Influences of Agro-wastes on the Physico-mechanical and Durability Properties of Unfired Clay Blocks

Nusrat Jannat [a, c *], Rafal Latif Al-Mufti [a], Aseel Hussien [b], Badr Abdullah [a], Alison Cotgrave [a]

[a] *School of Civil Engineering & Built Environment, Liverpool John Moores University, Byrom Street, Liverpool L3 3AF, United Kingdom*
[b] *Department of Architectural Engineering, University of Sharjah, Sharjah 341246, United Arab Emirates*
[c] *Department of Architecture, Chittagong University of Engineering & Technology, Chattogram-4349, Bangladesh*

Abstract

The increasing demand for construction materials along with the challenge of waste management has necessitated the development of sustainable materials utilising wastes properly. Therefore, this research examines the utilisation of various agricultural wastes, such as Eggshell Powder (ESP), Sawdust Powder (SDP) and Coconut Husk Powder (CHP), in the production of unfired clay blocks. Samples were made with various percentages of wastes: 10-50% of dry wt. of clay for ESP and 2.5-10% for SDP and CHP. In this study, the physico-mechanical and durability properties of unfired clay blocks were investigated by conducting density, linear shrinkage, capillary water absorption, flexural strength, compressive strength, ultrasonic pulse velocity test, drip test and water spray test. The tests were carried out in two phases, with the first phase including the individual integration of waste in the mixture and the second phase combining ESP (10-30%) with the optimum SDP (2.5%) and CHP (2.5%). The test results show that when the additives were used individually, the 40% ESP samples performed the best whereas for SDP and CHP 2.5% content showed better performance. Contrarily, the samples' overall characteristics deteriorated when ESP, SDP, and CHP were used together. Nevertheless, all of the samples met the strength requirement of the standards and passed the durability tests. The results of this study might be useful in assessing the potential of ESP, SDP and CHP for the production of unfired clay blocks as well as finding a solution to the waste management problem.

Keywords: Agro-wastes, Durability properties, Mechanical properties, Physical properties, Unfired clay blocks.

1. Introduction

Currently, a new awareness of the application of sustainable and healthy materials in the construction sector is emerging in both developing and developed countries. The manufacturing processes of conventional building materials like concrete and fired earth bricks are not only expensive but also has negative environmental effects such as excessive energy demand and greenhouse gas emissions [1-3]. On the other hand, unfired earthen materials require approximately 99% less energy for the manufacturing process compared to concrete [4] and have less embodied energy (0.45 MJ/kg) than fired earth bricks (3 MJ/kg) [5]. There are also many other benefits for unfired earthen building materials, including regionally available raw materials, easy-to-construct, cost-effective, good hygrothermal properties and ease of recycling with minimum environmental effects [6-8]. Hence, unfired earthen materials are gaining growing attention as natural sustainable materials for building construction. However, there are some disadvantages associated with earthen structures such as poor mechanical and durability properties as well as regular repair [9-12]. Consequently, researchers have experimented with different additives and stabilisation techniques to enhance its properties and a substantial number of studies on this issue have been published in recent decades [13-15]. These investigations indicate that different stabilisers impart strength and durability to earthen materials to different extents depending upon the chemical compositions and physico-mechanical properties of individual stabiliser. Researchers have suggested many kinds of man-made stabilisers such as cement, lime, plastic waste, synthetic fibre etc. to improve the performance of the earthen materials [16-20]. Cement, though, is a source of CO_2 emissions from these stabilisers, is the most commonly used one [21-23]. The use of man-made stabilisers, on the other hand, lowers the "green" aspects of earthen materials by increasing embodied energy levels and reducing the recycling potential of demolished wastes. To overcome this, the utilisation of natural materials such as agricultural residues for earth stabilisation is becoming widespread among researchers [24-28].

The global development of the agricultural industry produces large volumes of agro-wastes annually and a growing environmental concern has emerged from the accumulation of unmanaged residues particularly in developing countries. In recent years, scientists have tried to reduce the amount of agro-wastes by finding new applications. Since alternative material studies now explicitly prioritise the reduction of energy usage and the resolution of waste management problems, several studies have shown that this challenge can be achieved by using agro-wastes for building material production [14, 29, 30]. Studies reveal that utilisation of the agro-wastes as stabilisers in the production of unfired earthen materials is more beneficial than man-made materials in terms of environmental (energy-saving), economic (cost-reducing) and ecological (resource-saving) perspectives [31]. It is more economical to use regionally available vernacular agro-wastes as they require less processing and negligible transportation cost [32]. Depending on the availability, various agro-wastes have already been

* Corresponding author.
E-mail: N.Jannat@2019.ljmu.ac.uk

utilised to improve the characteristics of unfired clay bricks in different countries. According to several studies [14, 29, 30], the inclusion of agro-wastes into the unfired clay bricks has often resulted in improved characteristics. Therefore, this present study aims at utilising three agro-wastes namely eggshell, sawdust and coconut husk to evaluate their possible application as the alternative raw materials to enhance the performance of developed unfired clay blocks. Moreover, utilisation of these agro-wastes in the production of sustainable construction materials contributes to a feasible solution to the waste management problem.

Eggshells are considered waste materials mainly generated by the poultry and food industries. The total global production of eggshells is around 110 billion tonnes which eventually ends up going to landfill sites [33]. It is observed that eggshells are high in calcium levels ranging from 94% to 98% [34-36]. Also, calcium in eggshells is more absorbable than the calcium contained in limestone or coral sources [37] which contributes to reinforcing material bonding [38] and this feature of the poultry eggshells has made it an attractive choice for natural reinforcement. Hence, scientists have started investigations to use eggshells for developing different types of valuable and utilisable products [33, 37, 39-42]. Several recent studies showed that eggshell powder and eggshell ash can be used for soil stabilisation [43-47] and making building materials such as unfired laterite brick [38, 48], fired brick [49, 50], sandcrete block [51], concrete block [52, 53] and soil cement brick [54]. Ayodele et al. [48] developed lateralised unfired bricks incorporating combinations of sawdust ash and eggshell ash of 0-16 wt.%. The test results revealed that the density of the samples increased steadily up to 4% ash content, after which it started to decrease for higher ash percentage and the maximum compressive strength was achieved for 2-4% ash content. In another study, Adogla et al. [38] assessed the potentiality of eggshell powder (0-40 wt.%) in the production of unfired compressed bricks. It was observed that incorporation of eggshell increased the dry density of the samples and the samples with 30% eggshell showed better performance in compressive strength, water absorption and abrasion resistance test.

On the other hand, sawdust or wood dust is the fine wood particle produced as a by-product of the wood or timber industry. Generally, sawdust has wood-like characteristics although certain structural properties have been modified due to its particle nature. The chemical composition of dry wood varies by species of trees. The main chemical components in sawdust are lignin (18-35%) and carbohydrate (65-75%) while small quantities of extraneous materials (4-10%) are also found [55, 56]. The bulk density of sawdust is found to be very low (150-200 kg/m^3) [57] and it has a very low thermal conductivity, making it suitable for insulation material [58, 59]. Researchers conducted experiments using sawdust for manufacturing different types of building materials [60]. Some of the developed materials include particleboard [61-65], insulation material [66], cement concrete brick [67, 68], fired clay brick [58, 69-73] and unfired brick [24, 48, 74-80]. Demir [74] examined the compressive strength of unfired clay bricks containing 2.5 to 10% sawdust and found that adding sawdust to unfired bricks enhanced compressive strength. Similarly, Ouattara et al. [76] observed an improvement in the compressive strength of clay bricks with 15-20% of sawdust content. However, the study of Ganga et al. [75] showed no improvement in compressive strength of the samples with the addition of sawdust or mahogany shavings. In another study, Vilane [24] produced adobe bricks with sawdust (0-20%) and obtained the optimum percentage to be 15% as it gave the highest compressive strength. Jokhio et al. [79] found higher compressive strength values by replacing sand with 20% sawdust, while the study observed a decreasing trend in flexural strength. The water absorption properties of sawdust lignin and cement (4, 8 and 12% by mass) stabilised compressed earth blocks were assessed by Fadele and Ata [77] and the results indicated better performances of sawdust stabilised samples than the cement stabilised samples. According to Charai et al. [78], the density and thermal conductivity of the sawdust clay composites decreased with the increasing amount of sawdust from 2-10 wt.%. De Castrillo et al. [80] used straw and sawdust (30%-70% by volume) to produce traditional adobe bricks. According to the finding, the bulk density, thermal conductivity, flexural and compressive strength of the adobes all reduced as the proportion of both fibres in the samples increased. Moreover, sawdust adobes showed a gradual rise in capillary water absorption than the straw adobes with the increase in fibre percentage.

Coconut husk is another agricultural waste that is the by-product of coconut production mainly obtained from the outer shell. Coconut is a tropical plant that grows largely at latitudes between 20°N and 20°S [81]. Although billions of coconuts are produced each year, only 15% of the residual fibres from the harvesting process are used as materials for manufacturing purposes [82]. The coconut husk contains approximately 75% of coconut coir fibres and 25% of the pith [83, 84]. The coconut coir is reddish-brown and composed of cellulose, hemicellulose, lignin and pectin [85]. Studies show that the addition of coconut coir can reduce the thermal conductivity of the composite and result in a lightweight product due to its low bulk density [86, 87]. Coconut coir has been examined by many researchers in manufacturing different construction materials such as insulation board [88], fibreboard [89], particleboard [90], concrete block [91-94], fired brick [95-97] and unfired earth block [98-102]. Besides, it has been used for soft soil stabilisation [103-105]. Khedari et al. [90] [99] assessed the thermal properties of unfired soil blocks using coconut coir fibre (10-20% of reference cement volume) and the findings showed that the presence of coconut fibres reduced the density, thermal conductivity and compressive strength of the sample blocks. The study recommended a 20% ratio as the optimum for the best thermal performance. Danso et al. [98] produced unfired clay blocks using various proportions (0.25-1 wt.%) and lengths (38 mm, 50 mm and 80 mm) of coconut fibre. The findings showed that dry density reduced but water absorption increased with the addition of fibre. Also, both compressive and tensile strength improved significantly by adding fibre up to 0.5%. In the study of Thanushan et al. [100] incorporation of coconut fibre from 0.2-0.6% of mass portions caused a gradual decrease in compressive and flexural strength but an increase in water absorption values. Sangma et al. [101] studied the physico-mechanical properties of unfired earth blocks by adding 5% and 20 mm to 80 mm coir fibre. The study concluded that the reinforced blocks had higher tensile and compressive strength than the unreinforced blocks and the 40 mm long coconut fibre performed the best. Purnomo and Arini [102] performed experiments on coconut coir (treated) reinforced unfired bricks to investigate how humidity influences its physico-mechanical properties. The results revealed that in wet conditions the brick samples with 4% treated and 25 mm coir fibre exhibited better mechanical properties than the other samples.

From the literature, it can be noticed that research on the effect of eggshell, sawdust and coconut husk on selected properties of unfired clay blocks is limited. Hence, this study presents the physico-mechanical and durability properties of the developed unfired clay blocks utilising eggshell, sawdust and coconut husk. The experimental study was conducted in two series. In the first series of the tests, various percentages of eggshell, sawdust and coconut husk were added in the mixture individually to produce the samples and their properties were examined. Based on the results from the first series, a second series was performed to assess their combined effect. The results of both series of experimental tests were analysed and discussed.

2. Raw materials and sample preparation

2.1. Materials

The substances employed in the production of unfired clay samples are Red Clay Powder (RCP), Eggshell Powder (ESP), Sawdust Powder (SDP), Coconut Husk Powder (CHP) and water (Fig. 1). The clay used in this study was supplied by Bath Potters' Supplies, UK. It is a raw reddish powdered clay that is dug directly from the ground and contains some pebbles since it is in its natural state. The ESP, SDP and CHP used were obtained from the local retailers in the UK. The raw materials were sieved with the square mesh sieve to have a controlled particle size between 212 μm-150 μm for ESP and 600 μm-425 μm for SDP and 1.18 mm-300 μm for CHP. In the mixtures, normal tap water was used.

(a) (b) (c) (d)

Fig. 1. Raw materials: (a) RCP, (b) ESP, (c) SDP and (d) CHP.

2.2. Characterisation of raw materials

Standard proctor compaction test [106] was used to experimentally determine the optimum moisture content and maximum dry density while BS 1377-2:1990 standard [107] establishes the Atterberg limit of clay. Chemical properties and mineralogical phase evolution of RCP, ESP, SDP and CHP were assessed by means of X-ray Fluorescence (XRF) (EDX-720 Shimadzu, Japan) and X-ray Diffraction (XRD) (Rigaku MiniFlex) analysis respectively. Moreover, in this study, the surface morphology of raw materials was characterised by Scanning Electron Microscope using an FEI Inspect S SEM model at 20 kV accelerating voltage after gold-coating the materials. Besides, the density was determined by the cylinder method and porosity was measured following the method of Horisawa et al. [108]. Furthermore, specific gravity was obtained according to the BS EN 1097-6 standard [109].

The physical and chemical properties of the raw materials are summarised in Table 1 and Table 2 respectively. The proctor compaction test on clay revealed a maximum density of 2320 kg/m^3 at an optimum moisture content of 15.50%. Furthermore, the clay had a plastic limit of 19.25% water content and a liquid limit of 31.61%, indicating that it was a medium plastic clay with a plasticity index of 12.36%. Fig. 2 shows the grain size distribution curve of the RCP determined by sieve analysis [110]. The bulk densities of RCP, ESP, SDP and CHP were measured as 1.43 g/cm^3, 1.17 g/cm^3, 0.23 g/cm^3 and 0.13 g/cm^3 with specific gravities of 2.32, 1.74, 1.14 and 0.61 respectively. Besides, CHP was more porous in nature (7.65) compared to SDP (5.09) and ESP (0.56) and according to the water absorption test, CHP had a higher absorption rate (195.16%) than SDP (127.66%) and ESP (39.42%).

The XRD analysis (Fig. 3(a)) displays the presence of quartz (SiO_2), kaolinite ($Al_2(Si_2O_5)(OH)_4$) and haematite (Fe_2O_3) in RCP. This is also supported by the XRF test findings shown in Table 2. Silica and aluminium were found in the clay, making it a pozzolan. Furthermore, the presence of ferric oxide (Fe_2O_3) highlights the redness of clay. On the other hand, ESP was found as a non-pozzolanic material since it lacked siliceous and aluminous elements. However, ESP had a significant quantity of calcium oxide (CaO) obtained from the calcination of calcite ($CaCO_3$), which is necessary for a pozzolanic reaction to affect the cementitious characteristics of clay bricks (Fig. 3(b)) [111]. Also, the disordered XRD patterns indicate the presence of amorphous phases (hemicelluloses and lignin) in SDP and CHP (Fig. 3(c) and Fig. 3(d)).

The SEM images of the raw materials are illustrated in Fig 4. It can be observed that eggshells had agglomerated irregular stone-like shape particles (Fig. 4(b)). On the other hand, sawdust particles came in a variety of sizes and forms, with rough surfaces including heterogeneous fibres with multiple protrusions and folds (Fig. 4(c)). Fig. 4(d) shows that coconut husk particles had an irregular honeycomb-like spongy structure consisting of many pores.

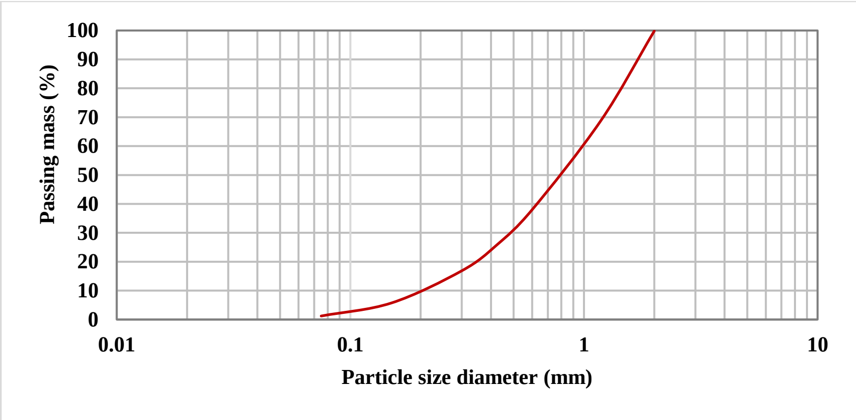


Fig. 2. Particle size distribution curve of RCP.

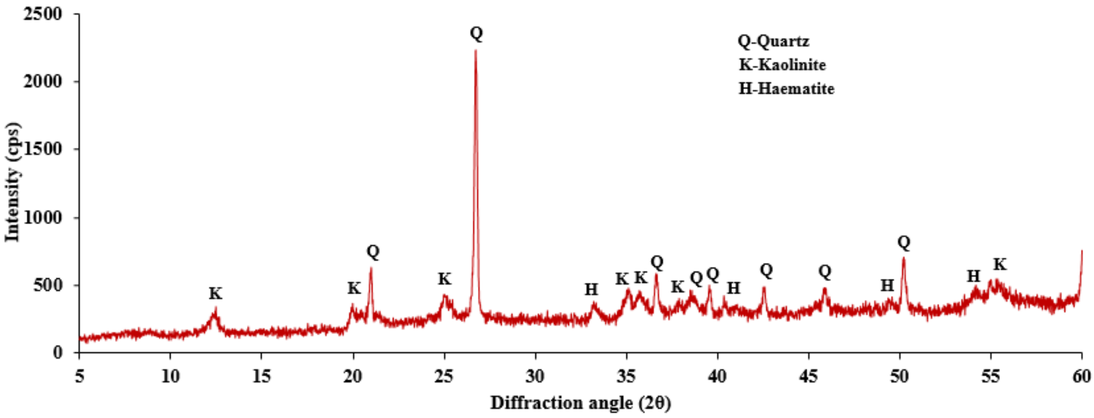
Table 1 Physical characteristics of raw materials.

