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Engineering properties and microstructure of a sustainable roof tile manufactured with waste rice husk ash and ceramic sludge addition

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ABSTRACT

Clay replacement with waste rice husk ash (RHA) and ceramic sludge (CS), helps to reduce the consumption of natural clay and solves the ecological issues created by waste disposal. In this study, properties of waste RHA and CS added fired clay tile were investigated, focusing on structural, durability, thermal performance as well as the water quality of the harvested run-off from fired clay roof tiles manufactured in an industrial scale plant. Tiles were cast by clay replacement with waste RHA and CS in four mixtures: 10 %RHA and 0 % CS, 10 % RHA and 10 % CS, 10 % RHA and 15 % CS, and 10 % RHA and 20 % CS (by weight). For 10 %RHA and 10 %CS tiles, dry mass was reduced by 4.9 %, compared with conventional roof tiles, promising a light weight roof tile. Roof tiles with 10 % RHA and 10 %CS showed a transverse breaking load of 1519 N, whereas that of 20 %CS tiles showed 1427 N, indicating that a further 6.5 % strength improvement can be achieved with clay replacement with a combination of two waste materials. Clay replacement with 10 % RHA and 10 % CS resulted in water absorption of 15.25 %. When increasing the clay replacement with combined waste from 10% (10 %RHA and 0%CS) to 30 % (10%RHA and 20 %CS), weight gain due to acid and alkaline attacks reduced from 3.5% to 3.0%, and from 2.2 % to 1.6 %, respectively, indicating enhanced durability performance by incorporating combined waste. High porosity, also confirmed by SEM, contributed to enhanced thermal performance: tile with 10 % RHA and 10 % CS achieved 4.4 °C temperature reduction, compared to the conventional tile. pH value and total solid concentration of run-off water were in the range of recommended values of water for agricultural purposes, ensuring that the collected run-off can be utilized as an alternative water source for potable activities.

1. Introduction

Population expansion and rapid urbanization requires many of dwelling units, which has increased the demand for construction materials [1]. Construction material cost is about 60 % of total cost of building [2]. For decades, clay is the most popular construction material that extracted from top soil for casting clay bricks and clay tiles. However, clay extraction depletes natural clay resources [3],

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which are naturally fertilized virgin soils that can be used for farming. Increases in consumption and limitations on the extraction of natural clay from earth have demonstrated an imperative need to identify natural or synthetic alternative materials to clay.

Clay has been replaced with waste materials, which have helped to reduce the consumption of natural clay and solve the ecological issues created by waste disposal. For example, in brick production, clay was replaced with waste rice husk ash by 4 % [4], waste sugarcane bagasse by 5 % [3], rice husk ashes by 5 % [3], industrial ceramic sludge by 20–40 % [5,6]. In floor tile production, clay was replaced with sewerage sludge by 7 % [7]. For roof tile production, clay was replaced with waste RHA by 10 % [8], ceramic sludge by 20 % [9], sewage sludge by 4 % [10], rock dust by 40 % [11], glass waste by 10 % [12], and granite waste by 40 % [13]. However, in previous studies [3–13], investigations were focused on clay replacement with single waste material.

Clay replacement with combined waste materials has been studied; however, most of the focus has been on clay brick production. For example, brick clay was replaced with 4 % fly ash (FA) and 4 % glass cullet (GC) [14], 40 % water treatment sludge (WTS) and 40% fired clay brick waste (BW) [15], 5 % paper mill sludge (PMS) and 15 % carbonation sludge (CS) [16]. Clay replacement with combined waste has shown several positive effects: increased level of clay replacements [15], lighter weight and greater porosity of the bricks [16], as well as improved strength and insulation properties [15,16]. Besides these positive effects, no attempt has been made to investigate properties of fired clay roof tiles manufactured with waste RHA and CS. In the current study, investigations on engineering properties and micro structure of waste RHA and ceramic sludge added clay roof tile are desired.

