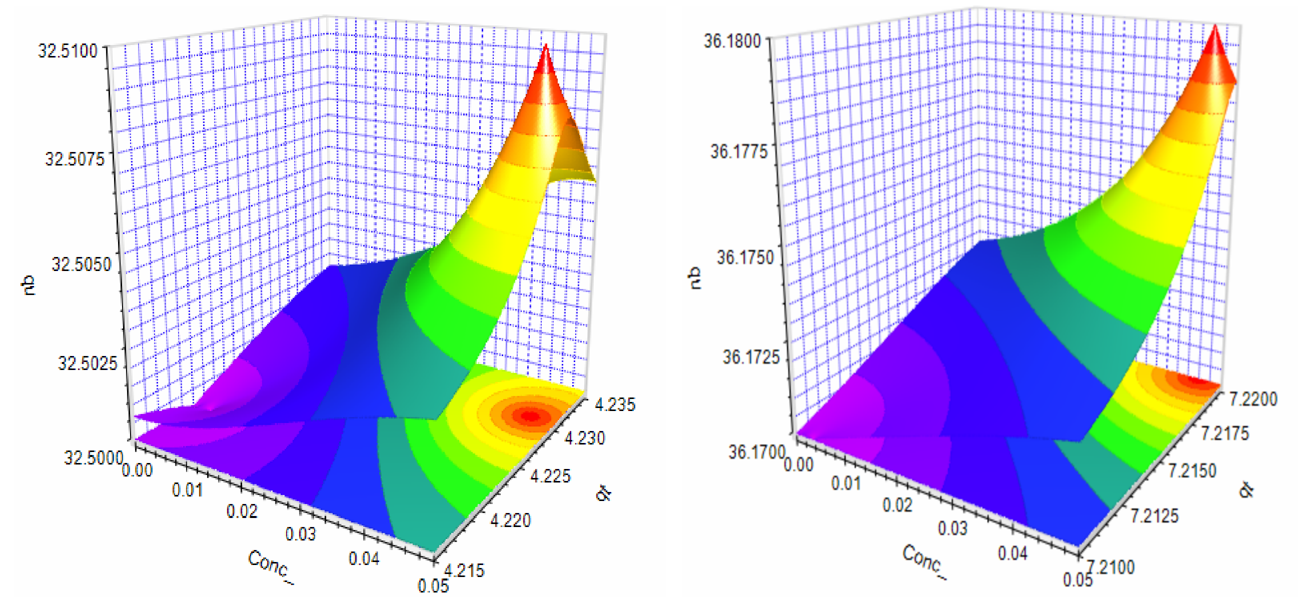
3.3 Correlation of Compressive Strength with MOR of the Bricks

This section of the study illustrates the relationship between the compressive strength and tensile strength using obtained results as shown in Fig. 6a through d. The results of the graph show that the data from the PWB-1 have more proximity to the regression line having a coefficient error value of 0.06. However, the points data for PWB-2 has a lesser distance to the regression line with a corresponding coefficient error value of 0.03. In furtherance, PWB-3 showed there is a significant relationship between the compressive strength and the tensile strength of the bricks, such that the coefficient error value of 0.07 is lower than the 0.12 coefficient error value rendered by the clay bricks. The result indicated that the possibility to estimate the tensile strength from the compressive strength is reliable. The slope of the line in the PW bricks is higher than that of the clay bricks, which importantly indicates that the PET waste has a significant influence on the values of the tensile strength of the PW bricks. However, with increasing the percentage of the melted PET waste, the slope of the line increases, and the estimated coefficient error value tend to the value zero. It is worthy to mention that the structural members of a masonry unit are designed to sustain both compressive as well as tensile stresses simultaneously (Merritt, 2012). Therefore, the correlation between the tensile and compressive strength is important to study for designing the flexural members.

