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Utilization of Plastic Waste Material in Masonry Bricks Production Towards Strength, Durability and Environmental Sustainability

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Abstract

The level of generated plastic waste has awash over a billion metric tonnes of this waste into our environment. If an effective long-lasting solution to this impending disaster is not provided through recycling, reengineering, and conversion of this waste to resourceful materials. Then sustainability and conservation of natural non-replenishable materials will be severely threatened. The aims to avert the impending consequences of this disaster and conserve natural materials have given rise to a sustainable future in the production of low carbon embedded construction materials. Under these circumstances, this study, therefore, presents the strengths and durability of waste plastic bricks (WPB) produced from blending scrap PET plastics and foundry sand. The WPB masonry bricks were produced using ratios of 10:90, 20: 80, and 30: 70 to the combined dry mass of PET and sand. Series of compressive strength tests, modulus of rupture (MOR) tests, apparent porosity tests, water absorption tests, salt-resistance tests, ultrasonic pulse velocity, and scanning electron microscopy (SEM) tests were conducted to investigate the strength and durability of the WPB in conformance with the South African National Standard (SANS 227) for individual load-bearing masonry face brick unit. Compared to the clay bricks with 18 MPa what of strength, the test result revealed that the WPB rendered an average compressive strength of 35.2 MPa. Furthermore, the test result showed that the WPB recorded significant strength resistance under tension compared to the clay brick due to the ductility properties of scrap plastic waste. Also, the acid effects were significantly resisted on the surface WPBs due to the hydrophobic property of the PET- waste. The stiffness of the clay bricks portrayed brittle response, whereas WPBs benefited with high ductility properties, therefore, revealed a great proportionality between the dynamic modulus and ultrasonic pulse velocity (UPV) with a coefficient of determination (R^2) of 90%.

Keywords: masonry bricks, PET waste, foundry sand, strengths, stiffness.

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Introduction

The increasing quantity of waste plastic (WP) in our ecosystems has reached the level of great concern for a clean and safe environment. Plastic is dangerous since it is not degradable therefore it ticks around in the environment for ages. As such threatens wildlife and spreads toxins to the waterbody. Trillion grocery bags are used each year without earning any form of recycling benefit, thereby causing severe environmental and waterbody pollutions (Free et al 2014; Xanthos and Walker, 2017).

Due to the growing quest for a clean and safe environment, material scientists have been working tirelessly for an effective technique of converting plastics and other industrial wastes into a resourceful material without compromising the greenhouse gas threshold (Dachowski, and Kostrzewa, 2016; Aneke and Awuzie, 2018). Despite notable attempts by various waste managers to reduce the excessive annual PW generation through four R's hierarchy i.e., reduce, reuse, recycle, recover. There is still a persistent increase in the generation of PW owing to rapid developments and population (Schneider and Ragossnig 2015; Vince and Hardesty 2016). As a result of these challenges, alternative and effective recycling techniques could assist the mitigation of PW pollution to ensure significant sustainability of the ecosystem. Other than recycling, PW has been utilised in several constructions through random inclusion in the production process of low carbon construction materials in order to improve waste management systems (Peter et al. 2018; Frank and Celumusa, 2021) several reports have been published on the use of PW in various constructions ranging from concrete, pavement, and soil stabilization (Choudhary et al. 2010; Leng et al. 2018). Besides its unit weight and ductility, of particular interest is the viable characteristics of PW to produce a lightweight composite that could withstand tensile stress (Arulrajah et al. 2017; Hama and Hilal, 2019). Albeit that PW is used in the production of paving stone, the PW has been also used as a placement for aggregate in pavements, owing to its resistance to shear, stiffness, as well as improving subgrade bearing capacity (Alexander et al. 2018).

Vasudevan et al. (2012) reported on the crushed PET used as an aggregate in the manufacturing of asphalt, concrete, and soils. Their study concluded that the inclusion of PET as an aggregate offered great benefits such as weight reduction, corrosion resistance, and proper mechanical performance. Despite the benefits of PW high volume of this waste is deposited in landfills, which causes severe environmental impact due to the non-biodegradable property of this material (Irwan et al. 2013). In furtherance, several studies suggested the re-use of PW in construction materials in different forms, including the aggregate in mortar/concrete mixtures, will serve as a great technique towards reducing environmental and ecosystem threats (Reis and Carneiro, 2012; Mohammed, 2017a, 2017b; Alfahdawi et al., 2018, 2019; Dawood et al., 2021)the influence of using polyethylene terephthalate (PET. In addition, many scholars have used PW in various construction projects; as the binder in mortar/concrete was reported by (Benosman et al., 2017), as aggregate/binder in asphalt pavement this study was presented by (Gürü et al., 2014; Sharma, 2020), as fibre reinforcement in concrete (Mohammed and Rahim, 2020; Chodankar and Savoikar, 2021), conducted several studies on PET fibre reinforcement. Most commonly, (Limami et al., 2020) presented a study on PW as an additive to clay brick and other innovative forms such as PET panels, mattresses. The reviews have shown and concluded that the inclusion of PW in any of the aforementioned studies pointed towards tensile and compression strength increase. Additionally, these studies demonstrated that the inclusion of plastic waste lowered the subgrade's bearing capacity, stiffness as well as resilient modulus. Thus, the response of the composite was generally acceptable for subgrades performance compared to non-treated subgrade. As such the reduction properties of the subgrade composite were associated with the interface debonding of the subgrade with the plastic waste fibre.

Following the reviewed literature, it could be established that not many studies have been reported on the complete conversion of wastes into construction material with lesser CO_2 embodiment. As such this present study contributes towards the development of greenfield construction material burgeoning on the increased inclusion of wastes as a substitute in the production of construction materials. Particularly in the utilization of PW and foundry sand to produce masonry bricks. Other than the significant strength and durability rendered by the PW bricks, this study also suggested a novel approach towards reducing environmental pollution and landfill burden. Different mix ratio was designed for the bricks following 90: 10, 80: 20, and 70:30, by combined dry mass of PW and foundry sand to explore the compliance of PW bricks in terms of strength as well as durability properties for unit masonry bricks. The mechanical and durability properties of formulated WPBs were evaluated and compared with conventional fired clay bricks, which are mostly used in masonry constructions in South Africa. Although, many existing studies regarding the utilization of clay in fired clay bricks; however, the production of PW bricks will benefit environmental sustainability and improve the energy efficiency of masonry bricks for building constructions.

Materials

PET-waste

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, moulded parts for automotive, electronics, packaging, and many more. With this view, Figure 1 presents the stockpile of PET waste sampled from Mariannhill landfill in Durban South Africa.

Fig. 1

PET waste stockpile

The PET plastics production depends on its thermal temperature heat, as it may also exist as an amorphous and as semi-crystalline material. The semicrystalline material might appear transparent or opaque relative to its crystal structure and particle size. 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 $(C_{10}H_8O_4)n$. The PET has a molecular structure of ten atoms of carbon linked double bond of eight hydrogens and four oxygen atoms as presented in Figure 2.