Item	RCP	ESP	SDP	CHP
Liquid limit (%)	31.61	-	-	-
Plastic limit (%)	19.25	-	-	-
Plasticity Index (%)	12.36	-	-	-
Maximum dry density (kg/m^3)	2320	-	-	-
Optimum moisture content (%)	15.50	-	-	-
Density (g/cm^3)	1.43	1.17	0.23	0.13
Specific gravity	2.32	1.74	1.14	0.61
Porosity	0.38	0.56	5.09	7.65
Water absorption after 24 hours under water (%)	27.57	39.42	127.66	195.16
Natural moisture content (%)	6.47	0.31	5.02	5.62
Colour	Red	White	Light brown	Brown

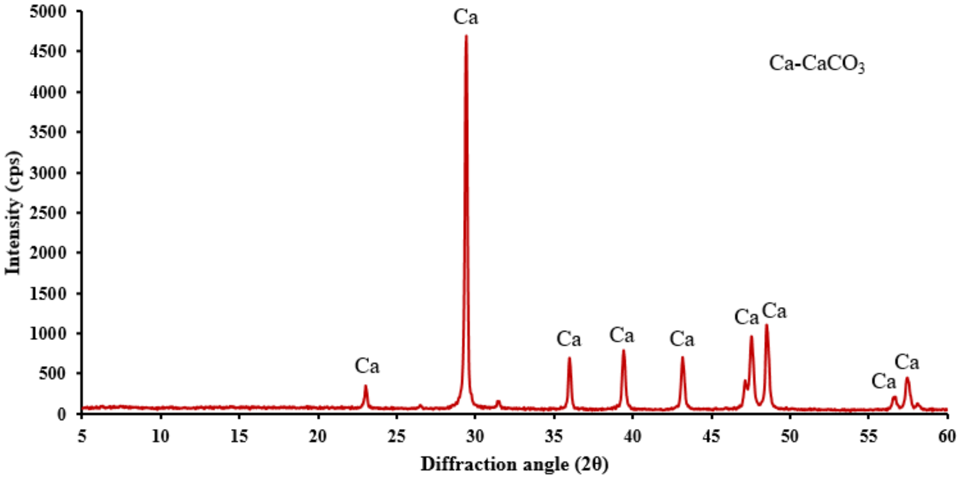
Table 2 Chemical compositions of the raw materials from the XRF test.

Chemical Compounds (%)	RCP	ESP	SDP	CHP
SiO_2	41.454	0.097	0.348	4.059
Al_2O_3	15.214	-	0.390	1.206
Fe_2O_3	8.104	-	0.186	1.184
MgO	5.114	0.522	0.408	0.767
K_2O	1.636	0.155	0.340	3.942
TiO_2	1.411	0.096	0.171	0.596
Na_2O	1.027	1.423	0.926	1.183
CaO	0.633	78.111	1.681	2.782
BaO	0.216	0.189	0.074	0.089
SO_3	0.047	0.345	0.049	0.275
MnO	0.040	-	0.026	0.013

ZrO_2	0.035	0.008	0.002	0.011
SrO	0.011	0.042	-	0.005
P_2O_5	-	-	0.021	0.094



(a)



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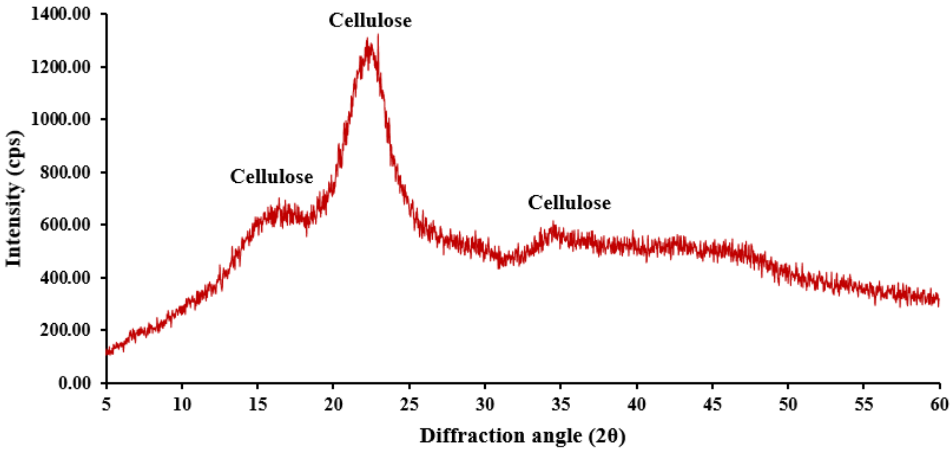

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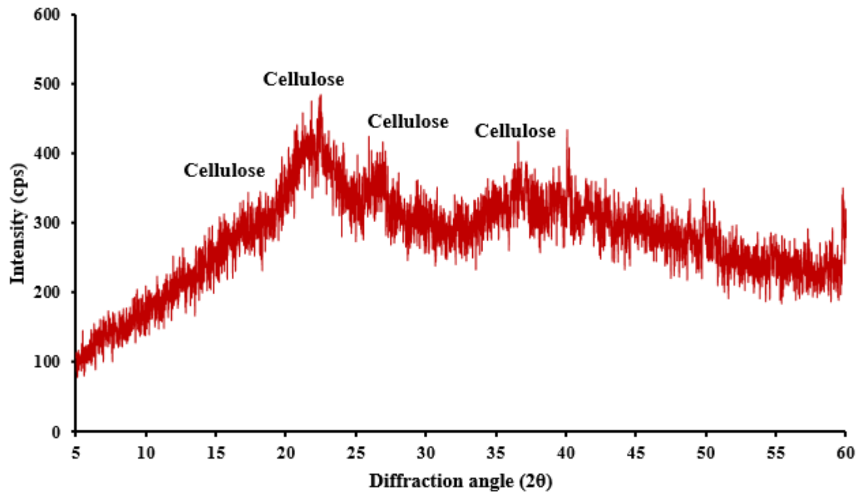


(d)

Fig. 3. XRD spectra: (a) RCP, (b) ESP, (c) SDP and (d) CHP.

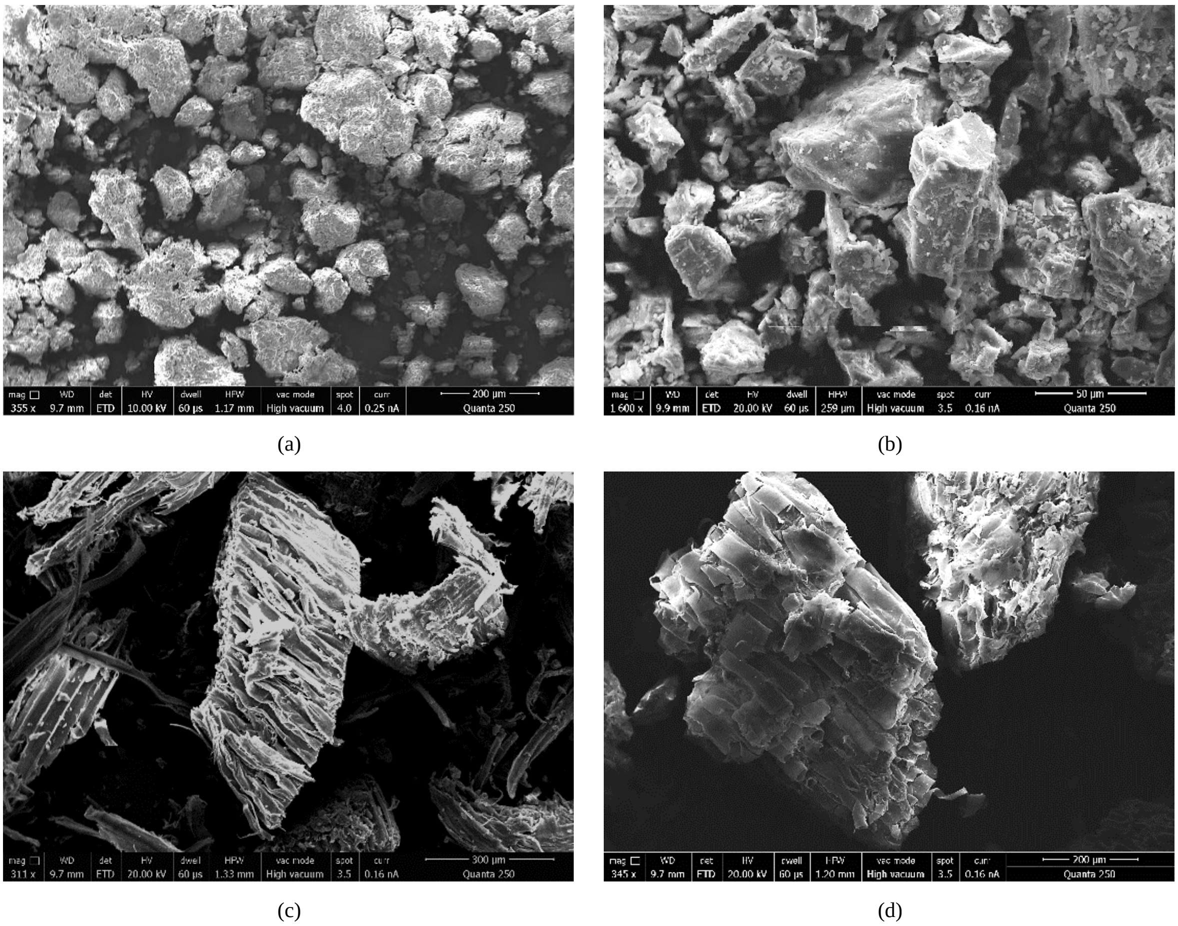


Fig. 4. SEM images: (a) RCP, (b) ESP, (c) SDP and (d) CHP.

2.3. Sample preparation

The experiment programme was conducted in two phases. In the first phase clay samples with five different percentages of ESP (10%, 20%, 30%, 40% and 50% by weight of clay) and four percentages of SDP and CHP (2.5%, 5%, 7.5% and 10% by weight of clay) were produced. According to the findings of the first phase, in the second phase, ESP was combined with optimum SDP and CHP to make the sample blocks. Table 3 gives the mixing proportions of the experiment of the first phase. Samples for the physical and mechanical properties tests were prepared in prismatic moulds of 40 mm × 40 mm ×160 mm (Fig. 5(a)) following the British standard BS-EN 1015-11 [112] for cement mortars which are frequently used for unfired brick studies due to the lack of the specific standards. Three samples were tested for each percentage and the tests included density, linear shrinkage capillary water absorption, flexural and compressive strength. On the other hand, for durability tests samples of 100 mm × 100 mm × 100 mm and 65 mm ×102 mm × 215 mm were cast (Fig. 5(b) and Fig. 5(c)). First clay was passed through a sieve with a 2.00 mm^2 mesh size to remove any lumps. Then dry clay and waste materials were thoroughly mixed in a mechanical mixer machine. Afterwards, based on the proctor test 15.50% of water by dry weight of clay was gradually added to the dry mixture to obtain the optimum moisture content and homogeneity for moulding the samples. To maintain the same consistency for moulding quantity of water in each series was adjusted. The mixture was put into the moulds in two layers and each layer was manually compacted with 25 blows. Uniform compaction may not have been accomplished in this investigation due to the hand compaction. However, hand compaction was applied to interpret the production of unfired clay brick in rural areas where advanced apparatus is unavailable. The samples were covered with plastic bags for 24 hours after being moulded to ensure uniform water absorption and no sudden loss of moisture. Before demoulding, the samples were then dried at the laboratory room temperature of around 23-26°C and relative humidity of 30-34% for 7 days. Clay samples were dried naturally to slowly dissipate the moisture and reduce internal crack due to shrinkage. After demoulding, the samples were dried for another 21 days in the same laboratory conditions before being examined. Although the absence of cement in the blends implies that no curing period is needed by the standards, this drying period was chosen as most traditional unfired clay brick manufacturers use it.

Table 3 Mix details (First phase).

Sample ID	Clay (g)	Waste (%)			Waste (g)		
		ESP	SDP	CHP	ESP	SDP	CHP
R	550	0	0	0	0	0	0
E-10	550	10	0	0	55	0	0
E-20	550	20	0	0	110	0	0
E-30	550	30	0	0	165	0	0
E-40	550	40	0	0	220	0	0
E-50	550	50	0	0	275	0	0
S-2.5	550	0	2.5	0	0	13.75	0
S-5	550	0	5	0	0	27.50	0
S-7.5	550	0	7.5	0	0	41.25	0
S-10	550	0	10	0	0	55	0
C-2.5	550	0	0	2.5	0	0	13.75
C-5	550	0	0	5	0	0	27.50
C-7.5	550	0	0	7.5	0	0	41.25
C-10	550	0	0	10	0	0	55

(a) (b) (c)

Fig. 5. Samples: (a) 40 mm × 40 mm ×160 mm, (b) 100 mm × 100 mm × 100 mm and (b) 65 mm ×102 mm × 215 mm.

3. Tests

Density, linear shrinkage, compressive strength, flexural strength, capillary water absorption, ultrasonic pulse velocity (UPV) test, drip test, and water spray tests were performed on the samples. A review study of prior research [22, 30] led to the selection of these tests, which included a wide range of physical, mechanical and durability properties relevant to unfired clay blocks. Moreover, XRD analysis was used to study the crystal structure of the clay composite. Samples dried for 28 days were grounded into fine powder to use for the analysis. Tests were performed on a Rigaku mini-flex X-ray diffractometer using Cu Kα radiation generated at 30kV and 15 mA. The samples were scanned in continuous scan mode at an angular speed of 2°/min and the measurements were taken for 2θ angle from 5° to 60°.

3.1. Density test

The density of materials has influences on their properties like strength, heat and conductivity. In this study, BS EN 771-1 [113] standard was followed to determine the densities of the samples. The test procedure can be described as follows: the 28-day dry samples (average of three samples per mix composition) were carefully cleaned with a cloth to eliminate any loose substance attached. Then all dimensions of the sample along the edge were measured using a digital calliper (precision 0.01 mm) and the average value for each dimension was calculated. The volume (V, m^3) and mass (M, kg) of the samples were measured and the density (ρ, kg/m^3) was determined using the following Eq. (1):

$$\rho = \frac{M}{V} \tag{1}$$

3.2. Linear shrinkage test

Shrinkage control is crucial for preventing the deformation and cracking of the samples. It is a physical phenomenon that is caused by the evaporation of moisture content in the samples during the drying process. The linear shrinkage test was performed following the BS EN 772-14 [114] standard on three samples per mix composition. For the test procedure, four dimensions of the prism mould length (L_i, mm) were measured and at the end of the 28-day drying period, the four dimensions of the prism sample length (L_d, mm) were recorded using a digital calliper. The average length was then taken and Eq. (2) was used to calculate the linear shrinkage (S_d, %):

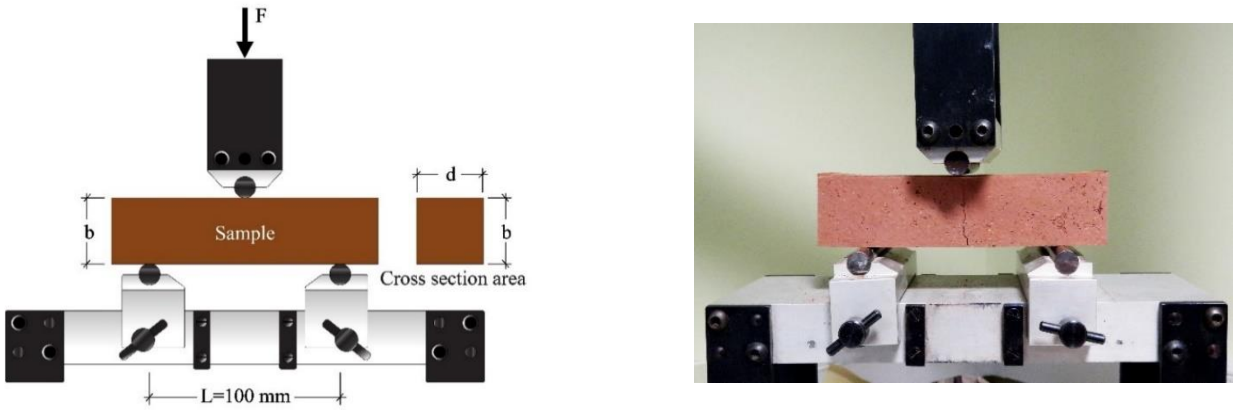
$$S_d = \frac{L_i - L_d}{L_i} \times 100 \tag{2}$$

3.3. Flexural strength test

A 25 kN frame capacity Tinius Olsen H25KS was used to test the flexural strength under three-point loading in accordance with BS EN 1015-11 [112]. The test was performed on the full prism samples (40 mm × 40 mm × 160 mm) after 28 days of the drying period. The clear span between the two supports was 100 mm as shown in Fig. 6 and the load was applied at a rate of 10 N/s at the middle of the samples until it failed. Three samples from each mix design were tested resulting in the formation of half samples at the end of the test which were then used for compressive strength and capillary water absorption tests. The following Eq. (3) from EN 1015-11 was used to determine the flexural strength:

$$f = \frac{1.5FL}{bd^2} \tag{3}$$

Where f (MPa) is the flexural strength, F (N) is the obtained load, L (mm) is the distance between the supports, b (mm) is the height of the sample, and d (mm) is the width of the sample.



(a) (b)

Fig. 6. Flexural strength test: (a) schematic and (b) experimental.

3.4. Compressive strength test

Half prism samples with an average dimension of 40 mm × 40 mm × 80 mm were tested for compressive strength according to the BS EN 1015-11 [112] standard. Three samples were examined and mean values were calculated for each mix design. A computerised and motorised triaxial machine was used for the test (Fig. 7). According to the standard, the samples were aligned centrally between two bearing steel plates of 40 mm × 40 mm and the charge velocity used was 0.40 MPa/s until visible damage was caused by the compression. The compressive strength was determined using the Eq. (4):

$$C = \frac{F}{A} \tag{4}$$

Where C (MPa) is the compressive strength, F (kN) is the ultimate load, A (mm^2) is the area of the bed face.