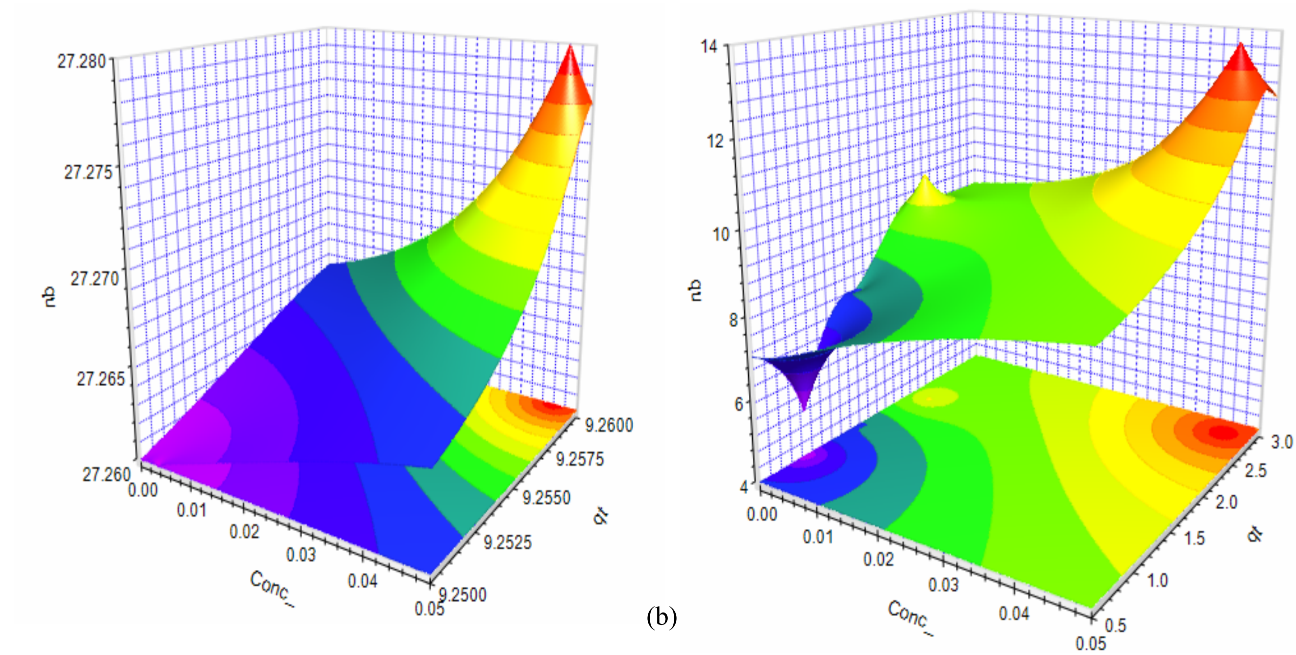
The curves substantiate bi-linear proportionality claims between tensile and compressive strengths, resulting in a coefficient of correlation (R^2) of 0.94, 0.98, 0.93, and 0.88 for PWB-1, PWB-2, PWB-3, and clay bricks, respectively. The correlation of the strength indices depends mainly on the percentages of recycled crushed glass, melted plastics, and brick porosity. The proposed relationship between q_t and q_u is close to the suggested ratio of compressive strength to tensile strength for concrete M20 grade. Various design codes suggest that tensile stresses are designed to be carried by reinforced material like steel, as part of tensile stresses is transferred to the concrete (Wight and McGregor, 2015). It is a well-established fact that the ratio of tensile to the compressive strength of concrete is 10%. Whereas the ratio of tensile to compressive strength for the produced bricks in this study is equivalent to 19.13% under dry testing conditions. This is an indication that the PWB produced in this study will render greater suitability for flexural stress. In furtherance, the tensile strength of the bricks governs the design of the unreinforced masonry, due to the proportionality between the brick strength and the mortar. It is evident that the tensile strength of a brick is controlled by the unit shape, type of mortar, mortar materials, percentage of grouting of hollow units, and the direction of loading.

3.4 Stress-Strain Response of the Bricks

The clay bricks are typically nonelastic and isotropic composed of fired clay material. Under tensile stress, clay bricks possess low tensile strength resistance even within a small range of deformations. The clay bricks are very weak in tension because it is a brittle response of fired stiff clay, therefore, bricks are normally provided and expected to resist only the compressive stress. The stress-strain response under compression stress is shown in Fig. 7. The fired clay bricks used herein rendered a brittle kind of failure between 2.8 mm and 3.2 mm of strain deformation. The brittle behaviour of the clay bricks was due to the production processes because the microstructure of the brick is highly influenced by the firing temperature. Further, the brittle failure of the fired clay bricks was due to the formation of vertical splitting cracks along with their height, causing failure of about 15% of bricks mobilized by a bond failure by flexural bending of bricks, probably due to poor morphological alignment.