The dry density of the used PET scrap plastic was evaluated to be 921 kg/m3 according to ASTM D792 (2020) testing protocols. The dry density was determined due to the low-molecular-weight mobilised by the constituent elemental compounds such as ethylene, propylene, and butene (butylene). In furtherance the PET waste was washed using a pressurized water pipe and subsequently left to dry for 3 days in open-air before it was shredded, leaving the waste material in

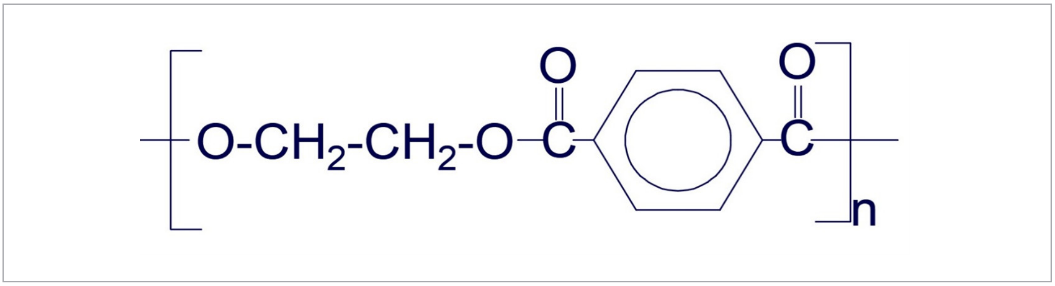


Fig. 2

PET waste molecular structure

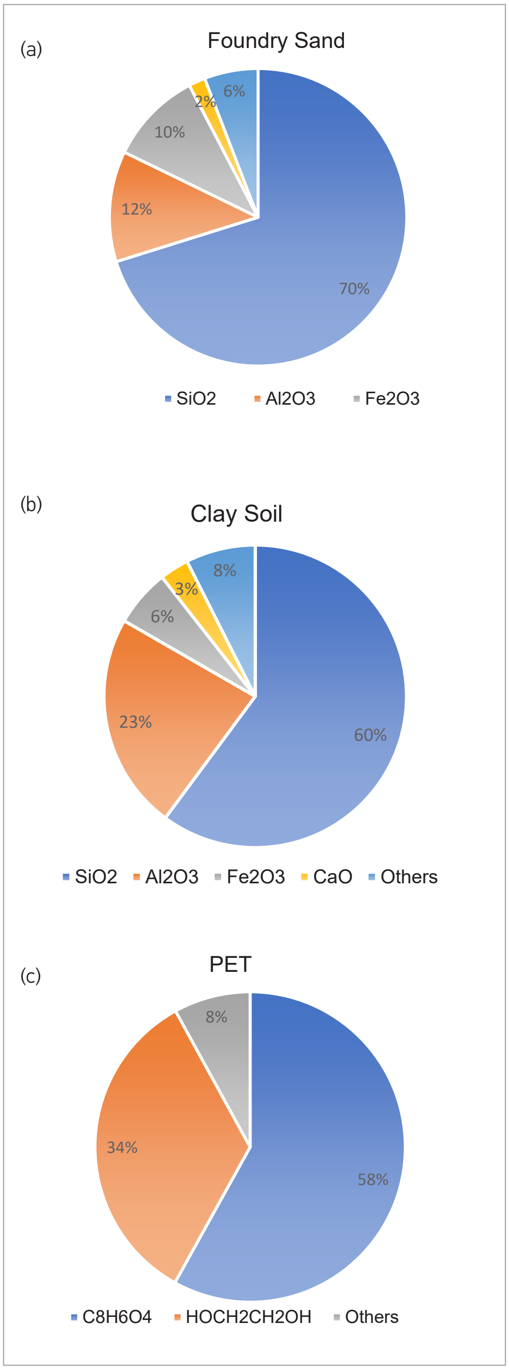


Fig. 3

Pie chart of the chemical composition of the materials used

a powder-like form. The chemical composition of the PET waste plastic was determined through the X-ray fluorescence (XRF) technique. The testing was achieved 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.

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.

The clay soil used to produce the fired clay bricks in this study was sampled from Pietermaritzburg South Africa. The clay soil is red with the particle passing sieve aperture of 2.36 mm (#8) with a corresponding plasticity index of 32.12%. To maintain a higher degree of consistency and eliminate result discrepancies, the soil size was maintained throughout the production of the clay brick. The X-ray fluorescence (XRF) test revealed that the soil possesses sufficient percentages of iron and aluminium oxides which is beneficial for strength development at high temperatures confirming the suitability of the clay for brick production. According to the XRF result, Iron oxide was discovered to exist mainly in the amorphous and crystalline inorganic forms. The chemical compositions of all the materials used in this study were obtained from XRF tests are presented in Figure 3.

Waste PET Bricks Preparation

Series of design mix was used to produce WPBs through mass ratio of 80%: 20%, 70%: 30%, and 60%: 40% of the combined dry mass of FS and WP. The identities of the produced bricks were formulated based on the percentages of FS and PW such as 80%:20% brick specimen is tagged WPB-1. Whereas the bricks produced through the mixed ratios of 70%: 30%, and 60%: 40% of FS and WP are designated as WPB-2 and WPB-3 respectively. The production process for the WPBs is presented as a flow chart in Figure 4. Prior to the shredding of scrap plastics, the waste material was dried in an open-air following the shredding of the waste plastic into tiny particles. The known quantities of the shredded plastic waste were measured placed in a steel container placed in a heat-controlled furnace capable of generating up to 1500 ^{0}C of heat. The waste plastic was gently melted at a heating rate of 2.0 ^{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, measured quantities of FS were gradually added as the composite was manually stirred for 5 minutes until a homogenous composite blend of melted PET waste plastic and FS was achieved. The homogenous composite blend was then cast into bricks mould 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 mould prior to casting of the composite blend. The casted composite blend was compressed using a compressive pressure of 10MPa to minimise void within the brick matrix before they were allowed to cool at room temperature of 24 ^{0}C.

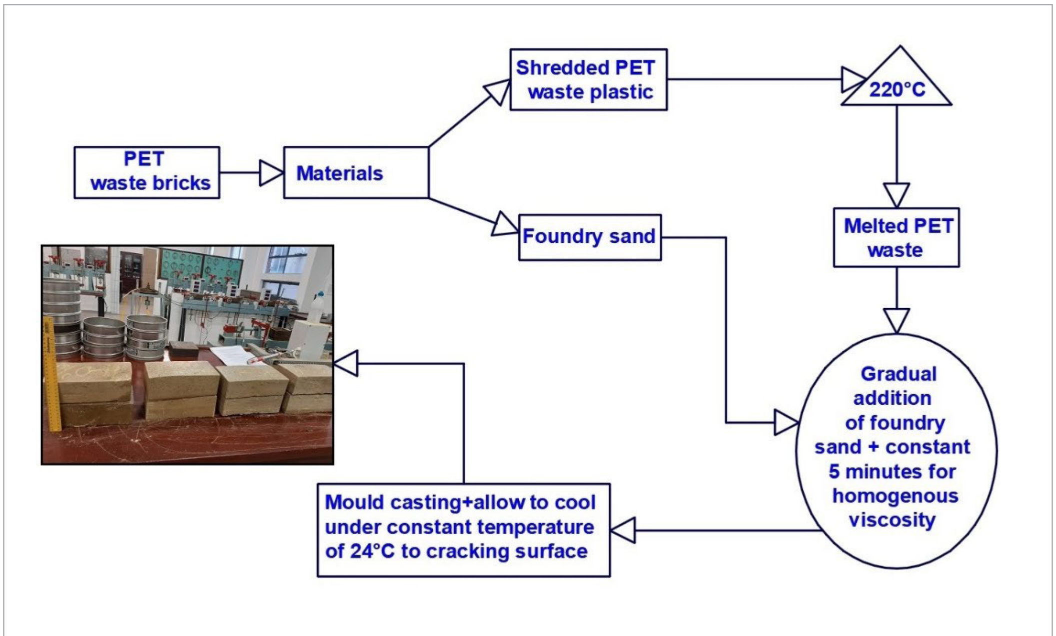


Fig. 4

Flow chart diagram of PW bricks making

Fired clay bricks were produced in this study to maintain consistency with the testing bricks. The clay material was thoroughly mixed for 5 min, using an automated mixer prior to water addition, the blends were further mixed for 10 min after addition of water to ensure a homogeneity mixed ratio of 2:1 blends of clay and water. The mixed lump weighing 5 kg were placed in moulds sizes of 222 mm x 106 mm x 73 mm. Following a confined pre-compression uniform stress of 20 kPa

Fig. 5
Produced clay bricks for the study

after 18 hours of specimen fabrication to eliminate void as well as to densify the fabricated bricks specimens without compromising the dimensions of the bricks. The excess material stuck at the corners of the mould was taken off using a spatula. Prior to specimen fabrication, the moulds were thoroughly greased with a silicone spray to eliminate mixture adhesion to the walls of the mould. Subsequently, the brick specimens were demoulded, placed on top of a damp cloth as they are laid on a flat surface. Additionally, the fabricated bricks were covered with plastic bags and left to cure for 3 days to prevent loss of hydration moisture and carbonation. After drying, the bricks were moved and placed in a furnace at a temperature of 1200 ^{0}C for 48 hours. They produced clay bricks were subsequently placed on a flat surface to cool prior to testing, as presented in Figure 5. The clay bricks produced in this study were used as a control specimen as the characteristic strength and durability of clay bricks were compared WPBs.