(a) (b)

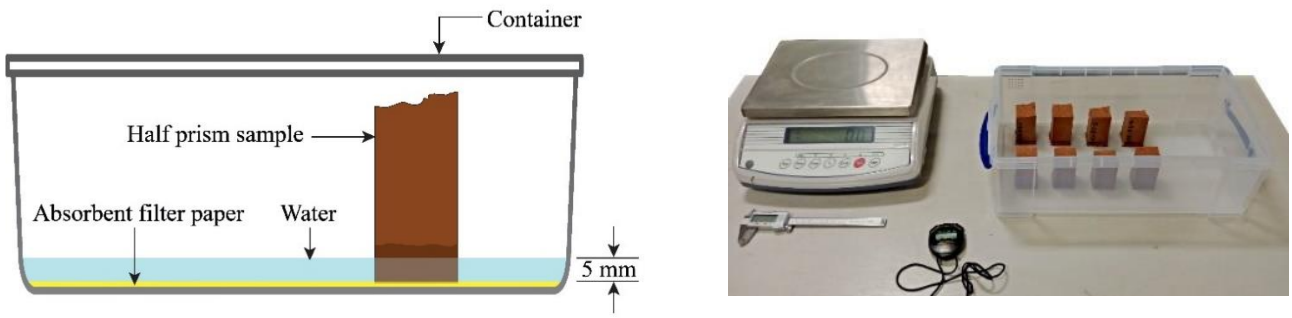
Fig. 7. Compressive strength test: (a) schematic and (b) experimental.

3.5. Capillary water absorption test

The capillary water absorption test was performed to determine the ability of the waste-incorporated clay samples to resist the absorption and retention of water. BS EN 1015-18 [115] specifies the test method on one half prism sample (40 mm × 40 mm × 80 mm) obtained from the flexural strength test. Following the standard, to attain constant mass the half prisms were first dried for 24 hours at 60 ± 5 °C in a ventilated oven and the mass of the oven-dried samples were recorded. As the samples had dissimilar sizes after the breakage in the flexural strength test, flat faces of the samples were immersed in a constant head-water bath to a depth of 5 mm for 10 min to ensure consistency (Fig. 8). Then after 10 min, the samples were removed from the water and their mass were noted. The capillary water absorption was calculated (average of three samples per mix composition) by the following Eq. (5) [115]:

$$C_w = 0.1 \times (M_t - M_i) \quad (5)$$

Where C_w (kg/(m^2×min$^{0.5}$) is the capillary water absorption coefficient, M_i (g) is the initial mass of the sample and M_t (g) is the mass of the sample after 10 min.

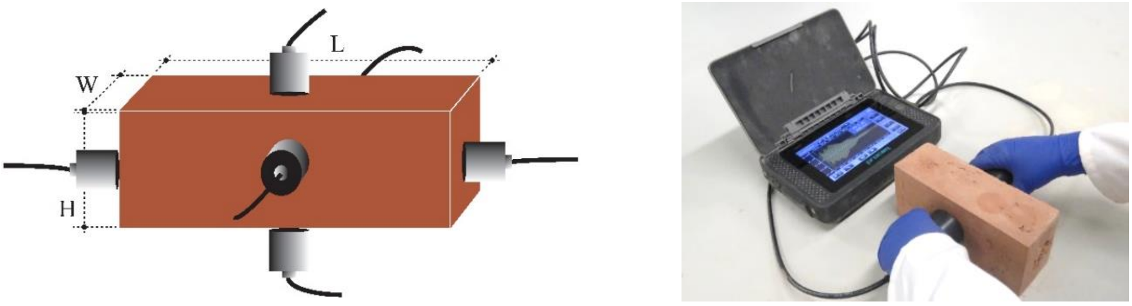


(a) (b)

Fig. 8. Capillary water absorption test: (a) schematic and (b) experimental.

3.6. UPV test

Low density and high absorption potential agro-wastes can affect the porosity and consequently, the strength of the samples. Hence, the UPV test which is a non-destructive procedure for assessing the presence of voids and density of samples. The test was performed on the 65 mm ×102 mm × 215 mm samples after 28 days of casting using a Proceq Pundit PL-200 ultrasonic pulse equipment. This equipment measures the delay time required for a transmitted ultrasonic wave to travel from the transducer and return to the transducer through the interposed sample. A coupling gel was applied between the samples and transducers to avoid the existence of voids in the contact area. The samples were measured for length (L), width (W) and height (H) prior to the test in order to determine UPV for each direction (Fig. 9(a)). The direct transmission (Fig. 9(b)) was used to measure the UPV as it is considered the most reliable configuration [116]. The test findings can be used in determining the durability of the samples by assessing the decrease of voids inside the samples as velocity increases with the decrease of voids suggesting a compact and denser composition.



(a) (b)

Fig. 9. UPV test: (a) schematic and (b) experimental.

3.7. Geelong drip test

The wet erosion test was performed following the New-Zealand Standard NZS 4298 [117] which is based on the Geelong drip test method. This test method was originally developed at Deakin University, Australia to evaluate the capacity of the earthen materials to withstand erosion caused by light and indirect rainfall. Later Frencham [118] categorised the earthen materials by relating the depth of pitting to an Erodability index (Table 4) which relates the erosion to real-life performance [119]. The test was carried out on the 100 mm × 100 mm × 100 mm samples by simulating rain droplets. According to the procedure, the samples were positioned at a 30° angle at the base and vertically 400 mm away from a water container, from which water was allowed to drop on the surface of the samples at a controlled flow for 60 min (Fig. 10). After testing, the erodibility index was calculated by measuring the pit depth created by the water drops on the samples with a calliper of 0.01 mm resolution. This simple test can be acceptable in areas where annual precipitation is around 500 mm but its applicability in areas with higher rainfall levels has yet to be determined [119].

3.8. Water spray test (Pressure spray method)

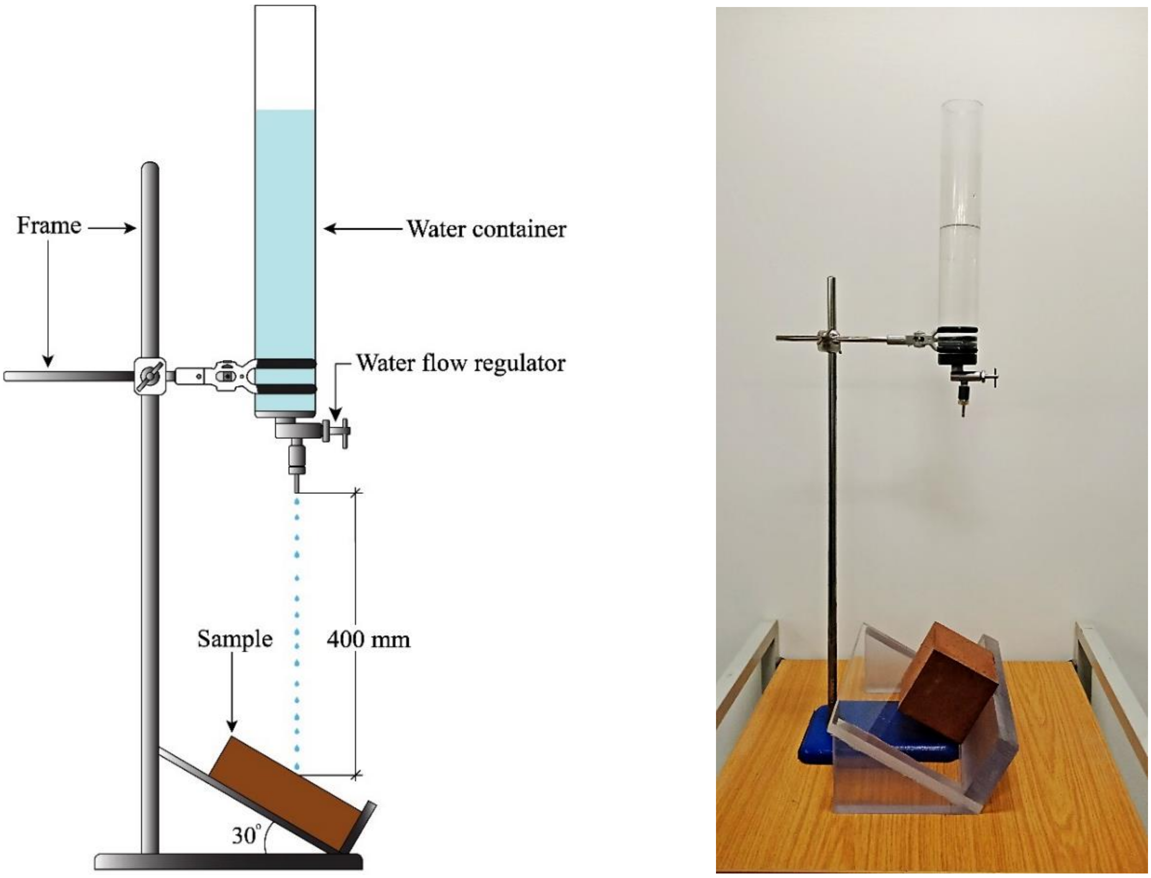
The pressure spray test is also known as the ‘accelerated erosion test’ and is frequently used in practice. However, according to Heathcote [120] and Walker et al. [121], this test is more extreme than real climatic conditions. The test was carried out in accordance with New Zealand Standard NZS 4298 [117] to assess the resistance of the samples against continuous rainfall conditions. The test simulates two real-life conditions that cause earthen materials to erode due to moderate to heavy rainfall: humidification and kinetic energy. Humidification reduces the internal cohesion between the material particles by increasing moisture content while kinetic energy is responsible for breaking the already weakened bonds of material particles. The test was performed on 65 mm ×102 mm × 215 mm samples imitating real-life conditions of average to heavy rainfall. The samples were placed behind a shield board and the external surface was exposed to a pressure spray through an 80 mm diameter hole (adapted from the standard from 100 mm diameter hole) on the shield board (Fig. 11). The pressure spray was positioned at 470 mm from the shield and tap water was sprayed through the nozzle at a pressure of 50 kPa onto the samples for an hour or until failure occurred. In every 15 min, the depth of pitting was measured using a calliper and the rate of erosion in mm per hour was determined by dividing the total depth of erosion by 60. In addition, samples were inspected by the eye to assess the degree of moisture penetration. The erodability index for the water spray test is specified in Table 5.

Table 4 Scale of assessment for ‘Drip test’.

Depth of erosion, d (mm)	Frencham [118] recommendation	Erodibility index as per NZS 4298 [117]
0	Non-erosive	1
$0 \leq d < 5$	Slightly erosive	2
$5 \leq d < 10$	Erosive	3
$10 \leq d < 15$	Very erosive	4
$15 \leq d$	-	5 (Fail)

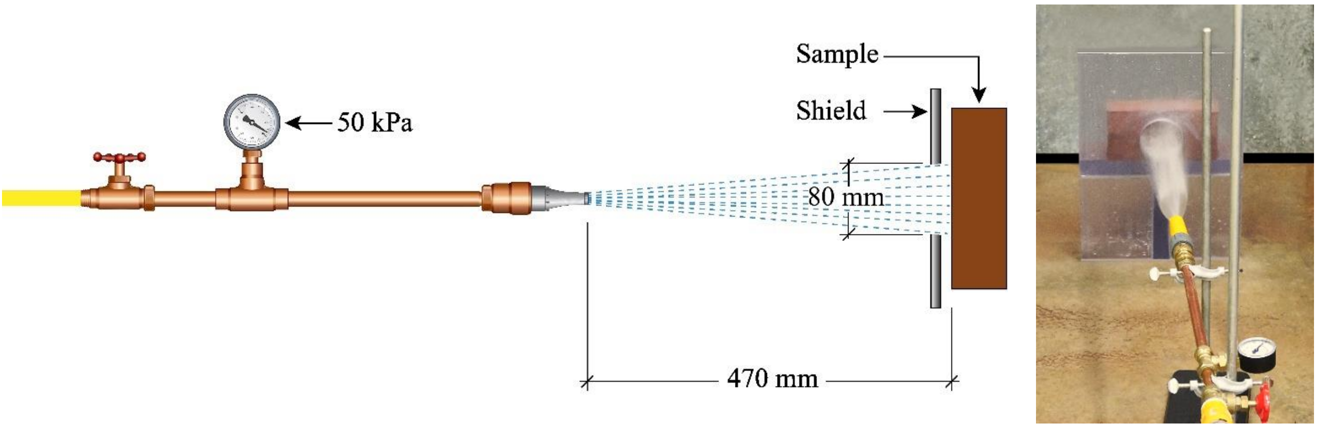
Table 5 Erodibility indices from pressure spray erosion test.

Erosion rate, d (mm/hr)	Erodibility index
0	-
$0 \leq d < 20$	1
$20 \leq d < 50$	2
$50 \leq d < 90$	3
$90 \leq d < 120$	4
$120 \leq d$	5 (Fail)



(a) (b)

Fig. 10. Drip test: (a) schematic and (b) experimental.



(a) (b)

Fig. 11. Water spray test: (a) schematic and (b) experimental.

4. Results and discussions

4.1. First phase

4.1.1. Density

The effect of various ESP, SDP and CHP ratios on the density of the samples is shown in Fig. 12. It can be observed that densities of the samples decreased with higher ESP, SDP and CHP content which were lower than that of the reference sample**.** This decrease in density is mainly attributed to the lower specific gravity of the ESP, SDP and CHP particles as compared to the RCP used in this study (see Table 1). The increased lighter wastes content displaced heavier clay content, resulting in a drop in sample density. The decrease in density for increasing ESP content from 10% to 50% in the mixture corresponds to a decrease of about 5.51% to 14.34% and for 2.5% to 10% addition of SDP and CHP the decrease was about 12.14% to 29.39% and 17.48% to 33.94% respectively in comparison to the reference clay sample. Besides, both reference and ESP incorporated samples achieved density values that exceeded the minimum value of 1750 kg/m^3 stipulated in Indian Standard: IS 1725 [122] and Sri Lankan Standard: SLS 1382 [123]. However, in the case of SDP and CHP addition, only samples with 2.5% content met the standard requirement. Other manufactured samples can be categorised as lightweight clay brick as a construction material by the standards [124]. Several authors noticed similar results with natural fibre addition in unfired clay blocks, where density dropped with increasing the amount of fibres [74, 78, 98-100, 124]. However, the results from this study was contrary to the findings of Amaral et al. [54] and Adogla et al. [38] which established that the density of the compressed laterite brick and soil-cement brick increased steadily with increasing ESP content. This might be due to the mechanical compaction technique used in block manufacturing [125, 126].

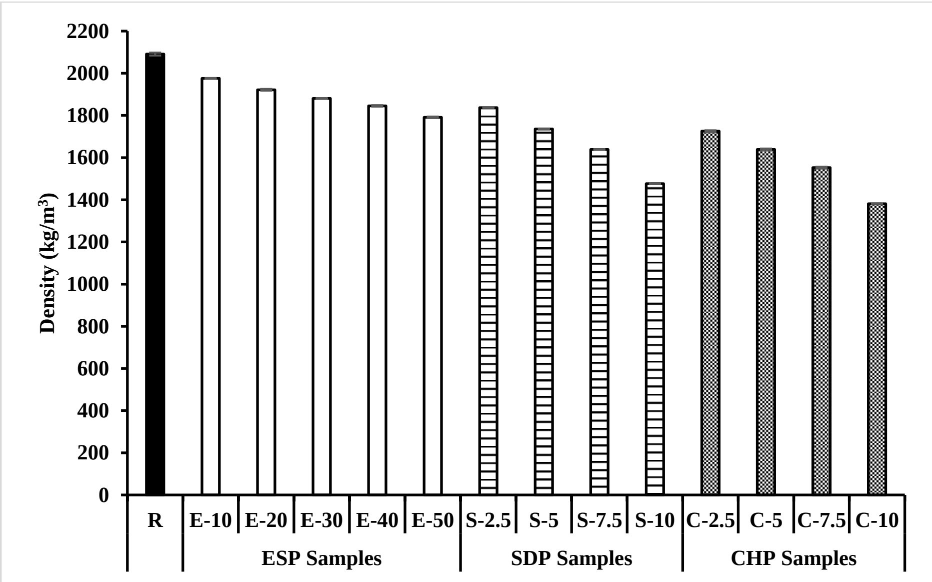


Fig. 12. Density results (First phase).

4.1.2. Linear shrinkage

Shrinkage is highly affected by the nature and quantity of additives, as well as their surface characteristic. Furthermore, the moisture absorption behaviour, water loss and porosity of the samples all have an impact on shrinkage [127, 128]. The results (Fig. 13) showed that when the SDP concentration increased from 2.5 to 10%, the linear shrinkage of the samples reduced from 6.05 to 5.53% which was up to around 31% reduction compared to the reference sample (8.07%). The bonding capabilities of SDP can be related to the presence of fibres in earthen materials like straw since they contain similar components. Straw in the earthen matrix plays a basic role in preventing shrinkage and subsequent fissuring during the drying process particularly if the earth is produced in blocks with high clay content [24]. Bouhicha et al. [129], Murillo et al. [130] and Danso et al. [98] reported a similar result in which natural fibres addition in the soil decreased the shrinkage by resisting soil matrix deformation via friction and/or adhesion. On the contrary, the samples with CHP tended to shrink gradually from 8.18 to 12.29% (around a 52% increase relative to reference sample) when the CHP content is increased from 2.5 to 10%. It may be due to the higher water absorption potential of CHP relative to SDP (see Table 1) which weakened the waste particle-clay bonding resulting in increased shrinkage during the drying period due to evaporation. Besides, CHP's ability to absorb water from capillary pores may cause volume reduction (contraction) and an increase in sample shrinkage (deformation). For ESP samples shrinkage gradually decreased from 6.92% to 5.61% with waste content varying from 10-50%. It might be related to the adsorption of calcium ions from ESP, which caused a rise in pore fluid viscosity [131-133]. It is stated that if the material shrinks more than 8%, the drying process can produce internal fractures and cracking [128]. Concerning this, the present study found shrinkage values in allowable ranges except for the reference and CHP samples.