(a)



(b)

Fig. 5. (a) Effects of acid concentrations on tension and compression resistance of PWB-1 and PWB-2
(b) Effects of acid concentrations on tension and compression resistance of PWB-3 and clay bricks

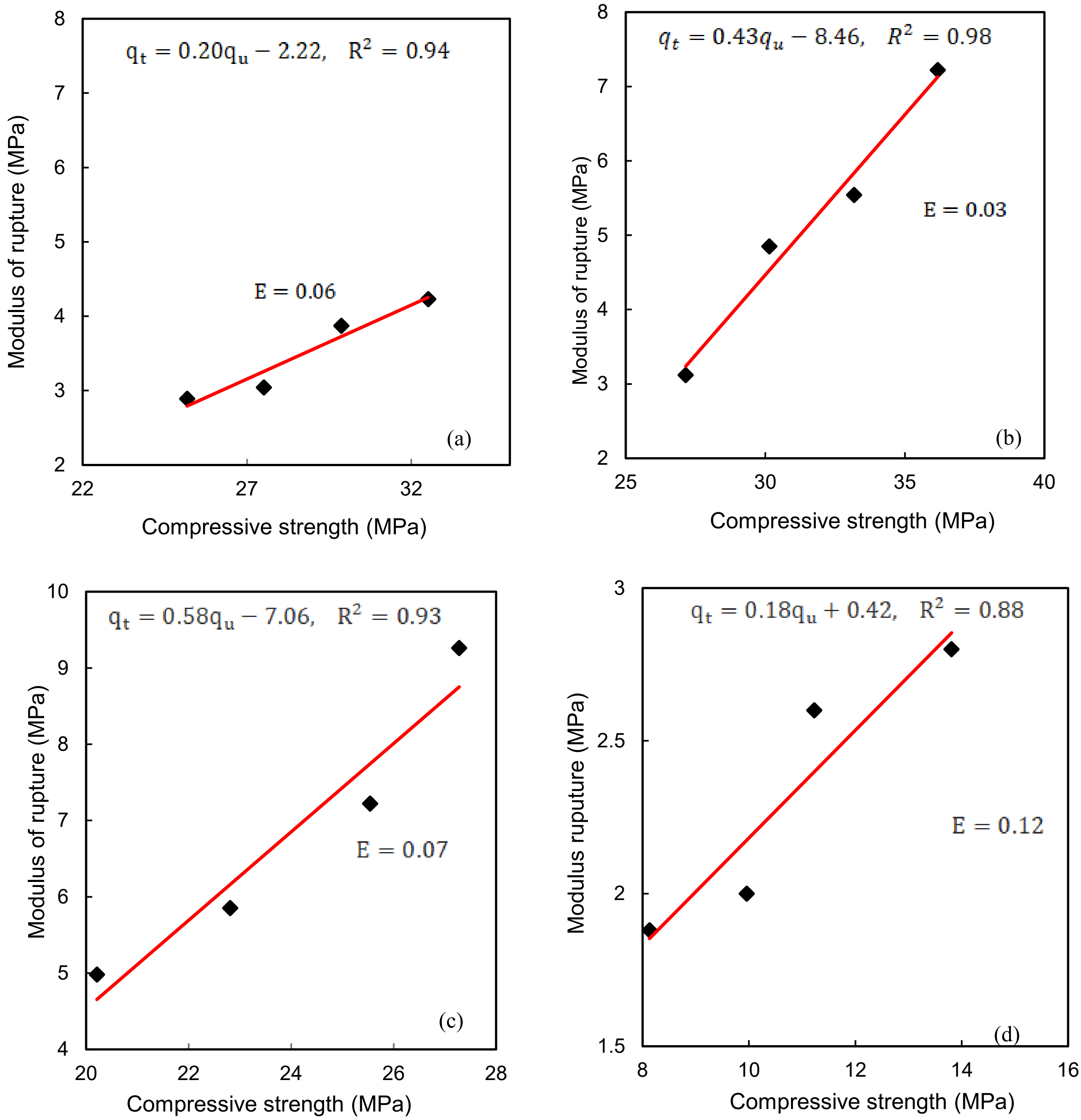


Fig. 6. (a) and (b). Correlation of compressive and tensile strengths of PWB-1 and PWB-2 bricks composites (c) and (d). Correlation of compressive and tensile strengths of PWB-3 and clay bricks