Test Methodology

The compressive strength and modulus of rupture tests were conducted following the ASTM C67 (2021) and ASTM C583-15 (2021) for testing of bricks. The bricks were tested at a loading rate of 1.25 mm/min towards the depth direction. For the modulus of rupture test, 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 midspan. 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 Eq (1).

$$\sigma_r = \frac{PL}{bd^2} \tag{1}$$

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

The durability studies of the bricks were conducted through the following tests: Initial rate of absorption, water absorption capacity, apparent porosity, efflorescence, and ultrasonic pulse velocity test tests. The absorption capacity of the bricks was measured according to ASTM C67/C67M-21. Following the standard procedure, the brick specimens were first dried and weighed to determine the dry mass of the bricks. Afterwards, the bricks were completely submerged in clean water at room temperature of 25 ^{0}C for 24 h. subsequently, the brick specimens were retrieved from the water bath and excess water from the surface of the bricks was wiped off and weighed again. The water absorption capacity of the bricks was determined using Eq. (2).

$$W_a = \frac{M_2\text{-}M_1}{M_1} \times 100 \tag{2}$$

where is the wet mass of the bricks, is equivalent to the dry mass of the bricks.

The apparent porosity of bricks was prescribed following ASTM C20 standard testing protocol for bricks. The bricks were submerged into boiling water for 2 h, followed by a cooling period of 16 hours until the hot water gets cold. The brick was then weighed while suspended in water, to measure the suspended weight and the saturated weight was also determined after cleaning the surfaces of the bricks with a dry cloth to remove excess water. The entire process was repeated three times before the average apparent porosity was determined using Eq (3). Again, the effect of apparent porosity on the compressive strength was evaluated, as each of the bricks was crushed after determining both the suspended and the saturated weight of the produced bricks.

$$\eta = \left(\frac{\text{w-D}}{\text{w-S}}\right) \times 100 \tag{3}$$

Where η is the apparent porosity, w is the saturated weight, D and S are the dry weight and the suspended weight of the bricks, respectively.

Prior to durability testing, immediately after the production of the bricks, they were left in the open air for 2 days under a constant temperature of 24 ^{0}C to dry up. The durability test was conducted according to ASTM C1012 procedures, as the bricks were fully submerged in different moles of 2.30E-05 M, 4.80E06 M, 6.80E-07, and 8.80E-08 M of sodium sulphate per litre of water for 90 days. The bricks were dried at 110 ^{0}C, weighed, and tested for compressive strength upon retrieved from the solution.

In furtherance, the ultrasonic pulse velocity (UPV) test was used to evaluate the flaws and homogeneity of the brick specimens. The principle of the UPV test is to produce a pulse wave coming from the electro-acoustical transducer. The pulse wave is then transduced through the brick prism and the pulse wave time of travel through the bricks is measured. With the help of this time, the longitudinal or pulse velocity was evaluated. Two transducers were used, one is a transmitter, and the other is a receiver (Al-Nu'man et al. 2013). The UPV test was attained following ASTM C-597 as shown in **Figure 6**. UPV test equipment used in this study is equipped with a measuring range of 0–3000 μs—accuracy +/−0.1 μs and two 55 kHz probes with connection cables. After the measuring exercise the. The UPV was determined using Eq. (4). Where the resonance frequency of the bricks specimens was recorded on the accelerometer on mechanical vibration using a claw hammer of 220 g.

$$V = \frac{L}{T} \tag{4}$$

where V is the ultrasonic pulse velocity, L is the distance between transducers and T is the transit time.

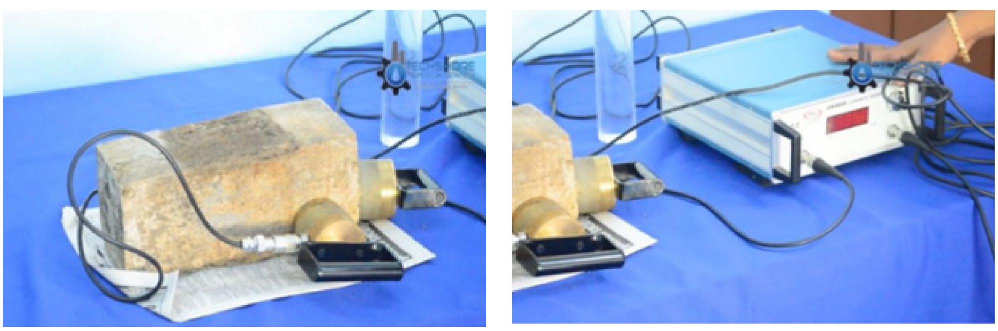


Fig. 6

Ultrasonic pulse velocity test setup for the brick specimen

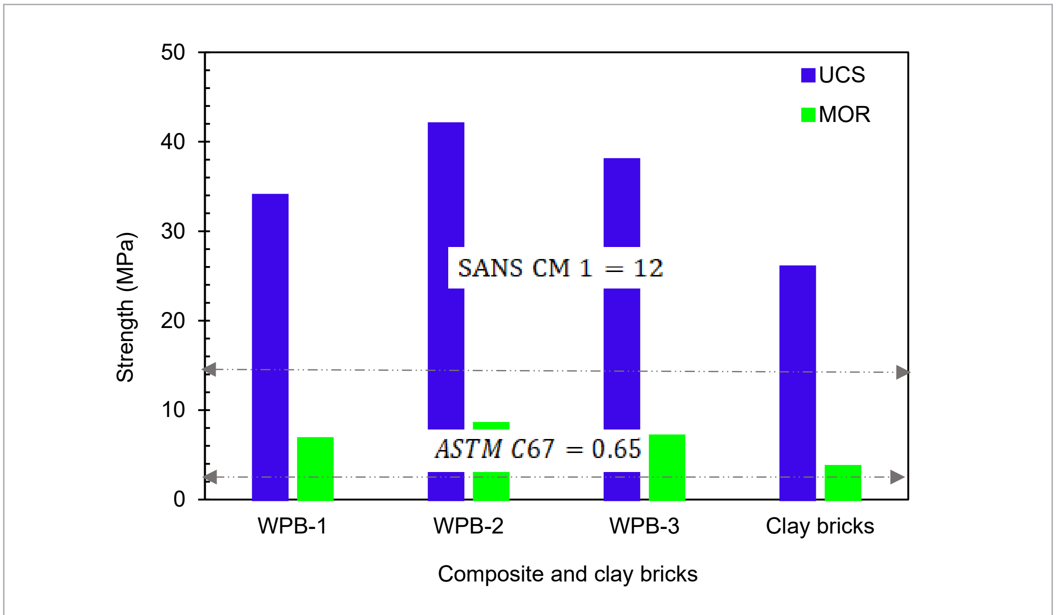
Results and Discussion

Compressive strength and Modulus of rupture results

Figure 7 prescribed both the compressive and MOR results of all the tested bricks in this study. The strength results were obtained from an average of two brick specimens with the mean value recorded as the final test result. The WPB-1, WPB-2, and WPB-3 rendered an average equivalent compressive strength of 34 MPa, 42 MPa, and 38 MPa, respectively. Where the average compressive strength of the produced clay bricks in this study was evaluated to be 26 MPa. The evaluated strengths for both clay bricks and WPBs conform with the South African National Standards (SANS 2001.CM1: 2007) to the minimum compressive strength for double-story construction and other load-bearing masonry units. However, SANS 2001.CM1: 2007 standards for load-bearing bricks specified 17.0 MPa compressive strength for a single unit brick. Generally, the WPBs were noted to be 1.2 greater than the produced clay bricks due to the great proportionality between melted PET plastic and FS. Furthermore, the cohesion bond between the PET plastic and FS as well as 20 kPa equivalent applied stress during specimen fabrication also contributed to the greater strength development compared to clay brick which rendered lower compressive strength value. The obtained test result is in line with the studies published by (Frank et al., 2021) which concluded that the strength development of PET-sand produced bricks is directly proportional to the dosage of sand, PET, and grain sizes of the foundry sand. The studies further confirmed that larger particles size greater than 2.36 mm will cause a significant decrease in strength up to 23%. Other than the proportionality of PET and FS, densification, low porosity, evenly pore size distributions, microstructure, and degree of pre-compressed stress during production all contributed to high compressive strength according to (Gorhan and Simsek, 2013).