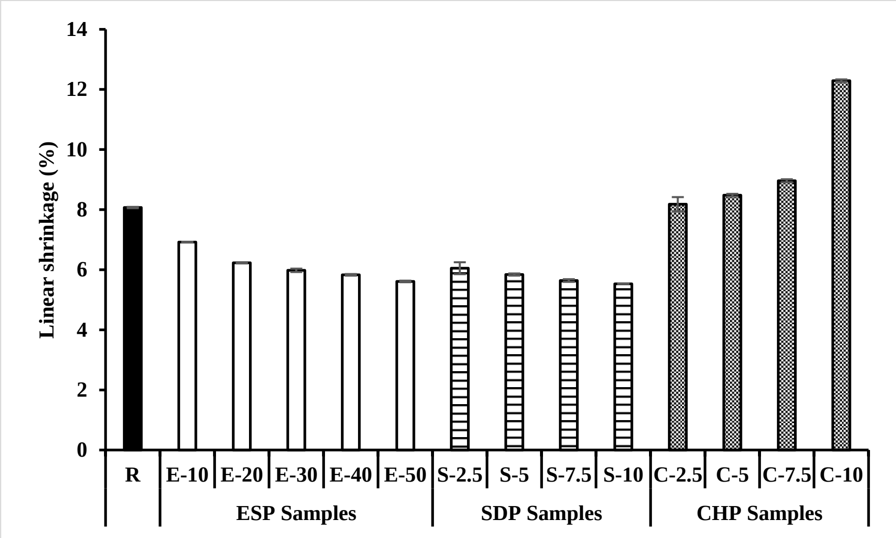


Fig. 13. Linear shrinkage results (First phase).

4.1.3. Compressive and flexural strength

The results of the mechanical strength tests have been summarised in Table 6. At each mixture, both compressive and flexural strength were determined by taking the average of the three results. The strength enhancement in waste-incorporated clay mixture largely depends on the development of waste particle-clay matrix adhesion, clay matrix-clay matrix bonding and waste particle-waste particle cohesion. These bonds can be influenced by particle size, surface conditions and the amount of waste present [134]. In this study, compressive strength was performed for both air-dried and oven-dried samples. After 28 days, both the reference and waste-incorporated samples fulfilled the minimum strength requirement of the standards (1 MPa-2.80 MPa) [117, 123, 135, 136]. The results show that compressive strength for the samples with ESP increased gradually with an increase in waste content up to 40% then the strength decreased for 50% ESP. This result is also accompanied by the XRD analysis (Fig. 14(a)). Amaral et al. [54] and Adogla et al. [38] reported comparable results where the highest compressive strength was recorded at 30% ESP for soil-cement brick and compressed earth block. The increase in strength can be explained by the pozzolanic reaction of the clay minerals with a high amount of calcium available in ESP which formed a cementitious compound that dispersed among the clay particles and improved the adhesion of the clay matrix and ESP particles. As a pozzolan the clay contains siliceous and aluminium elements, while ESP is a non-pozzolan material [137, 138]. When clay, ESP and water are mixed, a pozzolanic reaction occurs which produce samples with cementitious properties. The ESP's calcium oxide (CaO) reacts with water at first, leading to the production of calcium hydroxide ($Ca(OH)_2$), also known as portlandite. Subsequently, portlandite ($Ca(OH)_2$) and silica (SiO_2) or silicic acid ($Si(OH)_4$) are converted to form calcium silicate hydrate ($CaSiO_3 \cdot 2H_2O$) which has strong cementing properties responsible for the strength of the materials [111].

$$CaO_{(s)} + H_2O_{(aq)} \rightarrow Ca(OH)_{2\,(aq)} \quad (6)$$

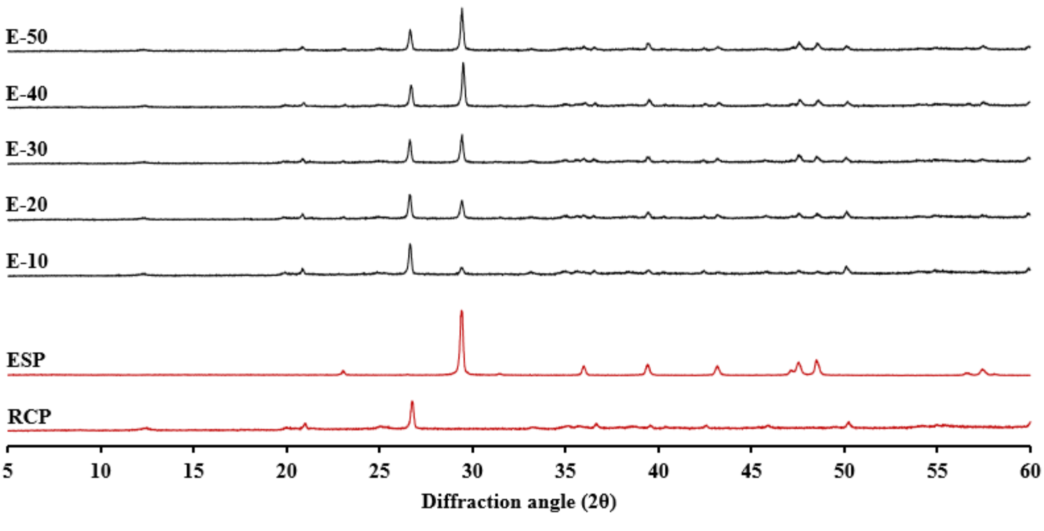
$$Ca(OH)_{2\,(aq)} + H_2SiO_{3\,(aq)} \rightarrow CaSiO_3 \cdot 2H_2O_{(s)} \quad (7)$$

The lower compressive strength associated with higher ESP content may be due to the insufficient presence of silica content in the clay matrix as a result of a higher additive amount. Therefore, fewer pozzolanic reactions occurred and unreacted portlandite was prevalent in the mixture, resulting in a decrease in mechanical resistance and an increase in porosity [139, 140]. On the other hand, the XRD spectra revealed that when SDP and CHP were mixed with clay no reaction occurred ((Fig. 14(b), Fig. 14(c)). It was observed that the addition of SDP and CHP enhanced the compressive strength of the samples in comparison to the reference sample, nevertheless, the highest compressive strength was obtained with the least amount of waste percentage (2.5%). This increase in strength for 2.5% dosage is due to the improved molecular cohesion since higher cohesion leads to better compressive strength. For SDP and CHP content of more than 2.5%, the strength value decreased due to poor adhesion of the clay with the waste particles. This loss in strength is also associated with the increase in porosity caused by the inclusion of lightweight SDP and CHP in the blend. The hydrophilic characteristic of natural fibres might cause them to absorb water and expand, efficiently pushing out on the clay matrix throughout the mixing and drying stages of sample production. Then at the end of the drying period, the fibres lose their absorbed water and shrink back nearly to their original dimensions forming very fine voids around their periphery which weakens the interfacial bond (Fig. 15) [141, 142]. Furthermore, SDP and CHP were added to the mixture at the expense of clay resulting in a reduction in silica content which led to producing more porous structures with lower compressive strength than silica composites without additives [124]. These findings are in line with the findings of Khedari et al. [99], Murillo et al. [130], Thanushan et al. [100] and Wang et al. [143]. The relatively lower compressive strength values of SDP samples compared to the CHP samples could be due to the roughness of the CHP particle surface which contributed to the good adhesion of the fibres to the clay matrix. ESP, SDP and CHP addition improved the compressive strength of the air-dried clay samples up to 39.90%, 16.75% and 17.73% and oven-dried samples up to 28.15%, 16.30% and 20.19% respectively compared to the reference sample.

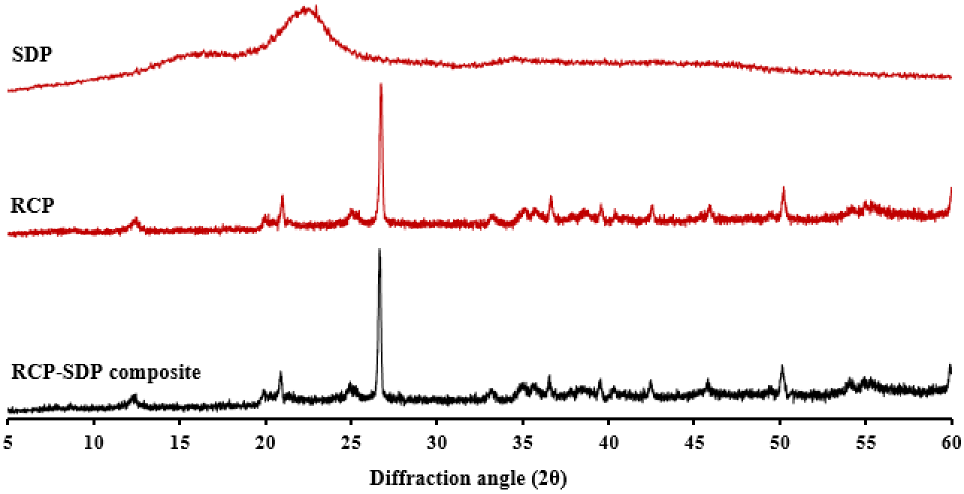
Table 6 shows that flexural strength had similar trends of compressive strength values with increasing the SDP and CHP waste content. All the samples met the requirements of the standards (0.25 MPa-0.50 MPa) [117, 122, 136] of unfired earth blocks. The optimum values of flexural strength were recorded as 2.24 MPa at 40% ESP and 2.00 MPa at 2.5% SDP and 2.14 MPa at 2.5% CHP representing 47.37%, 31.58% and 40.79% increase over the reference sample (1.52 MPa).

Table 6 Flexural and compressive strength test results of the stabilised clay blocks (First phase).

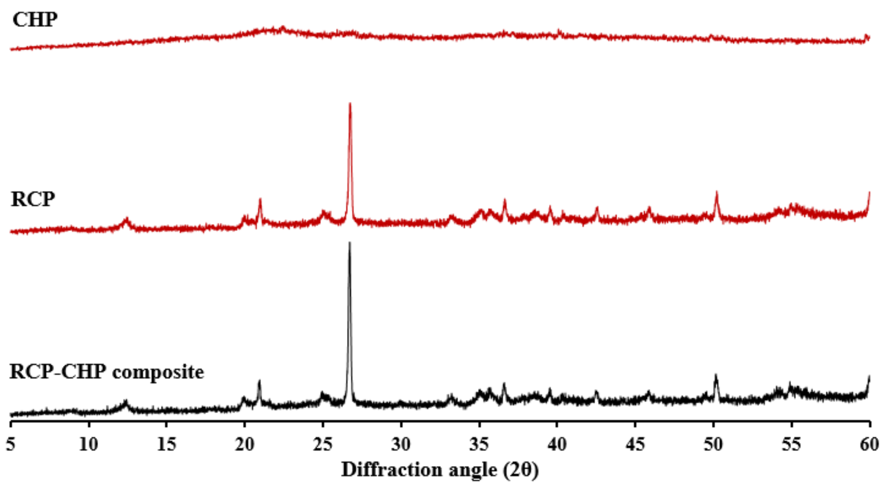
Sample ID	**Flexural strength (FS)**			**Air-dried Compressive strength (CS)**			**Oven-dried Compressive strength (CS)**		
	Av. FS (MPa)	Standard deviation	Coefficient of variance (%)	Av. CS (MPa)	Standard deviation	Coefficient of variance (%)	Av. CS (MPa)	Standard deviation	Coefficient of variance (%)
R	1.52	0.14	8.90	4.06	0.39	9.53	5.40	0.22	4.00
E-10	1.68	0.04	2.59	4.54	0.16	3.44	6.02	0.32	5.33
E-20	1.99	0.06	2.95	4.88	0.11	2.33	6.57	0.11	1.67
E-30	2.12	0.06	2.87	5.24	0.16	3.07	6.67	0.09	1.35
E-40	2.24	0.03	1.36	5.68	0.08	1.32	6.92	0.05	0.67
E-50	1.81	0.04	2.41	4.77	0.07	1.36	6.36	0.26	4.04
S-2.5	2.00	0.03	1.52	4.74	0.18	3.85	6.28	0.05	0.84
S-5	1.86	0.04	2.17	4.29	0.04	0.84	5.82	0.17	2.91
S-7.5	1.66	0.03	1.74	4.15	0.03	0.61	5.58	0.23	4.09
S-10	1.36	0.04	2.58	3.53	0.09	2.52	4.74	0.29	6.07
C-2.5	2.13	0.05	2.36	4.78	0.13	2.66	6.49	0.23	3.55
C-5	1.99	0.05	2.27	4.58	0.05	1.12	6.22	0.23	3.71
C-7.5	1.70	0.01	0.34	4.42	0.05	1.20	5.83	0.10	1.72
C-10	1.57	0.03	1.94	4.18	0.05	1.20	5.64	0.04	0.72



(a)



(b)



(c)

Fig. 14. XRD analysis: (a) ESP samples, (b) SDP samples and (c) CHP samples.

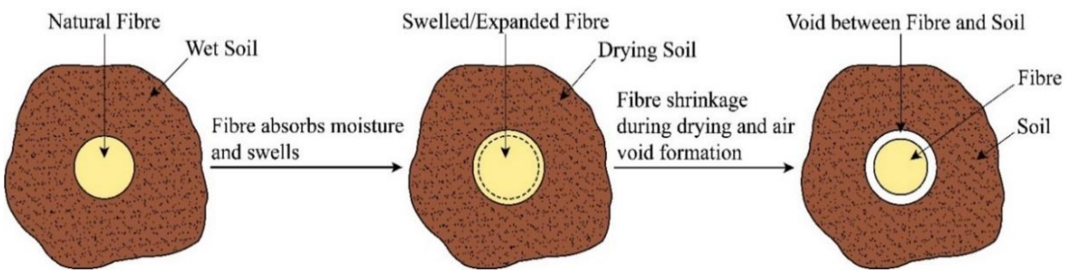


Fig. 15. Interaction between natural fibre and soil [141, 142].

4.1.4. Capillary water absorption

The capillary water absorption test is usually used to determine the immersion resistance and durability in wet environments of clay bricks. The incorporation of additives to clay bricks results in the formation of porosity which increases capillary water absorption. The structure of pores and how they are interconnected determine the rate of capillary water absorption [134, 144, 145]. Samples with higher coefficients absorb more water, showing higher porosity, whereas samples with lower coefficients absorb less water, indicating lower porosity. Fig. 16 presents a decreasing trend in capillary water absorption coefficient values with increasing ESP content from 0% to 40% before rising slightly at 50% ESP. This is consistent with the result of Amaral et al. [54] and Adogla et al. [38]. This decrease can be attributed to the pozzolanic reaction induced by the calcium ions in ESP, which increased bonding within the clay matrix while reducing open porosity, similar to traditional lime [38]. However, the capillary water absorption coefficient steadily amplified when SDP and CHP content increased from 2.5 to 10% since beyond 2.5% additives the bonding between the particles and the clay matrix became weak resulting in the formation of interconnecting voids which led to the increase in water absorption kinetics. Moreover, the absorbent nature of SDP and CHP may potentially play a role in the increase in capillary water absorption [146]. This finding is in accordance with previous research on lignocellulosic fibre-earth composites which found that increasing percentages of fibre resulted in higher absorption levels [98, 100, 147, 148]. On the other hand, Villamizar et al. [149] and Sharma et al. [150] found that increasing the amount of natural fibres in compressed and adobe blocks reduced the water absorption. In general, the discrepancies in the impacts of all the additives studied on capillary water absorption may be linked to their stabilisation mechanism, type of bonding and rearrangement pattern of particles which were influenced by the nature of the additives, their particle size and compaction method [77, 80, 149]. The addition of ESP resulted in a 15% decrease in capillary water absorption compared to the reference sample, whilst SDP and CHP boosted it by 26 and 45%, respectively.

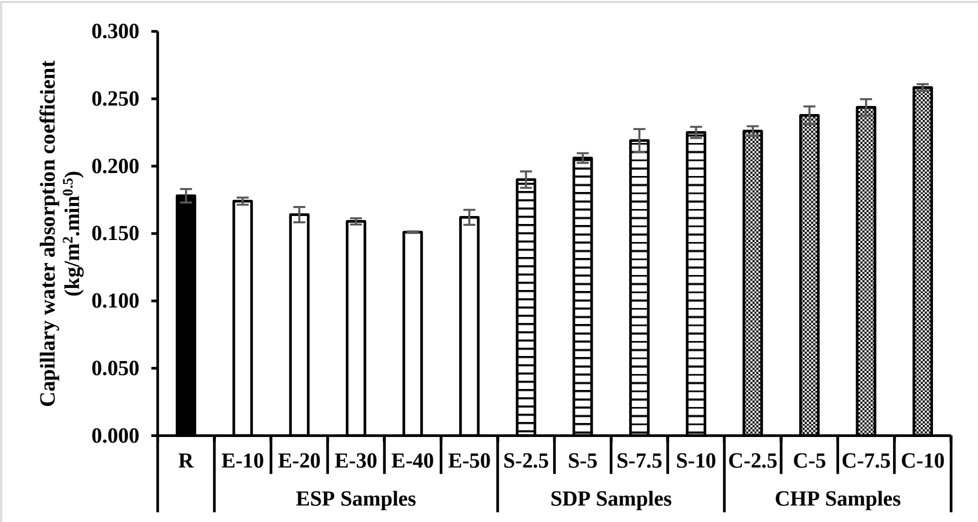


Fig. 16. Capillary water absorption results (First phase).