The representative stress-strain response of the PWB bricks under compressive stress exhibit considerable ductile stiffness behaviour relatively proportional to the percentage of added melted plastics at axial strain beyond 3.1 mm 4.3 mm deformation strain, such that the stress relaxation is indicated between 25 to 36 MPa mm. The stress-strain curves of PW-1 are linear since the onset of applied loading, such that the calculated modulus of elasticity corresponds to the initial tangent to the stress-strain curves. However, before reaching a peak compressive strength, the load increased gradually with cumulative strain displacement. Once the peak strength was attained, a gradual decrease in the compressive strength occurred, with the strain displacement gradually increasing further, a phenomenon known as the fracture stage or the residual strength. It was noted that the fracture stage of the bricks occurred almost at 1.3 mm strain displacement at this point the stress attained a steady-state interface compressive strength value referred to as the large displacement. Generally, the response of PWBs under compression rendered a nonlinear relationship between applied stress and strain deformation at strain hardening values of 3.1 mm, 3.4 mm, and 3.8 respectively for PWB-1, and 3 respectively beyond which critical stress state occurred. Furthermore, significant post-peak ductility was noted on the PWBs which are mobilized by the elastic characteristics of the melted scrap plastics in the bricks.On the contrary, clay bricks exhibited a low stiffness response in compression compared to the PW bricks. Significant post-peak ductility was observed beyond the 3.8 mm strain for PWBs. As such, without any potential residual strength, the clay bricks failed strain displacement at 2.8 mm. The failure pattern of the clay bricks is characterized by brittle behaviour while the PWBs show multiple planes of intended failures which could be referred to as ductile response. The stress-strain relationship obtained in this study was very similar to the resultspublished in past literature, (Gumaste et al., 2007; Kaushik et al., 2007). Strain hardening of the PWBs is relative to the resistance of the scrap plastic to deformation elongation. The multiple planes of ductility for PWBs under compression were due to the random distribution and percentages of melted plastics and foundry sand that aided the redistribution of the potential planes of ductility.

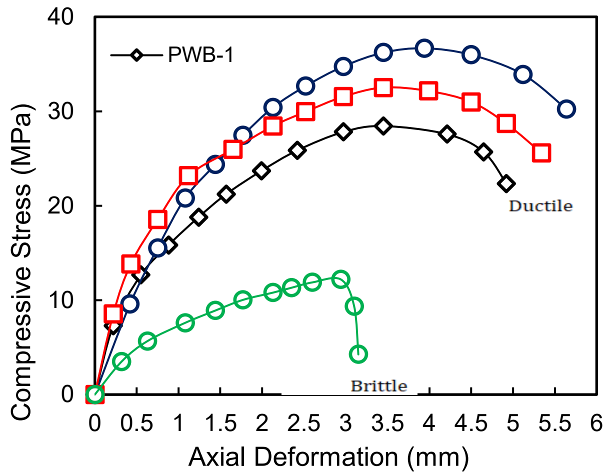


Fig. 7. Load-deformation relationship of PW and fired clay bricks

The compressive and tensile strengths of brick are important material properties parameters for structural applications. In general, an increase in the compressive strength of a brick unit will result in an increase in the masonry assemblage compressive strength and elastic modulus. Further, the strength of clay bricks is directly proportional to the fired temperature. As such, results in low strength, and stiffness as well as low elastic modulus and shear modulus. Therefore, causing the clay bricks not to meet the required design strength for a load-bearing masonry structure. Clay bricks are considered an isotropic material because it exhibits an orthotropic response to axial loading. The modulus of elasticity for this orthotropic material is different in the direction parallel to the bed joint usually termed the x-direction from the direction perpendicular to the bed referred to as the y-direction. The elasticity equations for the PW bricks produced in this study consistently produced higher stiffness for 20%, 30%, and 50% inclusion of PET waste plastic, elastic modulus, and shear modulus as analysed using Equation (2) through (7).