Fig. 7

Compressive strength and MOR of the produced brick specimens



On the other hand, the MOR results showed that the fired clay bricks had lower MOR values compared to the WPBs. The maximum MOR values for WPB-1, WPB-2, and WPB-3 were observed to be 1.6 MPa, 2.3 MPa, and 1.8 MPa. However, the clay brick rendered a significant tensile strength of 1.24 MPa signifying an average of 49.13% decrease in tensile strength compared to the WPBs. The variation in MOR strength of the plastic waste bricks was noted to be consistent with waste PET dosage. This response in MOR value for WPBs agrees with the previous study published (Mitchell et al., 2014; Youssef et al., 2015; Aneke and Celumusa, 2021) which concluded that the inclusion of melt PET triggered a significant increase in MOR value. It was observed that the brick MOR values are relative to the microstructure, porosity, and applied stress during the brick fabrication. However, the inclusion of PET triggered an increase in tension resistance failure of the PET waste bricks, which is mobilised by the tightly knitted porous structures within the bricks. The allowable value of MOR is 0.65 MPa according to (ASTM C67, 20201; Shakir et al., 2013). All the WPB specimens exhibited MOR values in the range of 1.6 to 2.3 MPa, whereas clay brick rendered a MOR value of 1.24 MPa. Therefore, this result implies that the bricks produced with PET and foundry sand can efficiently serve as an alternative to natural clay to produce sustainable masonry brick units that could contribute to massive scale economic benefits in the construction industry. The high tensile strength values of the plastic waste bricks could be attributed to the viscoelastic properties of the melted PET, as well as the percentage of added foundry sand. The effect of FS on the plastic ratio is directly proportional to the density and porosity of the bricks. As percentages of the FS increased, the tensile strength of the bricks increases. Upon 20% and 30% inclusion of PET, the bricks rendered 29% and 85.49% increase in tension resistance, beyond which tensile strength decreased by 40.33% compared to the clay brick.

Porosity is an important parameter that influences the strength of masonry bricks due to its mechanical effects on bricks (Franzoni et al., 2015). Apparent porosity is a property of adherence between brick and mortar. However, four sets of apparent porosity were performed on both the WPBs and clay bricks, as presented in Figures 8 to 9. A linear proportionality between compressive strength and apparent porosity of the produced brick was also demonstrated. The result revealed that a great proportionality exists between compressive strength and apparent porosity due to higher coefficient of determination (R^2) values which range from 70% to 99.8%. The fired clay bricks in this study rendered an apparent porosity of 32% whereas WPB-1, WPB-2, and WPB-3 recorded apparent porosity values of 18.41%, 12.11%, and 10.23% respectively. The apparent porosity of the WPBs in this study was low compared to the apparent porosity values of clay bricks. The result is consistent with the study published by (Casa and Castro, 2014; Syed, 2016) which indicated that apparent porosity ranges between 35% - 45% due to the inclusion of waste sugarcane bagasse and rice husk ashes. However, the amount of silica present in bricks is related to the ratio of FS, thus the preferred percentage of silica for bricks ranges from 50–60%, beyond this range the apparent porosity of the brick specimens will increase. The apparent porosity of WPBs was noted to be less, due to the hydrophobic property of PET waste used for the production of masonry bricks. The increase in apparent porosity of the fired clay brick was due to the void space created by the sintering temperature during production hence inducing defects within the fired brick specimens. The concentration of pressure due to open pores may attribute to the loss of structural compactness and decrease the compressive strength of clay bricks (Yongue-Fouateu et al., 2016).

Stress-strain failure response of bricks

The stress-strain response of the WPBs and clay bricks is shown in Figure 10. It was observed that both brick specimens exhibited considerable compression strength. The ductile characteristics are relative to the WPB-1, WPB-2, and WPB-3 specimens at axial deformation between strain value 0.028 to 0.04. However, the clay bricks are associated with brittle compression failure immediately after the strain value of 0.023, as the brittle failure is more pronounced after the peak load as evidenced by the stress-strain curve. The behaviour of the WPBs for compressive strength is characterised by a linear proportionality within a larger deformation strain, beyond which strain hardening occurs due to the percentage of PET waste plastic content in the bricks. However, both the fired and non-fired bricks portrayed different failure stiffness responses, hence considerable post-peak ductility was observed particularly on the bricks that contain waste plastic. On the other hand, the fired clay bricks specimens in compression exhibit lower stiffness than the plastic waste bricks. The compression failure mode for clay bricks is characterised by specimen crush-

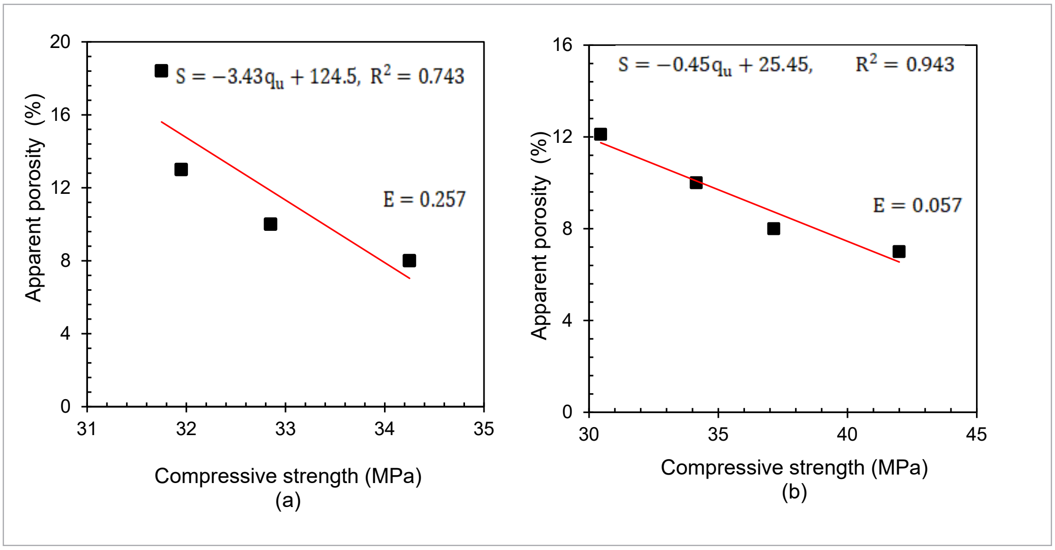


Fig. 8

Correlation of compressive strength with apparent porosity of: (a) WPB- 1 and (b) WPB-2