4.1.5. UPV

The shape, size and number of pores affect the wave propagation speed, making it a good indicator of porosity and compactness. The greater the increase in porosity, the lower the ultrasonic speed. This implies that porosity and ultrasonic velocity are inversely related. UPV values for ESP, SDP and CHP mixed samples are shown in Fig. 17, ranging from 1263 m/s to 1453.33 m/s, 1560.33 m/s to 1318.33 m/s and 1384.67 m/s to 1123.00 m/s, respectively. Unfired earth blocks are rarely studied for UPV and there is only a few research that shows a link between UPV and compressive strength of earthen materials [128, 151-154]. In this study, the UPV results showed a similar trend as the compressive strength (Fig. 18). The Maximum UPV values were obtained for samples containing 40% ESP and 2.5% SDP and 2.5% CHP which had the highest compressive strength. An increase in UPV for the addition of ESP might be attributed to the pozzolanic reactions of ESP, whereas a decrease in UPV for increasing SDP and CHP content could be related to increased porosity in the samples. The variations in sample performance for different orientations might be explained by a lack of homogenisation of the clay mixture. The UPV findings might give an intriguing supplementary data set that is closely related to the mechanical strength results. Consequently, this non-destructive method may be used to qualitatively assess the quality of unfired earth blocks.

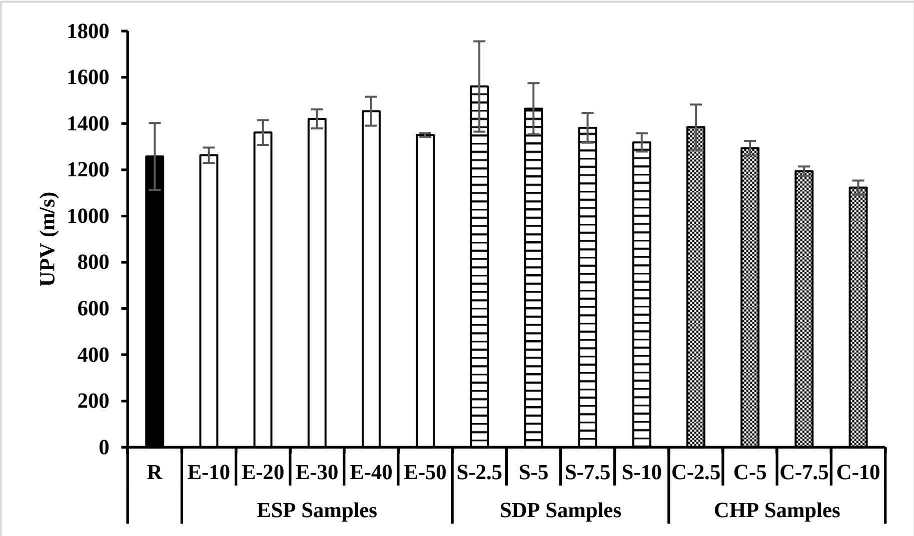


Fig. 17. UPV test results of stabilised clay blocks (First phase).

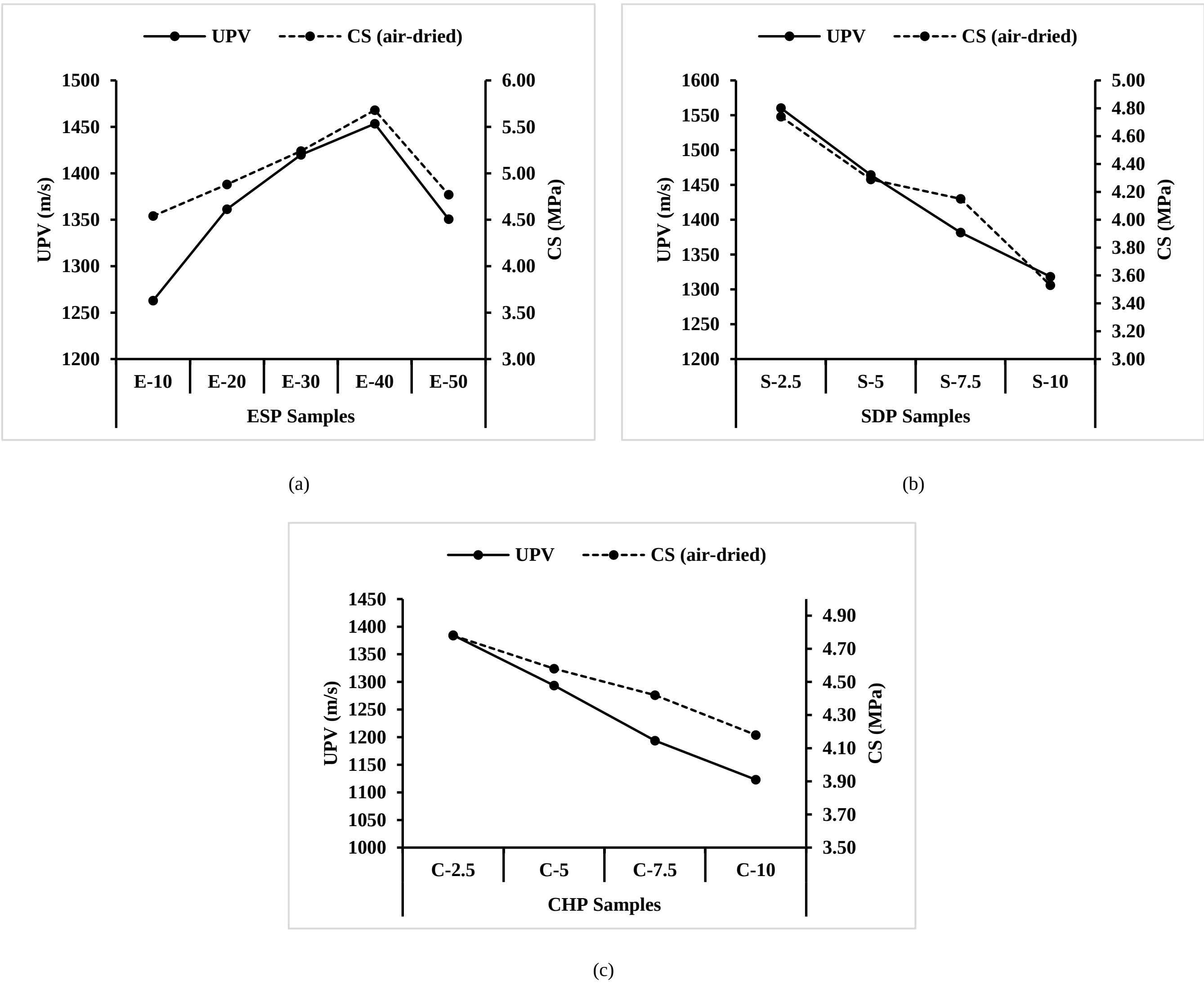


Fig. 18. UPV vs Compressive strength (First phase): (a) ESP samples, (b) SDP samples and (c) CHP samples.

4.1.6. Drip

The test was performed on cube samples of each mixture. The lower the depth, the better the sample's erosion resistance. Table 7 shows that all of the samples passed the drip test and the pitting depths were between 0 and 5 mm which means an erodibility index of 2 (see Table 4), indicating that they are " slightly erodible." The results demonstrate that ESP, SDP and CHP addition to clay improves its erosion resistance compared to the reference sample. The least erosive mixture with SDP and CHP was 2.5%, whereas the best performance with ESP was obtained with the mixture with 40% ESP. The good cohesion between waste particles and clay prevents water from penetrating the sample and clay particles from washing away by water which appears to be the explanation for the sample's good performance [155].

4.1.7. Water spray

The results of the water spray test show the durability of the clay brick under severe rains. The erosion rates of clay samples containing different amounts of waste percentages are shown in Table 7. All of the samples exhibited erosion rates of less than 1 mm/hr, indicating that they could resist exposure to harsh weather conditions. Since a little investigation on the impact of agro-wastes additives on the erosion resistance of earth bricks has been undertaken, it's difficult to generalise the findings, however, in this study, incorporating the ESP, SDP and CHP in the clay mixture considerably increased its resistance to water erosion when compared to the reference sample. Furthermore, when the results are compared it can be concluded that SDP brought better resistance than the other additives. It was also observed that the rate of erosion increased as the percentage of SDP and CHP increased in the sample. The poor interface between the waste particles and the clay was related to the reduced durability. But for ESP the erosion rate decreased gradually up to 40% of waste content and then increased for 50% ESP. This is related to the high filling capacity of the ESP in the clay matrix which resulted in firm bonding. Danso et al. [98] and Sharma et al. [150] showed that when the amount of natural fibre increased the durability of the soil matrix improved. According to the authors, this might be due to improved interaction between fibre and soil which binds soil particles together more firmly. Obonyo et al. [156], on the other hand, found that adding coir fibres in soil-cement blocks significantly reduced their durability against water. Also, Akinwumi et al. [157] observed that the durability of compressed earth bock decreased with the increasing percentage of shredded waste plastic due to the poor interaction of the shredded waste plastic with the soil.

Table 7 Drip test and water spray test results of stabilised clay blocks.

Sample ID	Drip test			Water spray test		
	Dept of pitting (mm)	Erodibility Index	Rating	Depth of erosion (mm)	Rate of erosion (mm/hr)	Erodibility index
R	4.87	2	Slightly erosive	44.94	0.75	2
E-10	3.58	2	Slightly erosive	39.45	0.66	2
E-20	3.75	2	Slightly erosive	36.52	0.61	2
E-30	2.60	2	Slightly erosive	35.92	0.60	2
E-40	2.16	2	Slightly erosive	30.88	0.51	2
E-50	2.37	2	Slightly erosive	38.47	0.64	2
S-2.5	2.18	2	Slightly erosive	22.46	0.37	2
S-5	2.38	2	Slightly erosive	25.95	0.43	2
S-7.5	2.46	2	Slightly erosive	27.71	0.46	2
S-10	3.23	2	Slightly erosive	28.68	0.48	2
C-2.5	2.73	2	Slightly erosive	32.56	0.54	2
C-5	3.10	2	Slightly erosive	33.49	0.56	2
C-7.5	3.64	2	Slightly erosive	38.78	0.65	2
C-10	3.82	2	Slightly erosive	40.63	0.68	2

4.2. Second phase

Results of the first phase indicate that the addition of 10-40% of ESP improved the strength and 2.5% SDP and CHP performed the best. Hence, in the second phase, 2.5% of SDP and CHP were combined with 10-30% of ESP to examine the properties of the clay samples (Table 8). It can be seen that when ESP was combined with SDP and CHP, the density (Fig. 19) and linear shrinkage reduced (Fig. 20) but capillary water absorption increased (Fig. 21) compared to the only 2.5% SDP and 2.5% CHP samples. Furthermore, strength exhibited a decreasing trend (Table 9), although, they met the standard criteria. This is again the fact that the calcium oxide (CaO) in the ESP interacts with water to produce portlandite ($Ca(OH)_2$), which then reacts with silica (SiO_2) in the clay to form calcium silicate hydrate ($CaSiO_3 \cdot 2H_2O$) which gives the materials their strength. However, when clay was substituted by SDP/CHP in a mixture, the amount of silica (SiO_2) available to react with portlandite $Ca(OH)_2$ decreased, and unreacted portlandite had a detrimental influence on strength [111]. Fig. 22 and Fig. 23 present the XRD analysis of the Eggshell-Sawdust and Eggshell-Coconut husk samples. Moreover, the UPV results presented in Fig. 24 revealed that when the amount of ESP increased with SDP/CHP, velocity declined, indicating the formation of more porous materials. Similar to the results of the first phase UPV is directly related to the strength values (Fig. 25(a) and Fig. 25(b)). Regarding the durability test, the samples showed a slight increase in erosion rate compared to the only 2.5% SDP and 2.5% CHP samples (Table 10). Besides, according to visual inspection following the water spray test, the reference sample displayed multiple surface cracking, where the other samples from the first and second phases had smoother surfaces (Fig. 26).

Table 8 Mix details (Second phase).

Sample ID	Clay (g)	Waste (%)			Waste (g)		
		ESP	SDP	CHP	ESP	SDP	CHP
ES-2.5/10	550	10	2.5	0	55	13.75	0
ES-2.5/20	550	20	2.5	0	110	13.75	0
ES-2.5/30	550	30	2.5	0	165	13.75	0
EC-2.5/10	550	10	0	2.5	55	0	13.75
EC-2.5/20	550	20	0	2.5	110	0	13.75
EC-2.5/30	550	30	0	2.5	165	0	13.75

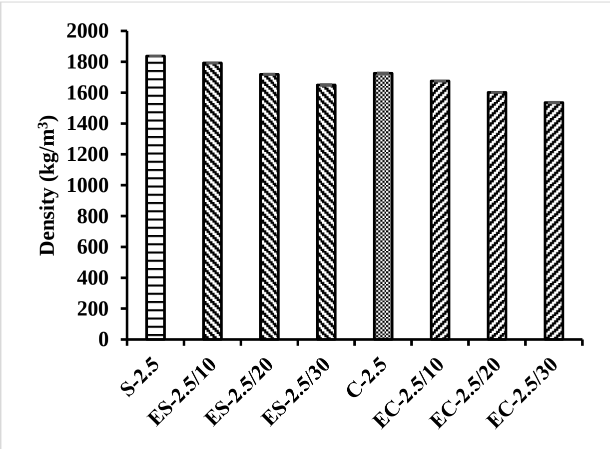


Fig. 19. Density results (Second phase)

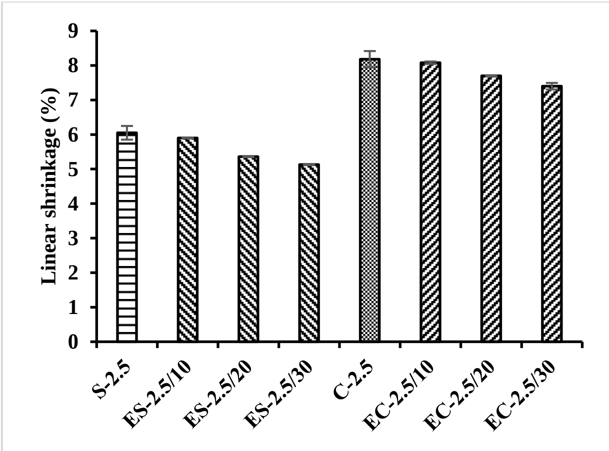
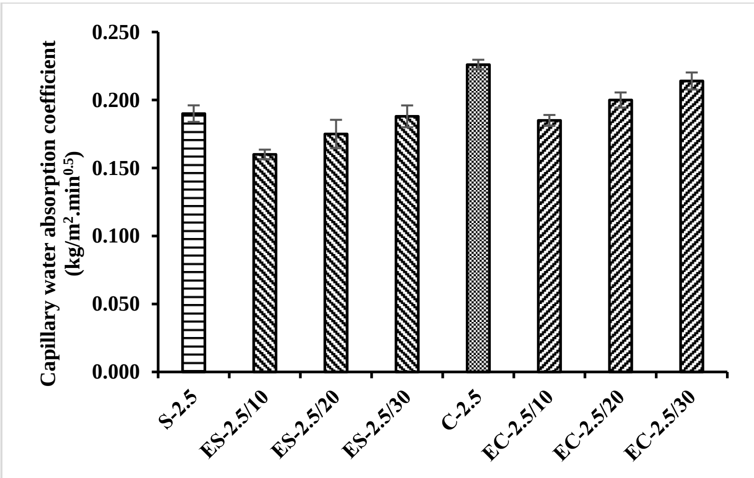


Fig. 20. Linear shrinkage results (Second phase)



(c)
Fig. 21. Capillary water absorption results (Second phase).

Table 9 Flexural and compressive strength test results of the stabilised clay blocks (Second phase).

Sample ID	Flexural strength (FS)			Air-dried Compressive strength (CS)			Oven-dried Compressive strength (CS)		
	Av. FS (MPa)	Standard deviation	Coefficient of variance (%)	Av. CS (MPa)	Standard deviation	Av. CS (MPa)	Coefficient of variance (%)	Standard deviation	Coefficient of variance (%)
ES-2.5/10	1.70	0.03	1.56	4.35	0.22	5.82	5.12	0.21	3.67
ES-2.5/20	1.55	0.05	2.90	4.07	0.04	5.44	0.89	0.05	0.97
ES-2.5/30	1.44	0.03	1.84	3.89	0.07	5.19	1.75	0.03	0.49
EC-2.5/10	1.78	0.07	4.13	4.49	0.27	6.02	6.06	0.12	1.92

EC-2.5/20	1.62	0.02	0.94	4.10	0.06	5.54	1.41	0.11	1.95
E-C2.5/30	1.47	0.16	11.20	3.91	0.08	5.21	2.07	0.01	0.22

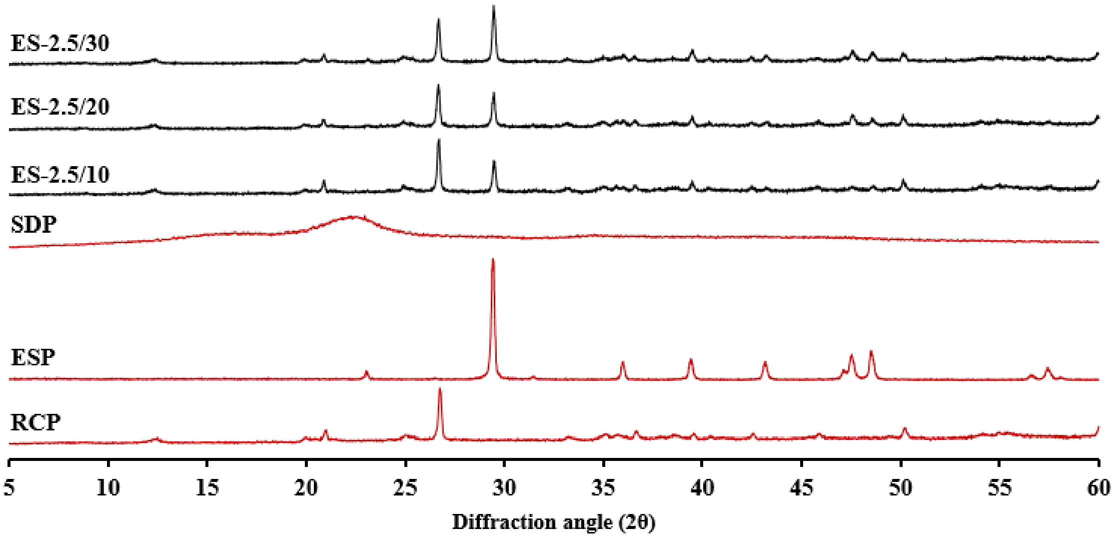


Fig. 22. XRD analysis of ES samples.