$$\varepsilon_x = \frac{1}{E_x}\tau_x - \frac{v_{xy}}{E_y}\tau_y \tag{2}$$

$$\varepsilon_y = -\frac{v_{xy}}{E_x}\tau_x + \frac{1}{E_y}\tau_y \tag{3}$$

$$\varepsilon_{xy} = \frac{1}{2G_{xy}}\tau_{xy} \tag{4}$$

$$v_{yx}E_x = v_{xy}E_y \tag{5}$$

Where v_{xy}, v_{yx}, E_x, E_y are the Poisson's ratio for the yx and xy components and Young's modulus for the x and y respectively, ε represents the strain components, τ represents the stress components. According to (Asteris, 2003) the shear modulus G_{xy} for the elasticity of the bricks is represented with D and the equation could be rearranged and presented in Equation (6) and finally the shear modulus is calculated using Equation (7) as Equation (6) is simplified.

$$D = \begin{bmatrix} \frac{E_x}{1-v_{xy}v_{yx}} & \frac{E_x v_{yx}}{1-v_{xy}v_{yx}} & 0 \\ \frac{v_{xy}E_y}{1-v_{xy}v_{yx}} & \frac{E_y}{1-v_{xy}v_{yx}} & 0 \\ 0 & 0 & G_{xy} \end{bmatrix} \tag{6}$$

$$G_{xy} = \frac{\sqrt{E_x E_y}}{2(1+\sqrt{v_{xy}v_{yx}})} \tag{7}$$

Based on the curve presented in (Fig. 7) the passion ratio v, values for PW and clay bricks are 0.23, 0.25, 0.24, and 0.22 for PW-1, 2, 3, and clay bricks, respectively. The modulus of elasticity of the clay bricks was evaluated to be 3815 MPa, the E values for the PW-1, 2, and 3 bricks are 4321 MPa, 5678 MPa, and 4876 MPa. The shear modulus of the clay bricks was computed to 1.86 GPa, where PW-1, 2, and 3 bricks recovered an average value of 2.23 GPa, 2.84 GPa, and 2.31 MPa. The test results indicated the PW bricks are more isotropic material, such that when used in masonry structures under seismic load will significantly portray stiff resistance based on their respective shear modulus values. The shear modulus is an intrinsic property of a material, and the values should not depend on the strength of the mortar.

3.5 Scanning Electron Microscopy (SEM)

The morphology of PWBs with different percentages of PW as well as the microstructure of the fired clay bricks were investigated using SEM analysis. The morphologies of the PWB-1, PWB-2, and PWB-3 are in Figs. 8a to 8c. It is noted that the bricks with 20% of melted PW are greyish, the grey color gradually changed to black as the PET content increases as can be indicated in the figures. The PWBs portrayed viscous floccules with foundry sand forming a tight matrix structure sealed within the surface and the inner part of the bricks. The morphology showed traces of quartz as the white identified spots on micrographs whereas the black and greyish patches with a glassy and unwrinkled surface are identified as ethylene and propylene that serve as binders. The same chemical compounds were identified on the PWB-2 and PWB-3 with a more blackish shinning microstructure. This was an indication of higher percentages of melted PET plastic used in the production of the bricks. Significant, changes were observed on the PWBs because of the PW inclusion, which coated and knitted the sand particles, as well as filled the pore spaces within the matrix structure. The chemical composition identified with the surfaces of the PWBs is C, H, and O, which are rendered by PET plastics, while Si, Fe, and Al are the dominant elemental compound that is from foundry sand. The inclusion of melted plastics in the PWBs resulted in the reduction of pore space with bricks and this observation is pronounced PWB-2 and PWB-3. The pore spaces in the bricks were minimized drastically causing them to relatively pose greater strength when compared with fired clay bricks.

In Fig. 8c, the energy dispersive X-ray analysis (EDX) of the fired clay bricks suggested the presents of aluminum, silicon, magnesium, and calcium as the primary elements. The designated dark areas are the partially burnt clay particles shown by irregular black porous parts. Whereas the greyish identified areas are the mixture of calcium and silicon which appeared to be spherical with a small bulging of siliceous and aluminous glass. Generally, the pore spaces in fired clay bricks are greater compared to the PWBs that rendered more of a knitted solid matrix structure within the bricks.