Waste RHA and ceramic sludge (CS) are by-products from wide range of industrial activities that significantly affect the environment because there are no specific measures to utilize them. In Sri Lanka, there is an annual production of 60,000 tons of CS [9]; has more than 50 % (by weight) of silico-aluminous based components [17]. Fired clay roof tile production has attracted CS [9], transforming this residual into a secondary raw material, while providing a solution to the disposal problem of industrial ceramic sludge. On the other hand, Sri Lanka is the 18th highest paddy production country, where annual rice production is found to be 2, 794,000 tons [18], and 279,400 tons of rice husks are processed annually, in rice milling industry. In Sri Lanka, rice husk is popular as a fuel for brick burning in kilns, making a sustainable energy practice. However, waste RHA is accumulating in landfills and contaminating water bodies [19–21], without being properly utilized. Considering the amount of rice production, efficient utilization of waste RHA is required. The characteristics of waste RHA is very promising: it has unusually high in amorphous silica [8,22,23], a large external surface area [22,24]. Waste RHA is lightweight and has a highly porous nature [22,24].

Clay replacement with waste RHA and CS can effect on roof tile properties, although combined waste RHA and CS can enhance the amount of waste utilization. During the firing of clay products, due to sintering, glassy bonds are forming with minerals and materials present in the mixture. The firing process is mainly required to transform the porous and weak dried clay into strong, dense clay products [25,26]. During the firing process, several reactions and transformations occur, which govern the final properties of ceramic products [27]. Adding combined waste into the tile will affect tile properties, which cannot be predicted from the properties of single waste added to a clay roof tile. Therefore, investigations of properties of waste RHA and CS added clay roof tiles are desired in this study.

Improved sustainability of clay based materials can be achieved by utilizing low cost materials focusing on enhanced strength and durability properties [28]. The enhanced strength, when waste is added to clay roof tiles, has often been reported, e.g. 46 % strength improvement was found with 10 % RHA [8] and 23 % strength improvement was found with 20 % CS [9]. However, not only the enhanced structural performance but also the enhanced thermal and run-off qualities of the roof tiles are an imperative need, in terms of sustainability.

Sustainable roof tiles should minimize the negative effects on occupants due to the heat from direct sunlight [29,30] and negative effect on the environment by adding pollutants into water bodies through run-off [8,9]. The large surface area of roofs, orientated directly facing the sky, contribute to the generation of a significant heat load from the roofing materials, affecting the indoor thermal environment [29] and, consequently, the energy demand for the occupant's thermal comfort. Over 40 % of global energy is consumed by the building sectors, [31]. Reduced energy consumption for thermally comfortable indoor environment is promising with a porous material: a 50 % increase in porosity reduces the thermal conductivity by 30 % in clay bricks [32]. A porous roof tile with improved thermal performances is promising with replacing finer clay particles with coarser waste RHA [8] and coarser CS [9] particles in the tile clay mixture.

Runoff water flowing, along the roof, is inevitable in an urban environment. In urban areas, roofs act as primary collectors of storm water pollutants [33]; roof surfaces in urban areas are efficient catchment surfaces for the deposition of fine particles, which can travel several miles along with the storm water [8]. By the year 2030, 47 % of the world's population may face to severe water scarcity [34]; threatening global water shortage is exacerbated by global warming. Rainwater harvesting could be a suitable practice and a popular way of addressing water scarcity due to the frequent summer droughts that are expected, even in developed countries.

Previous investigations on clay based products are mostly limited to developments at a laboratory scale, and are often found to have improved properties. Despite these positive performances, these findings have not been applied to the mass scale production in industry. More experiences for scaling up to the mass scale utilization of waste with enhanced tile properties, stimulate the transferring from a linear to a circular economy, while answering to managing natural clay. Investigation into the properties of locally manufactured clay roof tiles, where the industrial procedures, involved in shaping and firing are applied, will promote the use of finite natural resources together with industrial waste, closing the cycles of the products.