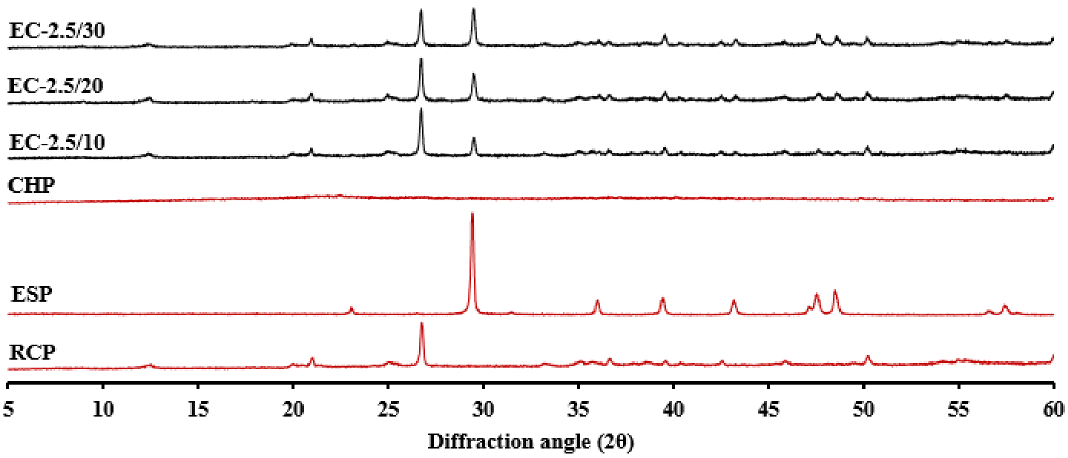


Fig. 23. XRD analysis of EC samples.

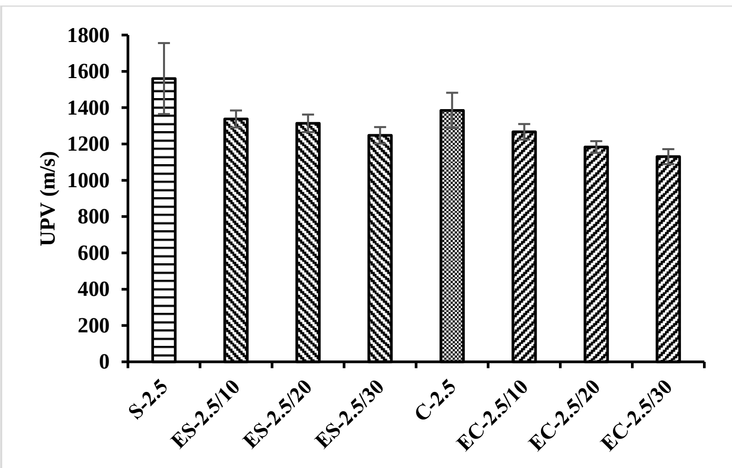
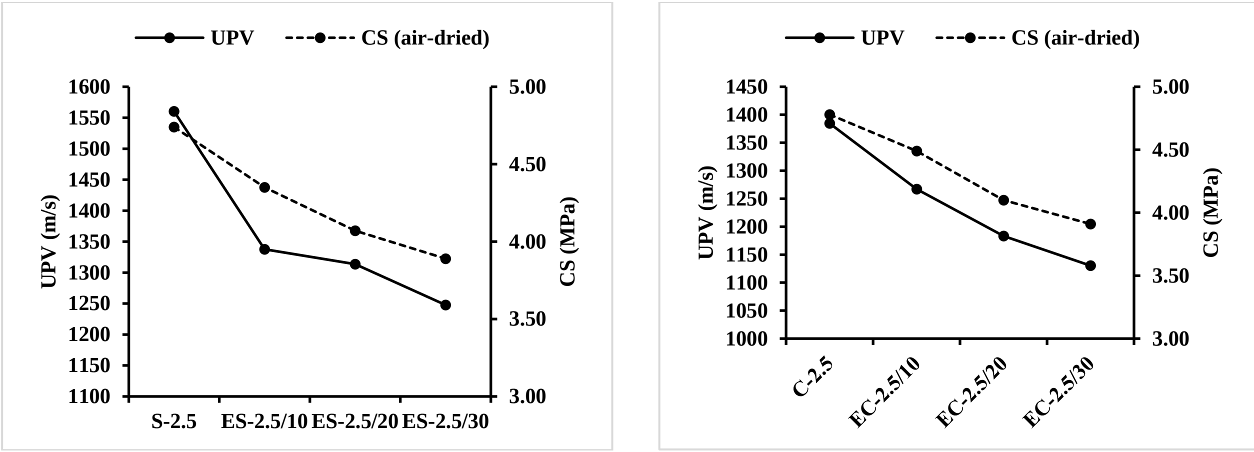


Fig. 24. UPV test results of stabilised clay blocks (Second phase).



(a) (b)

Fig. 25. UPV vs Compressive strength (Second phase): (a) ES samples and (b) EC samples.

Table 10 Drip test and water spray test results of stabilised clay blocks (Second phase).

Sample ID	Drip test			Water spray test		
	Dept of pitting (mm)	Erodibility Index	Rating	Depth of erosion (mm)	Rate of erosion (mm/hr)	Erodibility index
ES-2.5/10	3.12	2	Slightly erosive	33.05	0.55	2
ES-2.5/20	3.20	2	Slightly erosive	35.91	0.60	2
ES-2.5/30	3.28	2	Slightly erosive	36.79	0.61	2
EC-2.5/10	3.47	2	Slightly erosive	38.84	0.65	2
EC-2.5/20	3.53	2	Slightly erosive	40.09	0.67	2
EC-2.5/30	3.80	2	Slightly erosive	40.38	0.67	2

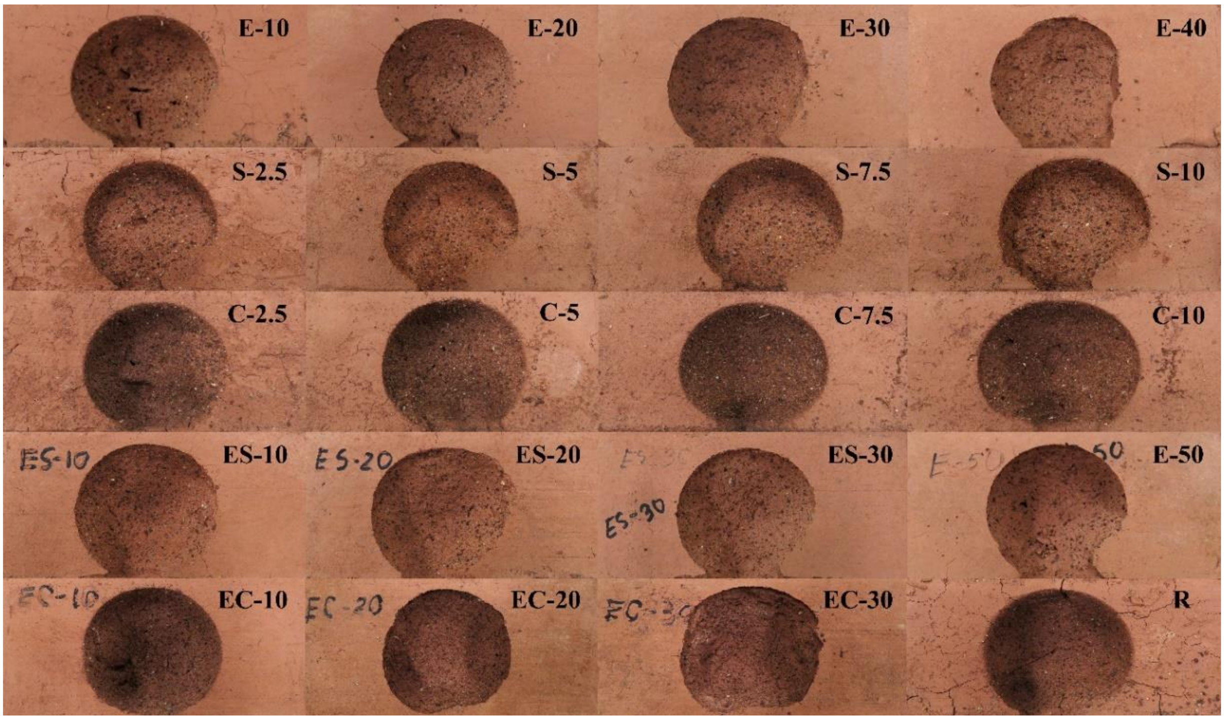


Fig. 26. Samples after water spray test.

6. Conclusions

This study evaluates the potential use of eggshell powder, sawdust powder and coconut husk powder in the production of unfired clay blocks. The physico-mechanical and durability properties such as density, linear shrinkage, capillary water absorption, flexural strength, compressive strength, ultrasonic pulse velocity test, drip test and water spray test were investigated. Experimental tests conducted on unfired clay blocks revealed the following conclusions:

1. When the amount of the waste materials was increased in the mixture the density of the samples gradually decreased. However, all the ESP incorporated samples reached the minimum value of 1750 kg/m^3 required by the Indian Standard: IS 1725 and Sri Lankan Standard: SLS 1382 for the load-bearing blocks. For SDP and CHP additives, only 2.5% content achieved the standard requirement. Other percentages can be used to produce lightweight masonry blocks.

2. The XRD analysis indicated that there was no reaction when SDP and CHP were mixed with clay. In the presence of water, however, ESP reacted with clay to create cementitious material, significantly improving the properties of the samples.

3. The linear shrinkage decreased with the addition of ESP and SDP but increased with CHP addition. Besides, the capillary water absorption coefficient decreased for ESP addition up to 40% and then increased for the higher amount. For the SDP and CHP samples, the capillary water absorption gradually increased with increasing the waste percentage.

4. In terms of mechanical properties, after 28 days, all the waste-incorporated samples fulfilled the minimum compressive strength (1 MPa-2.80 MPa) and flexural strength requirement (0.25 MPa-0.50 MPa) of the standards. ESP samples showed higher compressive and flexural strength values (FS: 2.24 MPa, CS: 5.68 MPa) compared to SDP (FS: 2 MPa, CS: 4.74 MPa) and CHP (FS: 2.14 MPa, CS: 4.78 MPa) samples. However, combining ESP with SDP and CHP resulted in a loss of strength.

5. It was noticed that the UPV measurements followed a similar pattern to the strength. The samples with the highest compressive strength of each group were found to have the highest UPV values, with 40% ESP, 2.5% SDP and 2.5% CHP.

6. According to New Zealand standard NZS 4298, all samples passed the drip test and water spray test, where an erodibility index of 2 was recorded, suggesting that they are "slightly erodible." The results showed that when ESP, SDP and CHP were added individually and in combination with clay, erosion resistance improved compared to the reference sample.

The results of this experiment revealed that ESP, SDP and CHP can be used to stabilise unfired clay blocks because they improved the samples' overall properties. Moreover, the results of the tests may be useful in finding a solution to the waste management problem as well as providing potential low-cost materials for the construction sector.

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References

[1] R. Latawiec, P. Woyciechowski, K.J. Kowalski, Sustainable concrete performance—CO_2-emission, Environments 5(2) (2018) 27. https://doi.org/10.3390/environments5020027.
[2] A.J. Nath, R. Lal, A.K. Das, Fired bricks: CO_2 emission and food insecurity, Global Challenges 2(4) (2018), 1700115. https://doi.org/10.1002/gch2.201700115.
[3] F. Colangelo, I. Farina, M. Travaglioni, C. Salzano, R. Cioffi, A. Petrillo, Innovative Materials in Italy for Eco-Friendly and Sustainable Buildings, Materials 14(8) (2021) 2048. https://doi.org/10.3390/ma14082048.
[4] P. Zak, T. Ashour, A. Korjenic, S. Korjenic, W. Wu, The influence of natural reinforcement fibers, gypsum and cement on compressive strength of earth bricks materials, Construction and Building Materials 106 (2016) 179-188. https://doi.org/10.1016/j.conbuildmat.2015.12.031.
[5] A. Heath, P. Walker, C. Fourie, M. Lawrence, Compressive strength of extruded unfired clay masonry units, Proceedings of the Institution of Civil Engineers-Construction Materials 162(3) (2009) 105-112. http://dx.doi.org/10.1680/coma.2009.162.3.105.
[6] P. Chauhan, A. El Hajjar, N. Prime, O. Plé, Unsaturated behavior of rammed earth: Experimentation towards numerical modelling, Construction and Building Materials 227 (2019) 116646. https://doi.org/10.1016/j.conbuildmat.2019.08.027.
[7] L.R. Valero, V.F. Sasso, E.P. Vicioso, In situ assessment of superficial moisture condition in façades of historic building using non-destructive techniques, Case Studies in Construction Materials 10 (2019) e00228. https://doi.org/10.1016/j.cscm.2019.e00228.
[8] D. Muheise-Araalia, S. Pavia, Properties of unfired, illitic-clay bricks for sustainable construction, Construction and Building Materials 268 (2021) 121118. https://doi.org/10.1016/j.conbuildmat.2020.121118.
[9] F.R. Arooz, R.U. Halwatura, Mud-concrete block (MCB): mix design & durability characteristics, Case Studies in Construction Materials 8 (2018) 39-50. https://doi.org/10.1016/j.cscm.2017.12.004.
[10] C. Costa, Â. Cerqueira, F. Rocha, A. Velosa, The sustainability of adobe construction: past to future, International Journal of Architectural Heritage 13(5) (2018) 639-647. https://doi.org/10.1080/15583058.2018.1459954.

[11] H. Anysz, P. Narloch, Designing the Composition of Cement Stabilized Rammed Earth Using Artificial Neural Networks, Materials 12(9) (2019) 1396. https://doi.org/10.3390/ma12091396.
[12] H. Lin, F. Liu, S. Lourenço, G. Schwantes, S. Trumpf, D. Holohan, C. Beckett, Stabilization of an earthen material with Tung oil: compaction, strength and hydrophobic enhancement, Construction and Building Materials 290 (2021) 123213. https://doi.org/10.1016/j.conbuildmat.2021.123213.
[13] A.A. Shubbar, M. Sadique, P. Kot, W. Atherton, Future of clay-based construction materials–A review, Construction and Building Materials 210 (2019) 172-187. https://doi.org/10.1016/j.conbuildmat.2019.03.206.
[14] A. Al-Fakih, B.S. Mohammed, M.S. Liew, E. Nikbakht, Incorporation of waste materials in the manufacture of masonry bricks: An update review, Journal of Building Engineering 21 (2019) 37-54. https://doi.org/10.1016/j.jobe.2018.09.023.
[15] V. Gupta, H.K. Chai, Y. Lu, S. Chaudhary, A state of the art review to enhance the industrial scale waste utilization in sustainable unfired bricks, Construction and Building Materials 254 (2020) 119220. https://doi.org/10.1016/j.conbuildmat.2020.119220.
[16] K.C. Onyelowe, F.O. Okafor, A comparative review of soil modification methods, ARPN Journal of Earth Sciences 1(2) (2012) 36-41. http://www.arpnjournals.com/jes/research_papers/rp_2012/jes_1112_07.pdf.
[17] H. Danso, B. Martinson, M. Ali, C. Mant, Performance characteristics of enhanced soil blocks: a quantitative review, Building Research & Information 43(2) (2015) 253-262. https://doi.org/10.1080/09613218.2014.933293.
[18] H. Van Damme, H. Houben, Earth concrete. Stabilization revisited, Cement and Concrete Research 114 (2018) 90-102. https://doi.org/10.1016/j.cemconres.2017.02.035.
[19] A. Karrech, V. Strazzeri, M. Elchalakani, Improved thermal insulance of cement stabilised rammed earth embedding lightweight aggregates, Construction and Building Materials 268 (2021) 121075. https://doi.org/10.1016/j.conbuildmat.2020.121075.
[20] A. Jesudass, K. Harish, S.S. Ram, S.M. Riyas, Earthen blocks with Synthetic Fibres–A Review, IOP Conference Series: Materials Science and Engineering 1145 (2021) 012039. https://doi.org/10.1088/1757-899X/1145/1/012039.
[21] C. Jayasinghe, N. Kamaladasa, Compressive strength characteristics of cement stabilized rammed earth walls, Construction and Building Materials 21(11) (2007) 1971-1976. https://doi.org/10.1016/j.conbuildmat.2006.05.049.
[22] F.V. Riza, I.A. Rahman, A.M.A. Zaidi, A brief review of compressed stabilized earth brick (CSEB), 2010 International Conference on Science and Social Research (CSSR 2010), December 5-8, Kuala Lumpur, Malaysia, 2010, pp. 999-1004. https://doi.org/10.1109/CSSR.2010.5773936.
[23] L. Guettatfi, A. Hamouine, K. Himouri, B. Labbaci, Mechanical and Water Durability Properties of Adobes Stabilized with White Cement, Quicklime and Date Palm Fibers, International Journal of Architectural Heritage (2021). https://doi.org/10.1080/15583058.2021.1959675.
[24] B.R.T. Vilane, Assessment of stabilisation of adobes by confined compression tests, Biosystems Engineering 106 (2010) 551-558. https://doi.org/10.1016/j.biosystemseng.2010.06.008.
[25] C. Udawattha, D.E. De Silva, H. Galkanda, R. Halwatura, Performance of natural polymers for stabilizing earth blocks, Materialia 2 (2018) 23-32. https://doi.org/10.1016/j.mtla.2018.07.019.
[26] V. Toufigh, E. Kianfar, The effects of stabilizers on the thermal and the mechanical properties of rammed earth at various humidities and their environmental impacts, Construction and Building Materials 200 (2019) 616-629. https://doi.org/10.1016/j.conbuildmat.2018.12.050.
[27] C. Turco, A.C.P. Junior, E.R. Teixeira, R. Mateus, Optimisation of Compressed Earth Blocks (CEBs) using natural origin materials: A systematic literature review, Construction and Building Materials 309 (2021) 125140. https://doi.org/10.1016/j.conbuildmat.2021.125140.
[28] G.K.M. Subramanian, M. Balasubramanian, A.A. Jeya Kumar, A Review on the Mechanical Properties of Natural Fiber Reinforced Compressed Earth Blocks, Journal of Natural Fibers (2021). https://doi.org/10.1080/15440478.2021.1958405.
[29] A. Laborel-Preneron, J.-E. Aubert, C. Magniont, C. Tribout, A. Bertron, Plant aggregates and fibers in earth construction materials: A review, Construction and Building Materials 111 (2016) 719-734. https://doi.org/10.1016/j.conbuildmat.2016.02.119.
[30] N. Jannat, A. Hussien, B. Abdullah, A. Cotgrave, Application of agro and non-agro waste materials for unfired earth blocks construction: A review, Construction and Building Materials 254 (2020) 119346. https://doi.org/10.1016/j.conbuildmat.2020.119346.
[31] C. Maraveas, Production of Sustainable Construction Materials Using Agro-Wastes, Materials 13(2) (2020) 262. https://doi.org/10.3390/ma13020262.
[32] J.-C. Morel, A. Mesbah, M. Oggero, P. Walker, Building houses with local materials: means to drastically reduce the environmental impact of construction, Building and Environment 36(10) (2001) 1119-1126. https://doi.org/10.1016/S0360-1323(00)00054-8.
[33] M. Waheed, M.S. Butt, A. Shehzad, N.M. Adzahan, M.A. Shabbir, H.A.R. Suleria, R.M. Aadil, Eggshell calcium: A cheap alternative to expensive supplements, Trends in Food Science & Technology 91 (2019) 219-230. https://doi.org/10.1016/j.tifs.2019.07.021.
[34] A. Shwetha, Dhananjaya, K.S.M. Shravana, Ananda, Comparative study on calcium content in egg shells

of different birds, International Journal of Zoology Studies 3(4) (2018) 31-33. https://www.researchgate.net/publication/327136024_Comparative_study_on_calcium_content_in_egg_shells_of_different_birds.