4. THE BENEFIT OF PET WASTE INCLUSION IN BRICKS

The production of bricks through the inclusion of PET wastes has resulted in the production of energy-efficient construction material, with a demonstrated improvement of the physical and mechanical properties. The process through which the PW bricks are produced could assist in the mitigation of environmental overburden caused by using natural resources as well as reducing the impact of CO_2 emission. The finds in this could address issues of sustainability, energy consumption, and cost-effective construction materials. The inclusion of PET waste in brick production is relatively associated with the conservation of non-renewable resources through effective waste management. Based on the stiffness analysis, the bricks produced in this study are fittingly suitable for the construction of masonry structures i.e., retaining walls, bridges, etc. The amount of cement and natural soil usage in the bricks-making industry could decrease to the lowest minimum through the conversion of waste to resourceful materials.

It is noted that the production cost of clay bricks is directly influenced by the amount of energy required to fire the clay. In that context, electricity in South Africa is 0.145 and 0.070 U.S. dollars per kWh for households and businesses, respectively. The unit cost for business electricity price is considered for this calculation analysis. Therefore, the generation and consumption of electricity are 0.070 US dollars for 1kwh based on commercial billing (Eskom, 2019). According to the unit price, 220°C is required to manufacture the PW bricks. The cost of PW bricks is 0.024 US dollars which is equivalent to R0.38 per brick, on the basis that 1 kWh of electricity will generate 1895.63°C of heat. Whereas 1.531 U.S. dollars is required to produce fired clay bricks which are equivalent to R2.29 per brick. The energy and time consumption analyses are summarized in Table 3. According to (Mary et al., 2018), the produced PW bricks could be quantified as energy-efficient bricks. Without the consideration of other costs, the calculation analysis presented herein is based on electricity consumption costs. From all indications the fired clay bricks require more time i.e., 10 and 40 hours from preparation time to end of production time depending. Whereas, 10 minutes is required to go through the process of melt of the PET plastics as well as getting the composite to a homogeneous viscosity. With the aspirations through the plethora of anthropogenic activities domiciled within the construction industry, it is worthy to mention that the construction industry can pilot the achievement of energy-efficient construction material (Kibert, 2013). The findings herein, contribute toward mitigating the issues surrounding economic efficiency, social responsibility, environmental performance, as well as material performance (Sfakianaki, 2015).

5. CONCLUSIONS

Different properties of masonry bricks made using PET plastic waste and foundry sands were investigated in this study. Results were compared with those of traditional clay brick. The following conclusions are derived based on the results.

Generally, the bricks made using PET waste and foundry sand gave significantly higher strength compared to the fired clay bricks. The compressive strength of PET waste-based bricks varied from 28.4 to 33.12 MPa, depending on the proportions of PET waste and foundry sand in their mix design. The best compressive strength was given by the bricks that were prepared with 70% foundry sand and 30% PET waste. Similarly, the tensile strengths of bricks based on the waste materials were significantly higher than those of fired clay bricks.