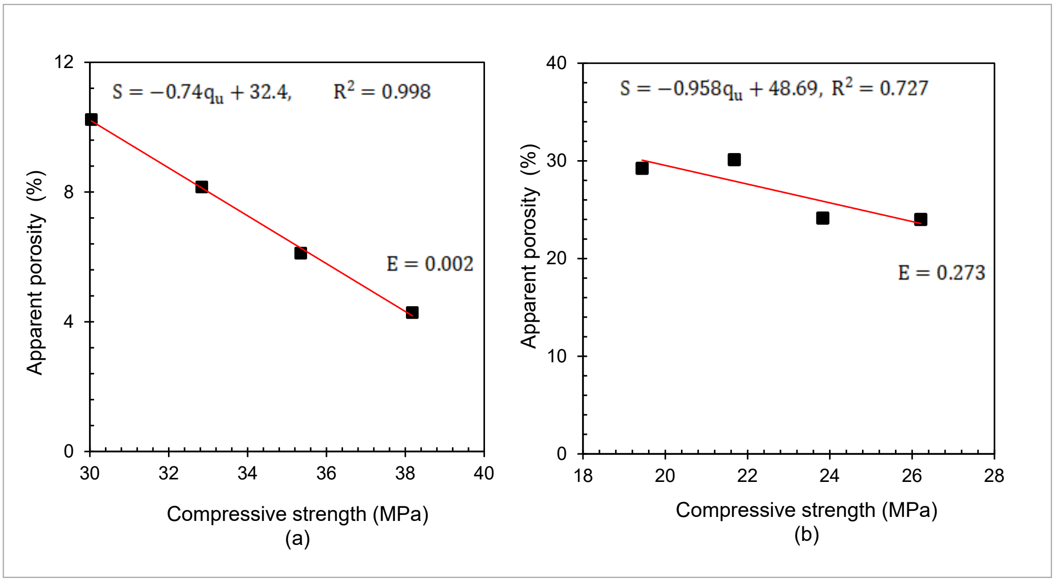


Fig. 9

Correlation of compressive strength with apparent porosity of (a) WPB- 3 and (b) clay bricks

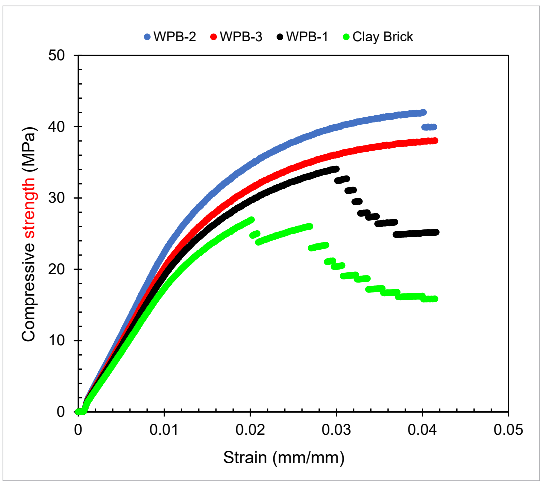


Fig. 10

Stress-strain variation of bricks

ing whereas the WPB specimens show multiple planes of failure. It is worthy to mention that the material relaxation might have been triggered by the content of PET waste and microstructural arrangement. However, (Stefanidou et al., 2015) reported on the stress-strain characteristics of clay bricks, which concluded that bricks do not behave elastically even in the range of small deformations due to the brittleness of the brick material.

The static equilibrium method was used to determine the elastic properties of produced bricks. The bricks were subjected to compression load in a direction perpendicular to the planes of bedding. However, the longitudinal compressive strain (ε_y) and the corresponding lateral tensile strain (ε_y) were measured from the electrical strain gauges mounted on both directions of forces. The load-deformation was converted to stress then allowing for the evaluation of the stress-strain curve data from the data logger. From the plotted stress-strain curve, Young's modulus (E) and Poisson's ratio (μ) were obtained from the slopes of the linear portions of the legends using Eqs. 5 and 6.

$$E = \frac{\sigma_y}{\varepsilon_x} \tag{5}$$

$$\mu = \frac{\varepsilon_x}{\varepsilon_y} = \frac{\sigma_y / \varepsilon_y}{\sigma_y / \varepsilon_x} \tag{6}$$

where E is the young modulus, μ is the Poisson's ratio, σ_y is the stress in the y-direction, ε_x and ε_y are the lateral tensile strain with the corresponding longitudinal compressive strain, respectively.

Durability properties of brick specimens

Initial rate of absorption (IRA)

The IRA of both the plastic waste and fired clay bricks is presented in **Figure 11**. The IRA test result for the fired clay bricks in this study was evaluated to be 32 g/m^2 /min. Similarly, for WPB-1, WPB-2, and WPB-3 rendered IRA values are 25.14 g/m^2 /min, 17.57 g/m^2 /min, and 10 g/m^2 /min, respectively. However, for a brick to have good adhesion strength, the IRA values must exceed 30 g/m^2 /min according to (Yorkdale, 1982) a study was adopted by ASTM C67. In furtherance, an IRA value greater than 30 g/m^2 /min, imply that the brick unit is highly absorptive and should be wetted prior to laying to achieve adequate bond strength, though the IRA limit values were derived based on tests carried out on clay bricks, additionally (Basha and Kaushik, 2014) reported that the IRA values for fly ash brick varied from 35 to 50 g/m^2/min with an average of 40 g/m^2 /min. Based on the obtained test result, it could be concluded that bricks produced using WP and FS in this study could completely be used as an alternative to clay brick, without

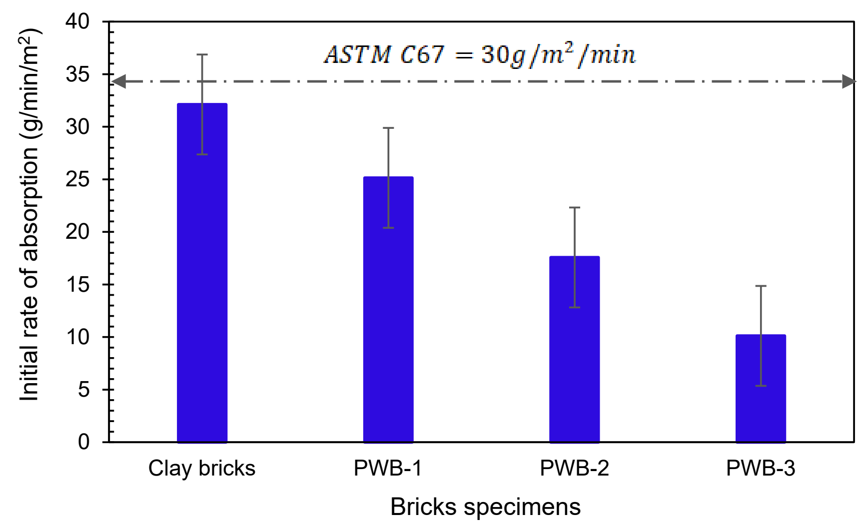
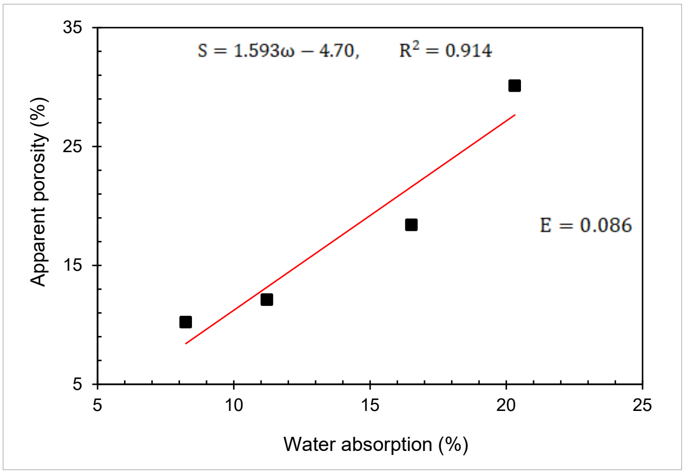


Fig. 11

Initial rate of absorption for the produced brick specimens influencing the fundamental properties of the bricks as stipulated by the ASTM C67. However, it could be understood that the value of IRA is found to be higher in fired clay bricks compared to WPBs. Regardless of the brick's IRA values, an adequate bond between bricks and mortar could be achieved with WPBs produced in this study since initial absorption through wetting before laying is not required because their IRA values are within the allowable limit. Thus, the IRA gives an insight into the pre-wetting time needed and bond strength of brick masonry. it was noted that the initial rate of absorption for brick specimens incorporating WP and FS rendered lower IRA values compared to that of fired clay bricks as such the produced fired clay bricks in this study requires pre-wetting for adequate brick mortar bond.