[35] E.O. Ajala, O.A.A. Eletta, M.A. Ajala, S.K. Oyeniyi, Characterization and evaluation of chicken eggshell for use as a bio-resource, Arid Zone Journal of Engineering, Technology and Environment 14(1) (2018) 26-40. https://www.azojete.com.ng/index.php/azojete/article/view/95/72.

[36] F.X. Philippe, Y. Mahmoudi, D. Cinq-Mars, M. Lefrançois, N. Moula, J. Palacios, F. Pelletier, S. Godbout, Comparison of egg production, quality and composition in three production systems for laying hens, Livestock Science 232 (2020) 103917. https://doi.org/10.1016/j.livsci.2020.103917.

[37] A.M. King'Ori, A review of the uses of poultry eggshells and shell membranes, International Journal of Poultry Science 10(11) (2011) 908-912. https://doi.org/10.3923/ijps.2011.908.912.

[38] F. Adogla, P.P.K. Yalley, M. Arkoh, Improving compressed laterite bricks using powdered eggshells, The International Journal of Engineering and Science (IJES) 5(4) (2016) 65-70. https://theijes.com/papers/v5-i4/K0504071075.pdf.

[39] A. Mittal, M. Teotia, R. Soni, J. Mittal, Applications of egg shell and egg shell membrane as adsorbents: a review, Journal of Molecular Liquids 223 (2016) 376-387. https://doi.org/10.1016/j.molliq.2016.08.065.

[40] H. Faridi, A. Arabhosseini, Application of eggshell wastes as valuable and utilizable products: A review, Research in Agricultural Engineering 64(2) (2018) 104-114. https://doi.org/10.17221/6/2017-RAE.

[41] J.W.d.L. Souza, N.G. Jaques, M. Popp, J. Kolbe, M.V.L. Fook, R.M.R. Wellen, Optimization of epoxy resin: an investigation of eggshell as a synergic filler, Materials 12(9) (2019) DOI: https://doi.org/10.3390/ma12091489.

[42] A. Rahmani-Sani, P. Singh, P. Raizada, E.C. Lima, I. Anastopoulos, D.A. Giannakoudakis, S. Sivamani, T.A. Dontsova, A. Hosseini-Bandegharaei, Use of chicken feather and eggshell to synthesize a novel magnetized activated carbon for sorption of heavy metal ions, Bioresource Technology 297 (2020) 122452. https://doi.org/10.1016/j.biortech.2019.122452.

[43] O.O. Amu, A.B. Fajobi, B.O. Oke, Effect of Eggshell Powder on the Stabilizing Potential of Lime on an Expansive Clay Soil, Journal of Applied Sciences 5(8) (2005) 1474-1478. https://doi.org/10.3923/jas.2005.1474.1478.

[44] A.J. Olarewaju, M.O. Balogun, S.O. Akinlolu, Suitability of eggshell stabilized lateritic soil as subgrade material for road construction, Electronic Journal of Geotechnical Engineering 16(H) (2011) 899-908.

[45] S. Walia, G. Singh, H. Singh, Effect of eggshell powder and stone dust on compaction characteristics and CBR value of clayey soil, 50th Indian Geotechnical Conference, December 17-19, Pune, Maharashtra, India, 2015. https://gndec.ac.in/~igs/ldh/files/igc%202015%20pune/THEME%2014%20INVESTIGATIONS%20%E2%80%93%20GEOLOGICAL,%20GEOTECHNICAL%20AND%20GEOPHYSIC/IGC-2015_submission_608.pdf.

[46] K. Prasad, N. Mathachan, P. James, T.L. Justine, Effect of curing on soil stabilized with eggshell, International Journal of Science and Technology & Engineering 2(12) (2016) 259-264. http://www.ijste.org/articles/IJSTEV2I12022.pdf.

[47] M.N.J. Alzaidy, Experimental study for stabilizing clayey soil with eggshell powder and plastic wastes, IOP Conference Series: Materials Science and Engineering 518(2) (2019) 022008. https://doi.org/10.1088/1757-899X/518/2/022008.

[48] A.L. Ayodele, O.M. Oketope, O.S. Olatunde, Effect of sawdust ash and eggshell ash on selected engineering properties of lateralized bricks for low cost housing, Nigerian Journal of Technology 38(2) (2019) 278-282. https://doi.org/10.4314/njt.v38i2.1.

[49] N. Tangboriboon, S. Moonsri, A. Netthip, A. Sirivat, Innovation of Embedding Eggshell to Enhance Physical-Mechanical-Thermal Properties in Fired Clay Bricks via Extrusion Process, MATEC Web of Conferences 78 (2016) 01003. https://doi.org/10.1051/matecconf/20167801003.

[50] P.T. Ashiq, A. Kumar, Experimental Investigation of Bricks Using Lithomargic Clay, Fly Ash and Egg Shells and Cement Blocks with Egg Shells, International Journal of Scientific & Engineering Research 10(3) 2019 25-27. https://www.ijser.org/researchpaper/EXPERIMENTAL-INVESTIGATION-OF-BRICKS-USING-LITHOMARGIC-CLAY-FLY-ASH-AND-EGG-SHELLS-AND-CEMENT-BLOCKS-WITH-EGG-SHELLS.pdf.

[51] J.O. Afolayan, F.O.P. Oriola, G. Moses, J.E. Sani, Investigating the effect of eggshell ash on the properties of sandcrete block, International Journal of Civil Engineering, Construction and Estate Management 5(3) (2017) 43-54. https://www.eajournals.org/wp-content/uploads/Investigating-the-Effect-of-Eggshell-Ash-on-the-Properties-of-Sandcrete-Block.pdf.

[52] S. Aarcha, N.S. Ameena Shirin, K.S. Suryalekshmi, T. Rasheed, S. Harindranath, Partial Replacement of Cement with Brick Powder and Egg Shell Powder in Concrete, International Journal of Innovative Research in Science, Engineering and Technology 8(6) (2019). http://www.ijirset.com/upload/2019/june/38_Partial.pdf.

[53] H.M. Hamada, B.A. Tayeh, A. Al-Attar, F.M. Yahaya, K. Muthusamy, A.M. Humada, The present

state of the use of eggshell powder in concrete: A review, Journal of Building Engineering 32 (2020) 101583. https://doi.org/10.1016/j.jobe.2020.101583.

[54] M.C. Amaral, F.B. Siqueira, A.Z. Destefani, J.N.F. Holanda, Soil–cement bricks incorporated with eggshell waste, Proceedings of the Institution of Civil Engineers-Waste and Resource Management 166 (3) (2013) 137-141. https://doi.org/10.1680/warm.12.00024.

[55] R.C. Pettersen, The chemical composition of wood, The Chemistry of Solid Wood, ACS Publications, Washington, DC, USA, 1984, pp. 57-126. https://www.fpl.fs.fed.us/documnts/pdf1984/pette84a.pdf.

[56] H. Lachowicz, H. Wróblewska, R. Wojtan, M. Sajdak, The effect of tree age on the chemical composition of the wood of silver birch (*Betula pendula* Roth.) in Poland, Wood Science and Technology 53 (2019) 1135-1155. https://doi.org/10.1007/s00226-019-01121-z.

[57] E. Thiffault, J. Barrette, P. Blanchet, Q.N. Nguyen, K. Adjalle, Optimizing Quality of Wood Pellets Made of Hardwood Processing Residues, Forests 10(7) (2019) 607. https://doi.org/10.3390/f10070607.

[58] E.A. Okunade, The Effect of Wood Ash and Sawdust Admixtures on the Engineering Properties of a Burnt Laterite-Clay Brick, Journal of Applied Sciences 8(6) (2008) 1042-1048. https://doi.org/10.3923/jas.2008.1042.1048.

[59] A.E. Tiuc, O. Nemeş, H. Vermeşan, A.C. Toma, New sound absorbent composite materials based on sawdust and polyurethane foam, Composites Part B: Engineering 165 (2019) 120-130. https://doi.org/10.1016/j.compositesb.2018.11.103.

[60] A. Mwango, C. Kambole, Engineering Characteristics and Potential Increased Utilisation of Sawdust Composites in Construction—A Review, Journal of Building Construction and Planning Research 7(3) (2019) 59-88. https://doi.org/10.4236/jbcpr.2019.73005.

[61] A.B. Akinyemi, J.O. Afolayan, E.O. Oluwatobi, Some properties of composite corn cob and sawdust particle boards, Construction and Building Materials 127 (2016) 436-441. https://doi.org/10.1016/j.conbuildmat.2016.10.040.

[62] O.D. Atoyebi, S.O. Ajamu, S.O. Odeyemi, D.J. Ojo, J.A.L. Ramonu, Strength Evaluation of Aluminium Fibre Reinforced Particle Board made from Sawdust and Waste Glass, IOP Conference Series: Materials Science and Engineering 1036 (2021) 012049. https://doi.org/10.1088/1757-899X/1036/1/012049.

[63] R. Mirski, D. Dukarska, A. Derkowski, R. Czarnecki, D. Dziurka, By-products of sawmill industry as raw materials for manufacture of chip-sawdust boards, Journal of Building Engineering 32 (2020) 101460. https://doi.org/10.1016/j.jobe.2020.101460.

[64] H. Orelma, A. Tanaka, M. Vuoriluoto, A. Khakalo, A. Korpela, Manufacture of all-wood sawdust-based particle board using ionic liquid-facilitated fusion process, Wood Science and Technology 55 (2021) 331-349. https://doi.org/10.1007/s00226-021-01265-x.

[65] A.S.L. Aminudin, Nor Hasanah, N.M.Z. Nik Soh, P.C. Leng, G.H.T. Ling, M.H. Ahmad, Coconut Fibre and Sawdust as Green Building Materials: A Laboratory Assessment on Physical and Mechanical Properties of Particleboards, Buildings 11(6) (2021) 256. https://doi.org/10.3390/buildings11060256.

[66] S. Zou, H. Li, S. Wang, R. Jiang, J. Zou, X. Zhang, L. Liu, G. Zhang, Experimental research on an innovative sawdust biomass-based insulation material for buildings, Journal of Cleaner Production 260 (2020) 121029. https://doi.org/10.1016/j.jclepro.2020.121029.

[67] M. Mageswari, B. Vidivelli, The use of sawdust ash as fine aggregate replacement in concrete, Journal of Environmental Research and Development 3(3) (2009) 720-726.

[68] A. Ghimire, S. Maharjan, Experimental Analysis on the Properties of Concrete Brick With Partial Replacement of Sand by Saw Dust and Partial Replacement of Coarse Aggregate by Expanded Polystyrene, Journal of Advanced College of Engineering and Management 5 (2019) 27-36. https://doi.org/10.3126/jacem.v5i0.26674.

[69] F.O. Aramide, Production and characterization of porous insulating fired bricks from Ifon clay with varied sawdust admixture, Journal of Minerals and Materials Characterization and Engineering 11(10) (2012) 970-975. https://doi.org/10.4236/jmmce.2012.1110097.

[70] B. Chemani, H. Chemani, Effect of Adding Sawdust on Mechanical-Physical Properties of Ceramic Bricks to Obtain Lightweight Building Material, International Journal of Mechanical and Mechatronics Engineering 6(11) (2012) 2521-2525. https://doi.org/10.5281/zenodo.1077395.

[71] H. Chemani, B. Chemani, Valorization of wood sawdust in making porous clay brick, Scientific Research and Essays 8(15) (2013) 609-614. https://doi.org/10.5897/SRE12.608.

[72] M.A. Hassan, A.M. Yami, A. Raji, M.J. Ngala, Effects of sawdust and rice husk additives on properties of local refractory clay, The International Journal of Engineering and Science 3(8) (2014) 40-44. https://www.theijes.com/papers/v3-i8/Version-2/E0382040044.pdf.

[73] G. Cultrone, I. Aurrekoetxea, C. Casado, A. Arizzi, Sawdust recycling in the production of lightweight bricks: How the amount of additive and the firing temperature influence the physical properties of the bricks, Construction and Building Materials 235 (2020) 117436. https://doi.org/10.1016/j.conbuildmat.2019.117436.

[74] I. Demir, Effect of organic residues addition on the technological properties of clay bricks, Waste Management 28(3) (2008) 622-627. https://doi.org/10.1016/j.wasman.2007.03.019.

[75] G. Ganga, T. Nsongo, H. Elenga, B. Mabiala, T.T. Tatsiete, Nzonzolo, Effect of incorporation of chips

and wood dust mahogany on mechanical and acoustic behavior of brick clay, Journal of Building Construction and Planning Research 2(03) (2014) 198-208. https://doi.org/10.4236/jbcpr.2014.23018.

[76] S. Ouattara, M.O. Boffoue, A.A. Assande, K.C. Kouadio, C.H. Kouakou, E. Emeruwa, Pasres, Use of Vegetable Fibers as Reinforcement in the Structure of Compressed Ground Bricks: Influence of Sawdust on the Rheological Properties of Compressed Clay Brick, American Journal of Materials Science and Engineering 4(1) (2016) 13-19. https://doi.org/10.12691/ajmse-4-1-3.

[77] O.A. Fadele, O. Ata, Water absorption properties of sawdust lignin stabilised compressed laterite bricks, Case Studies in Construction Materials 9 (2018) e00187. https://doi.org/10.1016/j.cscm.2018.e00187.

[78] M. Charai, H. Sghiouri, A. Mezrhab, M. Karkri, K. Elhammouti, H. Nasri, Thermal performance and characterization of a sawdust-clay composite material, Procedia Manufacturing 46 (2020) 690-697. https://doi.org/10.1016/j.promfg.2020.03.098.

[79] G.A. Jokhio, S.M.S. Mohsin, Y. Gul, Two-fold sustainability–Adobe with sawdust as partial sand replacement, IOP Conference Series: Materials Science and Engineering 342 (2018) 012069. https://doi.org/10.1088/1757-899X/342/1/012069.

[80] M.C. De Castrillo, I. Ioannou, M. Philokyprou, Reproduction of traditional adobes using varying percentage contents of straw and sawdust, Construction and Building Materials 294 (2021) 123516. https://doi.org/10.1016/j.conbuildmat.2021.123516.

[81] G. Nagaraj, Oilseeds: properties, processing, products and procedures, New India Publishing Agency, New Delhi, India, 2009.

[82] W. Wang, G. Huang, Characterisation and utilization of natural coconut fibres composites, Materials & Design 30(7) (2009) 2741-2744. https://doi.org/10.1016/j.matdes.2008.11.002.

[83] S. Harish, D.P. Michael, A. Bensely, D.M. Lal, A. Rajadurai, Mechanical property evaluation of natural fiber coir composite, Materials Characterization 60(1) (2009) 44-49. https://doi.org/10.1016/j.matchar.2008.07.001.

[84] W.R. Carlile, M. Raviv, M. Prasad, Organic soilless media components, Soilless Culture:Theory and Practice, second ed., Academic Press, London, United Kingdom, 2019, pp. 303-378. https://doi.org/10.1016/B978-0-444-63696-6.00008-6.

[85] M.R. Kosseva, Waste from fruit wine production, Science and Technology of Fruit Wine Production, Academic Press, London, United Kingdom, 2017, pp. 557-598. https://doi.org/10.1016/B978-0-12-800850-8.00011-9.

[86] J. Khedari, B. Suttisonk, N. Pratinthong, J. Hirunlabh, New lightweight composite construction materials with low thermal conductivity, Cement and Concrete Composites 23(1) (2001) 65-70. https://doi.org/10.1016/S0958-9465(00)00072-X.

[87] C. Asasutjarit, J. Hirunlabh, J. Khedari, S. Charoenvai, B. Zeghmati, U.C. Shin, Development of coconut coir-based lightweight cement board, Construction and Building Materials 21(2) (2007) 277-288. https://doi.org/10.1016/j.conbuildmat.2005.08.028.

[88] S. Panyakaew, S. Fotios, New thermal insulation boards made from coconut husk and bagasse, Energy and Buildings 43(7) (2011) 1732-1739. https://doi.org/10.1016/j.enbuild.2011.03.015.