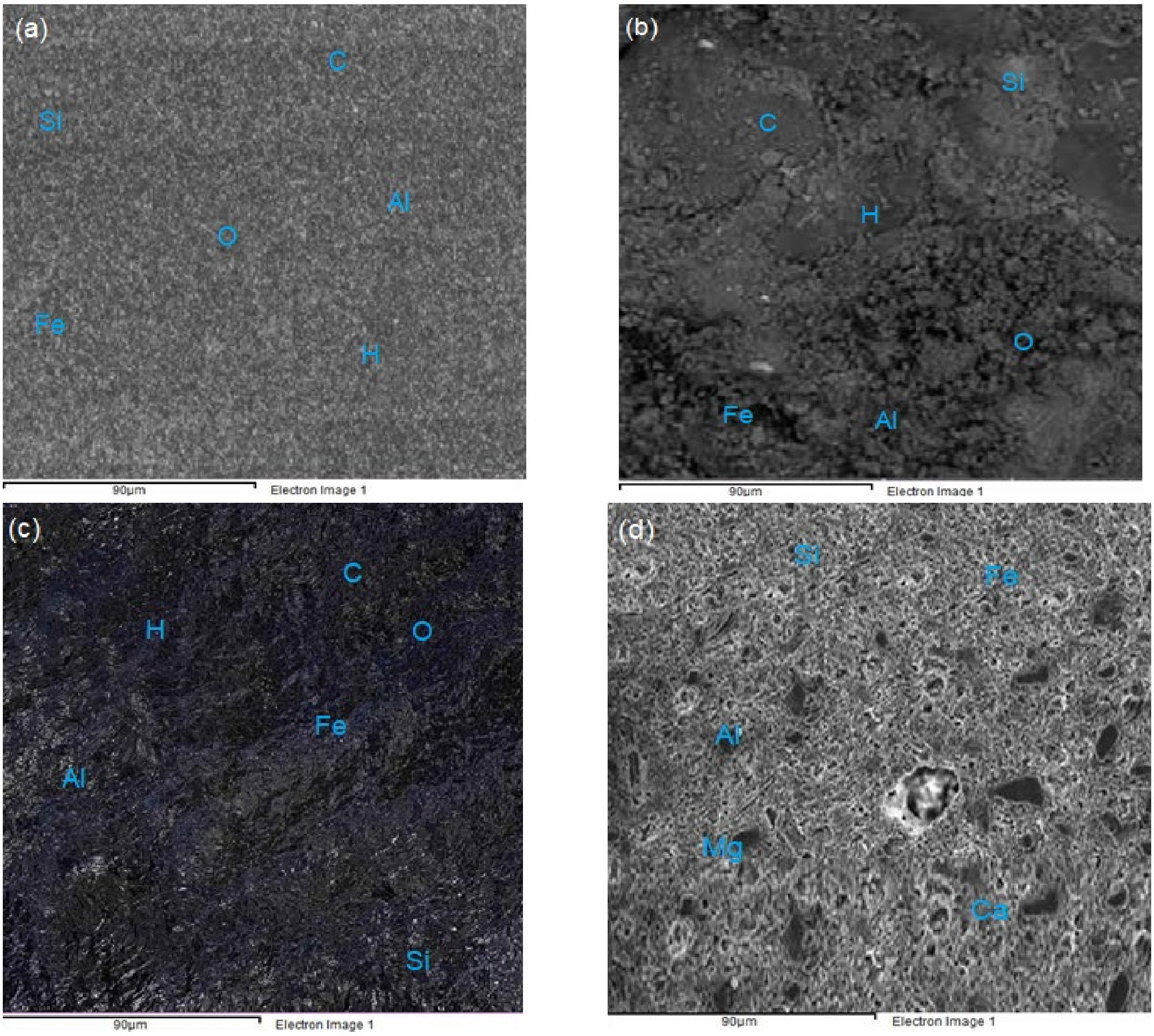


Fig. 8. The micrograph obtained by SEM PW and fired clay bricks

Table 3. Bricks and its sustainable status

Bricks	Compressive strength (MPa)	Time cost (Minutes)	Absorption capacity (%)	Average Density (kg/m^3)	Price/energy cost	Sustainability
PWB-1	33.45	10	1.0 -1.7	1784	R 0.36/bricks	Favorable
PWB-2	36.14	10	0.8-10	1887	R 0.36/bricks	Favorable
PWB-3	29.25	10	0.09-0.40	1828	R 0.36/bricks	Favorable
Clay bricks	13.41	15 -40 hours	6.0- 10.0	1894	R 2.29/bricks	Not Favorable

The tensile strength of the bricks increased from 4.23 MPa to 9.26 MPa due to increases in the inclusion of PET waste from 20% to 40%, while the tensile strength of the clay bricks was 2.8 MPa. The improvement in the strength due to an increase in the percentage of PET waste is attributed to a relatively high tensile strength of PET material, which serves as a binder in the bricks to form the composite matrix.

Based on the acid immersion test results, there was a significant strength loss of 4.32 MPa upon immersion of clay brick in acid solution, while exposure of PET waste-based bricks to the acid solution did not result in any significant change in the strength. This observation can be attributed to the relatively stable polymeric structure of PET against dissolution by H+ from the acid medium.

The stress-strain curve of fired brick exhibited a brittle behaviour, while there was a clear post-peak deformation in the case of PET waste bricks that suggests a ductile property for this material. The ductility of waste-based bricked is attributed to the plastic/plastic properties of PET material.

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DATA AVAILABILITY STATEMENT

Please, note that all data, models, and code generated or used during the study appear in the submitted article.

DECLARATION

No potential conflict of interest was reported by the authors.

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