Fig. 12

The proportionality of water absorption with apparent porosity of the WPBs



Correlation of water absorption with apparent porosity of the bricks

The water absorption of brick masonry is one of the major factors that affect brick durability (Aakash and Devendra, 2014). The water absorption capacity of brick is one of the parameters that determine the bond adhesion capacity between bricks and mortar. However, the correlation of water absorption with the apparent porosity of the bricks produced in this study is presented in Figure 12. This correlation rendered a high determination coefficient R^2 of 96.31%. This indicates a great proportionality between the water absorption due to the existing porosity within the brick specimens. It was noted that the water absorption capacity of the fired clay bricks is higher compared to the WPB-1, WPB-2, and WPB-3 which contained varying proportions of WP and FS. For instance, WPB-1 which contained 20% of WP and 80% FS recorded water absorption of around 16.52%; while WPB-2 with 70% of WP and 30% FS rendered a water absorption value of 11.21%. Similarly, 8.24% of water absorption was obtained for WPB-3 which contained 40% of WP and 40% FS. Whereas 20.31% values water absorption was obtained for fired-clay bricks. It is worthy to mention that the increase in WP percentage influenced the water absorption capacity due to the hydrophobic property of PET which repels water from the surface of the bricks thus preventing the bricks from absorbing water. On the contrary, the higher water absorption tendencies observed in fired clay bricks could be attributed to the percentage of clay minerals in soil used to produce the bricks. As such these clay minerals attract more water due to their two-layered silicate clay. The water absorption and apparent porosity portrayed a linear relationship due to the great proportionality between the clay soil, FS, and the porosity of the bricks. The result obtained in this study agrees with the observations reported by (Aneke et al. 2021). In reference to ASTM C62 which stated that a maximum of 17% of water absorption is allowed in bricks for severe weathering resistance hence 22% is recommended for moderate weathering for fired clay bricks. Based on the available literature, water absorption limits for fly ash brick specimens range from 20% to 30% (Banu et al., 2013). Thus, the result implies that all the WPBs produced in this study are suitable for construction in both moderate and severe weather regions without any form of pre-wetting process. Whereas, the fired clay brick, not suitable for construction in severe or moderate weathering regions hence requires pre-wetting. Therefore, it could be concluded that the inclusion of WP and FS in bricks production complied with the specified limits of water absorption leading to cost-effective and durable masonry construction.

Bricks resistance to sulphate salt

Salts like sodium chloride (NaCl) and calcium sulphate ($CaSO_4$) are usually present in bricks and the manifestation of these salts is usually from different sources such as groundwater, rainwater, mortar, and improper use of chemical cleaners. Previous studies have proved that NaCl salt usually migrates from mortar joints when NaCl is used as an accelerator. More so, NaCl could also manifest on the surface of the brick through the contamination of masonry units, and saltwater mortar sand (Zsembery 2001). However, all salts do not have structural implication damage, except Na_2SO_4 and NaCl, thus these salts are significantly resisted by bricks with sufficient contents of fly ash (Binda and Molina, 1990). In addition to the published reports, the obtained results in this study have also demonstrated that WPBs possess 100% capacity to resist sulphate salt attack due to the hydrophobic property of PET waste used in the production of the bricks. The WP serves as a waterproofing agent which prevents the sulphate salt from penetrating the bricks voids.

The fired clay bricks showed relatively low resistance against sulphate salt, this caused a decrease in compressive strength as presented in **Table 1**. The strength reduction in the fired clay bricks is approximately 22.25%. Whereas no strength reduction was evaluated from the WPBs. The reduction in compressive strength for the clay bricks is attributed to the precipitate generated through the crystallization of sulphate salts within the micro-pores of the bricks hence this triggered internal micro-cracking within the bricks. In addition, it was observed that the WPBs portrayed strong sulphate resistance as compared to fired clay bricks due to the hydrophobic property of PET contents that prevents NaCl salt solution from permeating the bricks pores space. The results also showed that weight gain in the fired clay bricks was around 15%. Though, the weight gain could be due to the partial infiltration of NaCl salt crystals within the brick's spaces. Whereas the weight gain in the plastic waste bricks as a result of soaking NaCl salt solution ranged from 1% to 3% which is insignificant to trigger any structural changes within the bricks microstructure. Comparatively, the result published by (Syed et al., 2016) agrees with the obtained results presented in this study on compressive strength reduction and weight gain of fired clay bricks submerged

Table 1

Bricks acidic submersion

Series	Molarities (M)	Initial strength (MPa)	Strength decrease (MPa)	Strength decrease (%)
Clays bricks	2.30E-05	26.21	5.96	29.43
	4.80E-06	26.21	3.67	16.28
	6.80E-07	26.21	2.04	8.44
	8.80E-08	26.21	0.11	0.422
WPB-1	2.30E0-5	34.00	0.90	2.72
	4.80E-06	34.00	0.90	2.72
	6.80E-07	34.00	0.90	2.72
	8.80E-08	34.00	0.90	2.72
WPB-2	2.30E0-5	42.10	0.60	1.45
	4.80E-06	42.10	0.60	1.45
	6.80E-07	42.10	0.60	1.45
	8.80E-08	42.10	0.60	1.45
WPB-3	2.30E0-5	38.00	0.50	1.33
	4.80E-06	38.00	0.50	1.33
	6.80E-07	38.00	0.50	1.33
	8.80E-08	38.00	-	-

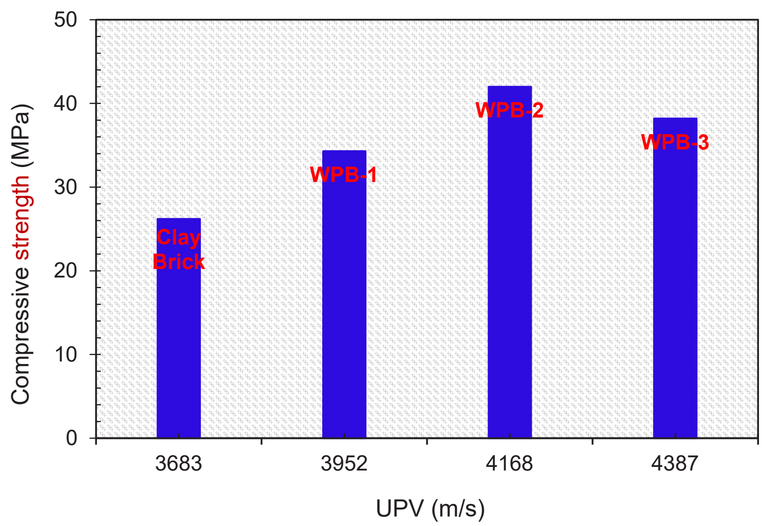
in a sulphate salt solution. Based on the obtained results, it is evident that WPBs produced with different contents of PET and FS provide significant resistance against sulphate salt attack.

Ultrasonic pulse velocity test

The Ultrasonic pulse velocity evaluates the homogeneity of brick quality. The brick quality is a noted parameter for robust construction, as such the quality of bricks produced herein was tested thus the homogeneity of the bricks were determined through the ultrasonic pulse velocity testing. Brozovsky and Zach (2007) stated that the UPV test is reliable in detecting detect flaws, microcracks as well as predicting the compressive strength of bricks. The uniformity and soundness of the bricks were evaluated using compressive strength as an indicator as presented in Figure 13. It was found that WPB-1, WPB-2, and WPB-3 yielded higher UPV values compared to that of fired-clay bricks before. However, the UPV values for WPB-1, WPB-2, and WPB-3 were recorded to be 3952 m/s, 3768 m/s, and 3587 m/s, whereas the UPV values for fired clay bricks increased from 3683 m/s. Generally, UPV values increase as strength increases. Koroth et al. (1998) suggested that bricks are certified suitable if their UPV is greater than 3500 m/s and non-suitable for UPV less than 1000 m/s. The UPV test results obtained in this study portrays similar consistency with the reported UPV test result. Therefore, the UPV values for all the tested brick specimens ranged from 3500 m/s to 4000 m/s hence both the WP and fired clay bricks are certified durable based on the recorded UPV values. It was noted that the percentage of FS used for the production of the WPBs has a significant influence on them. The bricks with 80% FS recorded higher UPV values,

Fig. 13

Ultrasonic pulse velocity versus compressive strength of the bricks



this implies that the percentage of FS increased as the UPV value increased. Furthermore, the UPV could also be influenced by the pre-compressed pressure applied on the bricks during fabrication, microstructural arrangement, porosity, and the percentage of FS.