[89] A.L.F. Freire, C.P. de Araújo Júnior, M. de Freitas Rosa, J.A. de Almeida Neto, M.C.B. de Figueirêdo, Environmental assessment of bioproducts in development stage: Thea case of fiberboards made from coconut residues, Journal of Cleaner Production 153 (2017) 230-241. https://doi.org/10.1016/j.jclepro.2017.03.100.

[90] J. Khedari, S. Charoenvai, J. Hirunlabh, New insulating particleboards from durian peel and coconut coir, Building and Environment 38(3) (2003) 435-441. https://doi.org/10.1016/S0360-1323(02)00030-6.

[91] M. Ali, A. Liu, H. Sou, N. Chouw, Mechanical and dynamic properties of coconut fibre reinforced concrete, Construction and Building Materials 30 (2012) 814-825. https://doi.org/10.1016/j.conbuildmat.2011.12.068.

[92] M. Ramli, W.H. Kwan, N.F. Abas, Strength and durability of coconut-fiber-reinforced concrete in aggressive environments, Construction and Building Materials 38 (2013) 554-566. https://doi.org/10.1016/j.conbuildmat.2012.09.002.

[93] M.A.O. Mydin, N.A. Rozlan, S. Ganesan, Experimental study on the mechanical properties of coconut fibre reinforced lightweight foamed concrete, Journal of Materials and Environmental Science 6(2) (2015) 407-411. http://www.jmaterenvironsci.com/Document/vol6/vol6_N2/49-JMES-1181-2014-Othuman.pdf.

[94] H. Syed, R. Nerella, S.R.C. Madduru, Role of coconut coir fiber in concrete, Materials Today: Proceedings 27(2) (2020) 1104-1110. https://doi.org/10.1016/j.matpr.2020.01.477.

[95] A.A. Kadir, S.N. Mohd Zulkifly, M.M.A. Al Bakri, N.A. Sarani, The utilization of coconut fibre into fired clay brick, Key Engineering Materials 673 (2016) 213-222. https://doi.org/10.4028/www.scientific.net/KEM.673.213.

[96] M.H. Hamzah, R. Deraman, N.S.M. Saman, Investigating the effectiveness of using agricultural wastes from empty fruit bunch (EFB), coconut fibre (CF) and sugarcane baggasse (SB) to produce low thermal conductivity clay bricks, AIP Conference Proceedings 1901(1) (2017) 030005. https://doi.org/10.1063/1.5010470.

[97] G.V. Kanna, G. Dhanalakshmi, Experimental Investigations on Bricks with the replacement of Coconut Fibre, International Research Journal of Engineering and Technology 5(2) (2018) 199-204.

https://www.irjet.net/archives/V5/i2/IRJET-V5I248.pdf.

[98] H. Danso, D.B. Martinson, M. Ali, J.B. Williams, Physical, mechanical and durability properties of soil building blocks reinforced with natural fibres, Construction and Building Materials 101 (2015) 797-809. https://doi.org/10.1016/j.conbuildmat.2015.10.069.

[99] J. Khedari, P. Watsanasathaporn, J. Hirunlabh, Development of fibre-based soil–cement block with low thermal conductivity, Cement and Concrete Composites 27 (2005) 111-116. https://doi.org/10.1016/j.cemconcomp.2004.02.042.

[100] K. Thanushan, Y. Yogananth, P. Sangeeth, J.G. Coonghe, N. Sathiparan, Strength and Durability Characteristics of Coconut Fibre Reinforced Earth Cement Blocks, Journal of Natural Fibers 18(6) (2019) 773-788. https://doi.org/10.1080/15440478.2019.1652220.

[101] S. Sangma, L. Pohti, D.D. Tripura, Size Effect of Fiber on Mechanical Properties of Mud Earth Blocks, Recycled Waste Materials, Springer Singapore, 2019, pp. 119-125. https://doi.org/10.1007/978-981-13-7017-5_14.

[102] H. Purnomo, S.W. Arini, Experimental Evaluation of Three Different Humidity Conditions to Physical and Mechanical Properties of Three Different Mixtures of Unfired Soil Bricks, Makara Journal of Technology 23(2) (2019) 92-102. https://doi.org/10.7454/mst.v23i2.3583.

[103] G.L. Sivakumar Babu, A.K. Vasudevan, Strength and Stiffness Response of Coir Fiber-Reinforced Tropical Soil, Journal of Materials in Civil Engineering 20(9) (2008) 571-577. https://doi.org/10.1061/(ASCE)0899-1561(2008)20:9(571).

[104] R.R. Singh, E.S. Mittal, Improvement of Local Subgrade Soil for Road Construction by the Use of Coconut Coir Fiber, International Journal of Research in Engineering and Technology 3(5) (2014) 707-711. https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.673.9620&rep=rep1&type=pdf#:~:text=Adding%20of%20coconut%20coir%20fiber,the%20soil%20to%20ductile%20behavior.

[105] S.M. Lakshmi, S. Sasikala, V. Padmavathi, S. Priya, V. Saranya, Utilization of Coconut Coir Fibre For Improving Subgrade Strength Characteristics Of Clayey Sand, International Jurnal of Inovative Research in Science Engineering and Technology 5(4) (2018) 2873-2878. https://www.irjet.net/archives/V5/i4/IRJET-V5I4635.pdf.

[106] ASTM D698, Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lbf/ft3 (600 kN-m/m3)), ASTM International (ASTM), West Conshohocken, PA, 2012.

[107] BS 1377-2, Methods of test for soils for civil engineering purposes, Part 2: Classification Tests, British Standards Institution, London, 1990.

[108] S. Horisawa, M. Sunagawa, Y. Tamai, Y. Matsuoka, T. Miura, M. Terazawa, Biodegradation of nonlignocellulosic substances II: physical and chemical properties of sawdust before and after use as artificial soil, Journal of Wood Science 45 (1999) 492-497. https://jwoodscience.springeropen.com/track/pdf/10.1007/BF00538959.pdf.

[109] BS EN 1097-6, Tests for mechanical and physical properties of aggregates, Determination of particle density and water absorption, British Standards Institution, London, 2013.

[110] ASTM D422-63, Standard Test Method for Particle-Size Analysis of Soils, ASTM International (ASTM), West Conshohocken, PA, 2002.

[111] B.H. Ngayakamo, A. Bello, A.P. Onwualu, Development of eco-friendly fired clay bricks incorporated with granite and eggshell wastes, Environmental Challenges 1 (2020) 100006. https://doi.org/10.1016/j.envc.2020.100006.

[112] BS EN 1015-11, Methods of test for mortar for masonry. Part 11: Determination of flexural and compressive strength of hardened mortar, British Standards Institution, London, 2019.

[113] BS EN 771-1, Specification for masonry units. Part 1: Clay masonry units, British Standards Institution, London, 2003.

[114] BS EN 772-14, Methods of test for masonry units. Part 14: Determination of moisture movement of aggregate concrete and manufactured stone masonry units, British Standards Institution, London, 2002.

[115] BS EN 1015-18, Methods of test for mortar for masonry, Part 18: Determination of water absorption coefficient due to capillary action of hardened mortar, British Standards Institution, London, 2002.

[116] A. Ndagi, A.A. Umar, F. Hejazi, M.S. Jaafar, Non-destructive assessment of concrete deterioration by ultrasonic pulse velocity: A review, IOP Conference Series: Earth and Environmental Science 357 (2019) 012015. https://doi.org/10.1088/1755-1315/357/1/012015.

[117] NZS 4298, Materials and Workmanship of Earth Buildings, Standard New Zealand, New Zealand, 1998.

[118] G.J. Frencham, The Performance of Earth Buildings, Deakin University, School of Architecture, Geelong, Australia, 1982.

[119] K.A. Heathcote, Durability of earthwall buildings, Construction and building materials 9(3) (1995) 185-189. https://doi.org/10.1016/0950-0618(95)00035-E.

[120] K.A. Heathcote, An investigation into the erodibility of earth wall units, University of Sydney, 2002. https://opus.cloud.lib.uts.edu.au/bitstream/10453/20153/2020/02Whole.pdf.

[121] P. Walker, R. Keable, J. Martin, V. Maniatidis, Rammed earth: design and construction guidelines,

BRE Bookshop (2005). https://www.brebookshop.com/samples/148940.pdf.

[122] IS: 1725, Specification for Soil Based Blocks Used in General Building Construction, Bureau of Indian Standards, New Delhi, 1982.

[123] SLS 1382, Specification for Compressed Stabilized Earth Blocks, Sri Lanka Standards Institution, Colombo, Sri Lanka, 2009.

[124] H. Limami, I. Manssouri, K. Cherkaoui, A. Khaldoun, Mechanical and physicochemical performances of reinforced unfired clay bricks with recycled Typha-fibers waste as a construction material additive, Cleaner Engineering and Technology 2 (2021) 100037. https://doi.org/10.1016/j.clet.2020.100037.

[125] B.K. Baiden, C. Asante, Effects of orientation and compaction methods of manufacture on strength properties of sandcrete blocks, Construction and Building Materials 18(10) (2004) 717-725. https://doi.org/10.1016/j.conbuildmat.2004.04.032.

[126] H. Danso, Influence of Compacting Rate on the Properties of Compressed Earth Blocks, Advances in Materials Science and Engineering 2016 (2016) 8780368. https://doi.org/10.1155/2016/8780368.

[127] S. Parveen, S. Rana, R. Fangueiro, Macro-and nanodimensional plant fiber reinforcements for cementitious composites, Sustainable and Nonconventional Construction Materials using Inorganic Bonded Fiber Composites, Woodhead Publishing, Cambridge, UK, 2017, pp. 343-382. https://doi.org/10.1016/B978-0-08-102001-2.00020-6.

[128] İ. Türkmen, E. Ekinci, F. Kantarcı, T. Sarıcı, The mechanical and physical properties of unfired earth bricks stabilized with gypsum and Elazığ Ferrochrome slag, International Journal of Sustainable Built Environment 6(2) (2017) 565-573. https://doi.org/10.1016/j.ijsbe.2017.12.003.

[129] M. Bouhicha, F. Aouissi, S. Kenai, Performance of composite soil reinforced with barley straw, Cement and Concrete Composites 27(5) (2005) 617-621. https://doi.org/10.1016/j.cemconcomp.2004.09.013.

[130] C.G. Murillo, P.J. Walker, M.P. Ansell, Henequen fibres for reinforcement of unfired earth blocks, Proceedings of the Eleventh International Conference for Renewable Resources and Plant Biotechnology (NAROSSA), January 1, Poznan, Poland, 2005. https://www.researchgate.net/publication/259800546_Henequen_fibres_for_reinforcement_of_unfired_earth_blocks.

[131] S. Bhuvaneswari, T. Thyagaraj, R. Robinson, S. Gandhi, Alternative technique to induce faster lime stabilization reaction in deeper expansive strata, Proceedings of Indian Geotechnical Conference–2010, GEOtrendz, December 16–18, Mumbai, India, 2010, pp. 609-612. https://gndec.ac.in/~igs/ldh/conf/2010/articles/t034.pdf.

[132] P.V. Sivapullaiah, A.K. Jha, Gypsum Induced Strength Behaviour of Fly Ash-Lime Stabilized Expansive Soil, Geotechnical and Geological Engineering 32(5) (2014) 1261-1273. https://doi.org/10.1007/s10706-014-9799-7.

[133] A.K. Jha, P.V. Sivapullaiah, Mechanism of improvement in the strength and volume change behavior of lime stabilized soil, Engineering Geology 198 (2015) 53-64. https://doi.org/10.1016/j.enggeo.2015.08.020.

[134] M.M. Salih, A.I. Osofero, M.S. Imbabi, Critical review of recent development in fiber reinforced adobe bricks for sustainable construction, Frontiers of Structural and Civil Engineering 14(4) (2020) 839-854. https://doi.org/10.1007/s11709-020-0630-7.

[135] TS 2514, Adobe Blocks and Production Methods [in Turkish], Turkish Standards Institute, Ankara, Turkey, 1977.

[136] CID-GCBNMBC-91-1, New Mexico Adobe and Rammed Earth Building Code, General Construction Bureau, Regulation & Licensing Department, Santa Fe, New Mexico, 1991.

[137] ASTM C618-9, Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete, American Society of Testing and Materials, West Conshohocken, PA, 2005.

[138] V.G. Papadakis, S. Tsimas, Supplementary cementing materials in concrete: Part I: efficiency and design, Cement and Concrete Research 32(10) (2002) 1525-1532, https://doi.org/10.1016/S0008-8846(02)00827-X.

[139] Y. Millogo, M. Hajjaji, R. Ouedraogo, Microstructure and physical properties of lime-clayey adobe bricks, Construction and Building Materials 22(12) (2008) 2386-2392. https://doi.org/10.1016/j.conbuildmat.2007.09.002.

[140] A.S. Muntohar, Engineering characteristics of the compressed-stabilized earth brick, Construction and Building Materials 25(11) (2011) 4215-4220. https://doi.org/10.1016/j.conbuildmat.2011.04.061.

[141] K. Ghavami, R.D. Toledo Filho, N.P. Barbosa, Behaviour of composite soil reinforced with natural fibres, Cement and Concrete Composites 21(1) (1999) 39-48. https://doi.org/10.1016/S0958-9465(98)00033-X.

[142] S.M. Hejazi, M. Sheikhzadeh, S.M. Abtahi, A. Zadhoush, A simple review of soil reinforcement by using natural and synthetic fibers, Construction and building materials 30 (2012) 100-116. https://doi.org/10.1016/j.conbuildmat.2011.11.045.

[143] Z. Wang, C. Zhao, Y. Zhang, B. Hua, X. Lu, Study on Strength Characteristics of Straw (EPS Particles)-Sparse Sludge Unburned Brick, IOP Conference Series: Materials Science and Engineering 490(3) (2019) 032005. https://doi.org/10.1088/1757-899X/490/3/032005.

[144] K.A. Harries, B. Sharma, Nonconventional and vernacular construction materials: Characterisation, properties and applications, first ed., Woodhead Publishing, Cambridge, UK, 2016.

[145] J. Lu, K. Wang, M.-L. Qu, Experimental determination on the capillary water absorption coefficient of porous building materials: A comparison between the intermittent and continuous absorption tests, Journal of Building Engineering 28 (2020) 101091. https://doi.org/10.1016/j.jobe.2019.101091.

[146] H. Danso, D.B. Martinson, M. Ali, J.B. Williams, Mechanisms by which the inclusion of natural fibres enhance the properties of soil blocks for construction, Journal of Composite Materials 51(27) (2017) 3835-3845. https://doi.org/10.1177/0021998317693293.

[147] B. Taallah, A. Guettala, S. Guettala, A. Kriker, Mechanical properties and hygroscopicity behavior of compressed earth block filled by date palm fibers, Construction and Building Materials 59 (2014) 161-168. https://doi.org/10.1016/j.conbuildmat.2014.02.058.

[148] M. Ouedraogo, K. Dao, Y. Millogo, J.-E. Aubert, A. Messan, M. Seynou, L. Zerbo, M. Gomina, Physical, thermal and mechanical properties of adobes stabilized with fonio (*Digitaria exilis*) straw, Journal of Building Engineering 23 (2019) 250-258. https://doi.org/10.1016/j.jobe.2019.02.005.

[149] M.C.N. Villamizar, V.S. Araque, C.A.R. Reyes, R.S. Silva, Effect of the addition of coal-ash and cassava peels on the engineering properties of compressed earth blocks, Construction and Building Materials 36 (2012) 276-286. https://doi.org/10.1016/j.conbuildmat.2012.04.056.

[150] V. Sharma, B.M. Marwaha, H.K. Vinayak, Enhancing durability of adobe by natural reinforcement for propagating sustainable mud housing, International Journal of Sustainable Built Environment 5(1) (2016) 141-155. https://doi.org/10.1016/j.ijsbe.2016.03.004.

[151] C. Galán-Marín, C. Rivera-Gómez, F. Bradley, Ultrasonic, Molecular and Mechanical Testing Diagnostics in Natural Fibre Reinforced, Polymer-Stabilized Earth Blocks, International Journal of Polymer Science 2013 (2013) 130582. https://doi.org/10.1155/2013/130582.

[152] G. Araya-Letelier, J. Concha-Riedel, F.C. Antico, C. Valdés, G. Cáceres, Influence of natural fiber dosage and length on adobe mixes damage-mechanical behavior, Construction and Building Materials 174 (2018) 645-655. https://doi.org/10.1016/j.conbuildmat.2018.04.151.

[153] J.J. Martín-del-Rio, J. Canivell, R.M. Falcon, The use of non-destructive testing to evaluate the compressive strength of a lime-stabilised rammed-earth wall: Rebound index and ultrasonic pulse velocity, Construction and Building Materials 242 (2020) 118060. https://doi.org/10.1016/j.conbuildmat.2020.118060.

[154] R. Abid, N. Kamoun, F. Jamoussi, H. El Feki, Fabrication and properties of compressed earth brick from local Tunisian raw materials, Boletín de la Sociedad Española de Cerámica y Vidrio (2021). https://doi.org/10.1016/j.bsecv.2021.02.001.

[155] A. Laborel-Préneron, P. Faria, J.-E. Aubert, C. Magniont, Assessment of Durability of Bio-based Earth Composites, Recent Progress in Materials 3(2) (2021) 23. https://doi.org/10.21926/rpm.2102016.

[156] E. Obonyo, J. Exelbirt, M. Baskaran, Durability of Compressed Earth Bricks: Assessing Erosion Resistance Using the Modified Spray Testing, Sustainability 2(12) (2010) 3639-3649. https://doi.org/10.3390/su2123639.

[157] I.I. Akinwumi, A.H. Domo-Spiff, A. Salami, Marine plastic pollution and affordable housing challenge: Shredded waste plastic stabilized soil for producing compressed earth bricks, Case Studies in Construction Materials 11 (2019) e00241. https://doi.org/10.1016/j.cscm.2019.e00241.