The thermal performance of roof tiles and the water quality of run-off are rarely reported [8,9] although these properties have greatly influence on occupants' comfort, health and safety. Investigation of these performances, together with structural and durability performance is an imperative need, to characterize the sustainability of clay roof tiles. In this study, engineering properties and micro-structure of fired clay roof tiles manufactured in an industrial scale plant are investigated.

2. Methodology

The method of conducting this research is summarized in Fig. 1.

2.1. Collecting raw materials

Clay tile was cast with three materials: Clay, Ceramic sludge (CS) and Waste rice husk ash (RHA). Clay was collected from Waikkal in the Puttalum district while CS was collected from ceramic product manufacturing company located at Dankotuwa in the Puttalum district. Waste RHA was collected from a brick kiln located at Mirissa in the Matara district.

2.2. Mix proportions

Four mix proportions (Table 1) were used for casting tiles. These mix proportions were selected based on the previous literature for waste RHA incorporated roof tiles [8] and CS incorporated roof tiles [9]. De Silva and Surangi (2017) [8] found that 10 % clay can be replaced with waste RHA, while achieving 46 % strength improvement comparing to the conventional tiles. De Silva and Mallwattha (2018) [9] found that 15 % of clay can be replaced with CS, while enhancing strength and durability performances of the roof tiles. Therefore, in the current study, 10 % clay was replaced with waste RHA. Further clay replacement was performed with ceramic sludge (by 10 %, 15 % and 20 %) to determine the effect of combined waste RHA and CS on the tile performances.

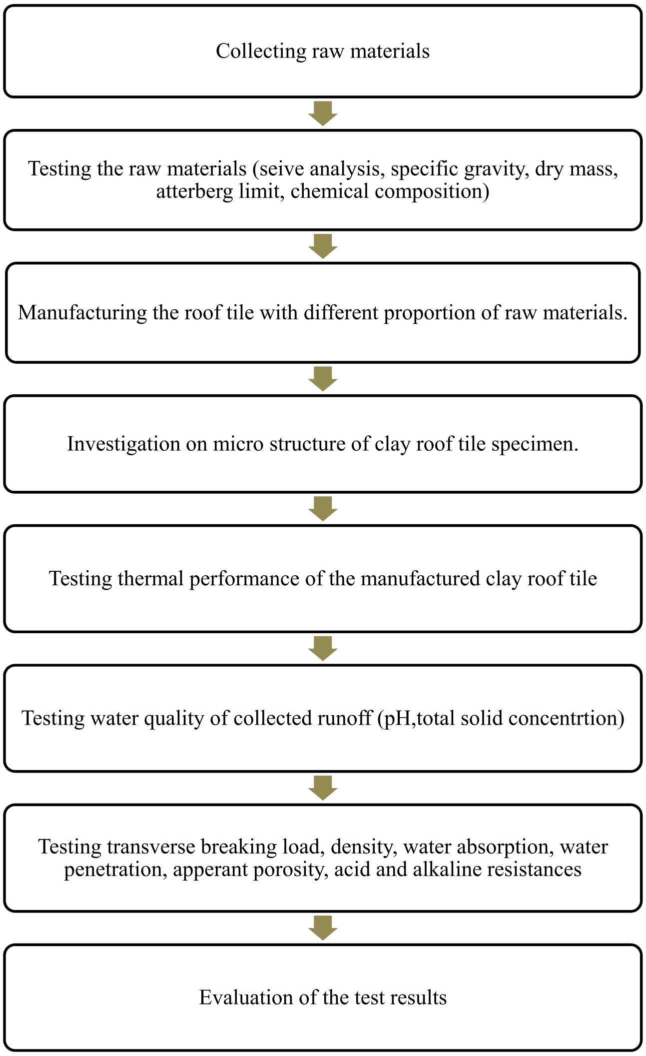

Fig. 1. Flow chart of methodology.