Correlation between Dynamic of elasticity (E_d) and UPV

The elastic modulus of brick is a fundamental parameter that characterises the deformation response of masonry brick structures under compression. However, the elastic modulus in compression is often the most relevant material property relative to stiffness. The experimental procedure utilised to evaluate this elasticity modulus could be either static or dynamic. The former involves direct loading of a specimen and measuring the corresponding change using strain as the stress is applied. The static elastic modulus is then computed by evaluating the slope of the experimental stress-strain curve in the elastic deformation range. On the other hand, the E_d of the bricks produced in this study was evaluated through pulse waves using Eqs. 7 and 8, as per ASTM C-597 protocol. Hence the E_d of the bricks is evaluated by substituting the values of density, UPV, and poisons ratio. To quantify the dynamic performance of the bricks, the dynamic modulus of elasticity is correlated with UPV for both fired-clay bricks and WPBs as shown in Figure 14. The working principle behind the UPV testing is that the pulse wave is produced when the brick specimen is slightly tapped due to the electro-acoustical transducer. As the pulse wave moves through the bricks the time that the pulse wave takes to travel through the bricks specimen is then measured.

$$V = \sqrt{\frac{E_d(1-\mu)}{\rho(1+\mu)(1-2\mu)}} \tag{7}$$

$$E_d = \frac{V^2[\rho(1+\mu)(1-2\mu)]}{(1-\mu)} \tag{8}$$

Where E_d is the dynamic modulus of elasticity, V is the ultrasonic pulse velocity test of the bricks, ρ is the density at 90 days curing, μ is the Poisson's ratio obtained from the stress-strain graph of the bricks in Figure 10.

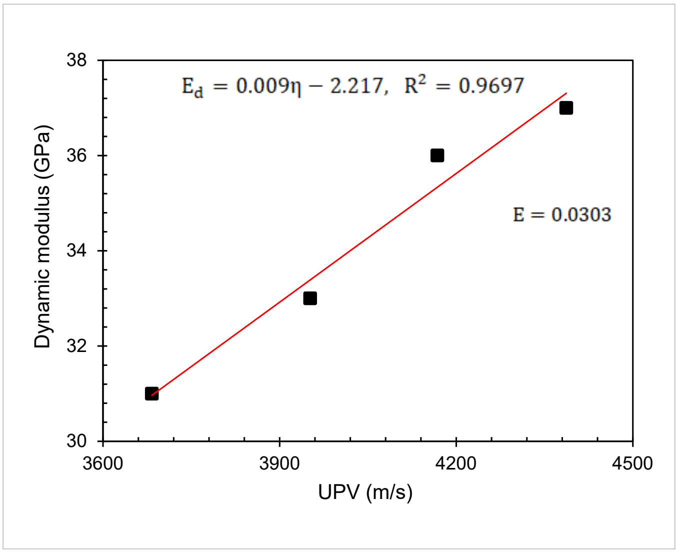


Fig. 14

The relationship between dynamic modulus of elasticity and UPV of the bricks

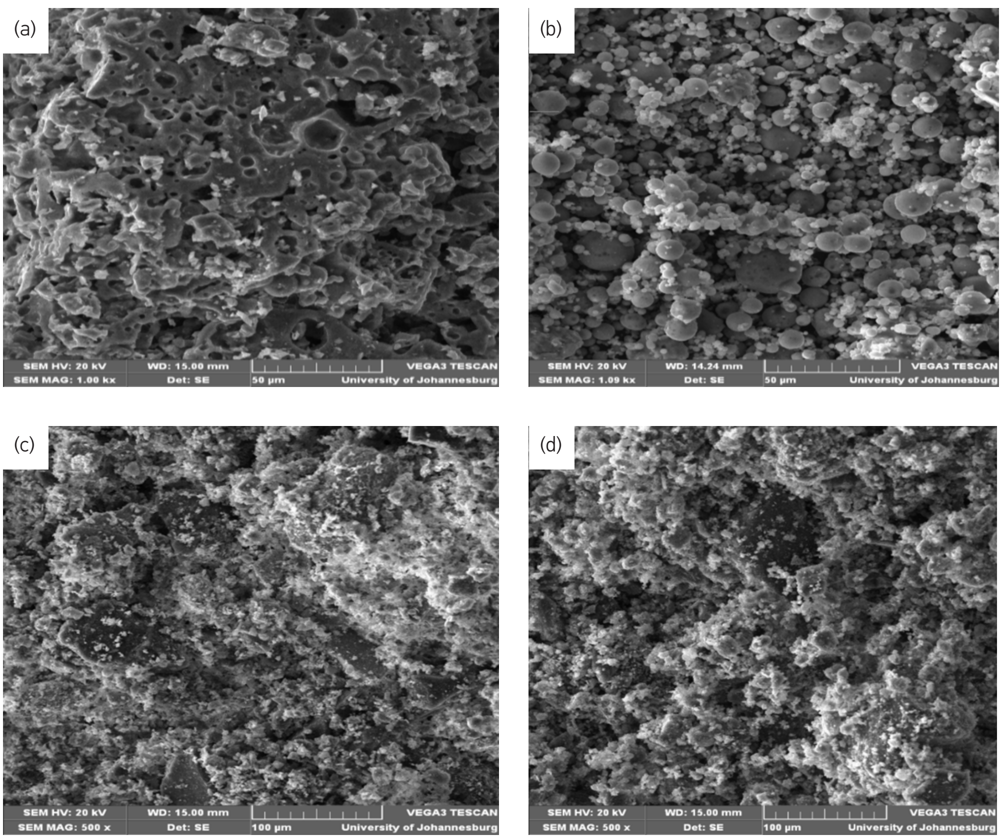
It can be seen that the WPBs gave relatively higher E_d values compared to the fired clay bricks. The E_d value for the WPB-1, 2, and 3 was evaluated to be 33 GPa, 36 GPa, and 37 GPa, respectively, whereas the dynamic modulus of the fired clay bricks was evaluated to 31 GPa. The obtained dynamic modulus results for WPBs increase according to the percentages of foundry sand content. The correlation between E_d of elasticity and UPV of bricks showed a higher coefficient of determination of 90%, indicating a great proportionality between dynamic modulus and UPV. The E_d values of all the bricks investigated in this study imply that the bricks specimens are homogeneous thus will resist seismic deformation as a masonry prism unit. The dynamic modulus values of the plastic waste bricks are higher which could be attributed to the microstructure, precompression applied pressure during brick production and less apparent porosity values of the fired clay bricks. However, WPBs portrayed a stiffer elastic behaviour than the fired clay bricks. Generally, it was observed E_d of elasticity of all tested bricks increased as UPV increased. Although the obtained result in this study agrees with a report published by (Fei et al., 2016) which concluded that UPV measurements estimate isotropic information of bricks under dynamic stress path with detailed validity through the interpretation of P-wave, thus the evaluated dynamic modulus is equivalent to the P-wave values.

Morphological study

The microstructure of the investigated bricks was accessed through scanning electron microscopy (SEM) micrographs as presented in **Figures 15 a, b, c,** and **d**. The micrograph showed irregular shapes of clay minerals knitted as a matrix due to firing temperature indicating the presence of the following crystalline phases: quartz, Kaolinite, celadonite, and hematite having quartz and glauconite at the dominant phase. It is noted that the bricks with 20% of melted PW are greyish, the grey colour gradually changed to black as the PET content increases as can be indicated in the micrograph. The WPB portrayed viscous floccules with FS 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 scattered solid 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 WPB-2 and WPB-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 WPB-3 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 is within the surfaces of the WPBs are C, H, and O elements, which are rendered by PET plastics, while Si, Fe, and Al are the dominant elemental compound that is from FS. The inclusion of melted plastics in the WPBs resulted in the reduction of pore space within bricks and this observation is pronounced WPB-2 and WPB-3. The pore spaces in the bricks were minimized drastically causing them to relatively pose greater strength when compared with the fired clay bricks.

Fig. 15

(a). Micrograph of fired clay, (b). (c) and (d). Micrograph of WPB-1, 2, 3 and 4



Waste plastic has several health-threatening impacts on the environment, humans as well as ecological systems. Some of these health-threatening challenges are more obvious and could be proven by the entanglement and decrease in aquatic wildlife. Other concerns of waste plastic in the ecological system are the transport and possible concentration of contaminants by waste plastic which is subtler. Additionally, monitoring of ecological and human health impacts is more in the marine environment than on land where all the waste plastics are generated and transported to the water bodies (Zettler et al. 2013) With these challenges, this current study made a salient contribution towards the conversion of waste plastic to green-efficient construction material without negative impact on ecological and microclimate.

Estimation of CO_2 production Embodiment

To further evaluate the impact of the produced WPBs, a CO_2 emission comparison analysis was made between the fired clay and plastic waste bricks in order to quantify the CO_2 embodiment of these bricks when used for the construction of houses. The mix formulation used in the production of the bricks is presented in section 3. However, it is presumed that cost of extraction and transportation of clay, PW, and FS will be the same therefore, these costs are excluded in this analysis. The cost of energy to produce these bricks and the construction of a 2-bedroom masonry structure were used for this analysis of the estimation of CO_2 production embodiment. Moreover, the cost of electricity for households and businesses which includes all components of the electricity bill such as the cost of power distribution and taxes is R 2.38 and R1.83 per kWh. This is equivalent to 0.145 USD and 0.070 USD per kWh. Hence, 1 kWh is equivalent to 1895.63 ^{0}C of heat. Therefore, it requires 0.58 kWh to generate 1100 ^{0}C worth of heat for the production of 1 fired clay brick unit. Whereas 0.12kWh is required to generate 220 ^{0}C worth of heat to produce 1 unit of plastic waste brick. Based on the energy production cost for fired clay bricks, the cost for 1 brick unit is R1.428 while the plastic waste brick will cost R 0.286. To evaluate the quantities of CO_2 emission of embodiment in both the production of fired clay and plastic waste bricks. In South Africa, coal-based power plants emitted an average of 915 grams of CO_2 per kilowatt-hour of electricity produced. It has been calculated that 0.58 kWh and 0.12 kWh electricity are required for the production of fired clay and WPBs, respectively. Therefore, to calculate the quantities of CO_2 emission for clay brick, (915 g x 0.58 kWh) 531 g of CO_2 will be emitted into the environment whereas (915 g x 0.12 kWh) 110 g of CO_2 is discharged into the environment during the production of plastic bricks. Based on the calculated bill of material quantity made in this study, it requires 7120 pieces of bricks for the construction of a two-room masonry structure of 20 m in length and height of 3 m. Each brick weighs an average of 3.3 kg, therefore it required (7120 x 3.3) 23496 kg of clay to produce 7120 pieces of clay bricks. Therefore, the total quantities of CO2 in grams that will be discharged into the environment for the construction of a 2-bedroom masonry structure are (0.531 kg x 23496 kg) 12476.38 kg worth of CO_2. To calculate the quantities of CO2 embodiment for the production of plastic bricks in kilogram, hence 30% of WP inclusion rendered the ultimate strength therefore the quantities of material required for the construction of 2-bedroom masonry structure will be 30% multiplied by the quantities of material required for the construction multiply by the quantity of CO_2 emission required for a single unit of plastic waste bricks (0.3 x 23496 kg x 0.11 kg) and this corresponds to 775.37 kg of CO_2 emission. The summary of the estimation of the bricks quantity of CO_2 emission is presented in Table 2. It is worthy to mention that the calculated CO_2 emission for both fired clay and WPBs is based on the kilograms of energy required and CO_2 embodiment cost to produce these bricks. Using the information provided in Table 2, it follows that over 7048.8 kg of plastic waste could be diverted from landfills, compared to about 23496 kg of clay required for the construction of a two-room structure, with a consequent saving of 2476.38 kg of carbon dioxide.

Table 2

Bricks and its sustainable status

Bricks	Heat (^{0}C)	Time cost (Minutes)	Average Density (kg/m^3)	CO_2 Emission (kg)	Price/energy cost	Sustainability
WPB-1	220	10	1784	516.91	R 0.286/brick	Favourable
WPB-2	220	10	1887	775.37	R 0.286/brick	Favourable
WPB-3	220	10	1828	1033	R 0.286/brick	Favourable
Clay bricks	1100	15-40 hours	1894	2476.38	R 1.428/brick	Not Favourable

Conclusions

In this research, the development of plastic waste brick has been studied through the indices of strength, durability, microstructure, and CO_2 embodiment. Based on the findings of this study, the inclusion of production masonry bricks using plastic waste and foundry sand could be considered an effective way and cost-effective approach towards the conversion of dwindling natural clay for the production of sustainable, green-efficient, and re-engineering of wastes.

The utilization of plastic waste and foundry as raw materials for the manufacturing of masonry bricks is one of the rational ways of recycling abundant wastes, leading to conservation of space including water and soil. The plastic waste and foundry used in this study were abundantly waste materials, having a high percentage of causing environmental pollution.

The utilization of plastic waste with varying percentages of the foundry is proven in this study as resourceful material for load-bearing bricks masonry. The bricks also portrayed great potentiality against dynamics stress due to their high values of dynamic modulus. It was observed that the blend of 70% sand and 30% foundry sand of plastic bricks resulted in 42 MPa with approximately 60.31% increase in strength compared to fired clay bricks. These compressive strength values of plastic bricks satisfy the requirement of compressive strength specified by South African standard for burnt clay masonry units (SANS 227, 2007), which requires nominal compressive strength for face bricks to be greater 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. These low compressive strength resistance values recorded for WPB-1, WPB-2 and WPB-3 specimens are mobilised by viscoelastic blends of PET waste and foundry sand.

Resistance against sulphate attack is recommendable for the WPB-1, WPB-2 and WPB-3, indicating their suitability in sulphate salt environment due to their high resistance capacity as a result of their hydrophobic properties. It was found that UPV values of the bricks complied with compressive strength resistance and bricks homogeneity. A great correlation between the dynamic modulus and UPV is mobilised by the homogeneous characteristics of all the tested bricks which implies that dynamic modulus increases with an increase in UPV as the percentage of foundry sand increases.

Furthermore, it was observed that the apparent porosity of the fired clay bricks increased with a higher percentage of plastic waste which triggered an increase in water absorption compared to WPB-1, WPB-2 and WPB-3. The fired clay bricks showed the highest water absorption among all the produced bricks in this study due to the high content of clay minerals and double-layer structure, which absorbs more water to fill up the structure. The SEM revealed that the microstructure of the hence WPB-1, WPB-2 and WPB-3 is mobilised with a lower initial rate of absorption of 25 g/m^2 /min, 19 g/m^2 /min, and 12 g/m^2 /min respectively. Therefore, the WPBs require no form of pre-wetting prior to their use in masonry construction.

The present study evaluated the physical, mechanical and durability properties of formulated WPBs under normal temperature. Since the stability of construction materials under varying temperatures is also a crucial parameter, further investigations on the properties of WPBs upon their exposure to different temperatures focusing on the thermal deformation of the formulated materials are needed.

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