Table 1
Mix proportion of roof tile samples (% by weight).

Sample number	RHA (%)	Ceramic Sludge (%)	Laterite Clay (%)
Mixture 1 *Control tile* 10 % RHA 0 %CS	10	0	90
Mixture 2 (10 % RHA 10 %CS)	10	10	80
Mixture 3 (10 % RHA 15 %CS)		15	75
Mixture 4 (10 % RHA 20 %CS)		20	70

2.3. Properties of raw materials and mixtures

Laboratory experiments were performed to determine physical and chemical properties of the raw material. XRF was performed on the clay, waste RHA and CS used for the study. The particle size distribution of raw materials was investigated as per ASTM D422 [35]. Atterberg limit tests were conducted as per ASTM D4318 [36].

X-ray fluorescence (XRF) was conducted as per the method in [37]. X-ray diffraction (XRD) was conducted by using Rigaku Ultima IV as per the process explained in [22]. Carl zeiss evols 15 was used to conduct SEM. The specific gravity of waste RHA was determined, as described in ASTM C188 [38], while the specific gravity of clay and ceramic sludge was determined as in ASTM D854 [39]. The fineness of raw materials was determined as per ASTM C184 [40].

2.4. Tile preparation

The tiles were cast in a tile manufacturing factory situated in Lunuwilla, Puttalam. Tile preparation method was as same as the procedure described in previous studies [8,9]. First, raw materials were trampled manually. Further mixing was done by using a machine to achieve the mixture was ground and well mixed. The mixture was excreted into cuboidal shaped plates and then they were pressed by an electrical machine. The wet tiles, which were placed on a wooden plate, were subjected to natural drying process, before firing in a kiln.

2.5. Roof tile testing

The manufactured tiles were tested to study the strength properties (transverse breaking load, dry mass), durability properties (water absorption, water penetration, apparent porosity, acid and alkaline resistance), thermal properties, water quality of the runoff (pH and total solid concentration) and micro structure analysis.

2.5.1. Transverse breaking load and dry mass

Transverse breaking load and dry mass were determined as per ASTM C1167 [41] and ASTM C 67 [42], respectively. The manufactured tiles were tested in a horizontal plane for a three-point bending mode using a universal testing machine (INSTRON 600DX) (Fig. 2(a)).

2.5.2. Water absorption, water penetration and apparent porosity

Water absorption and apparent porosity were performed as per ASTM C 67 [42] and ASTM C 20 [43], respectively.

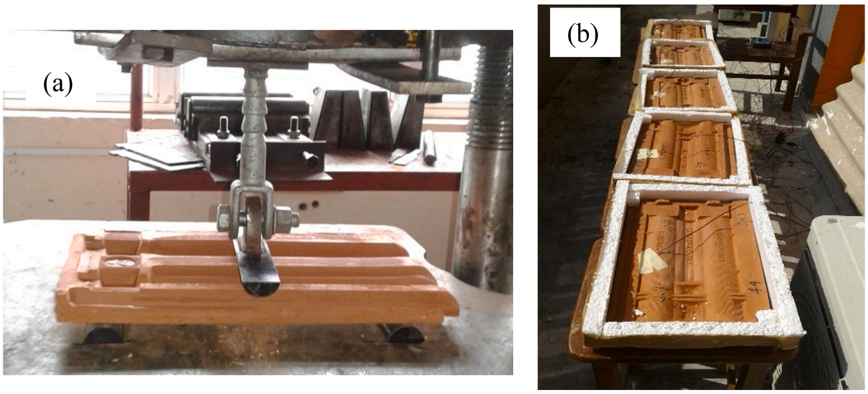

Fig. 2. Experimental set-up for (a) measuring transverse breaking load (b) monitoring thermal performance.

The water penetration test was carried out in a rectangular trough with an open at the bottom, similar to the method presented in [8,9]. Roof tiles were fixed to the bottom of the trough. Water tight sealant were plugged in the space between the tile specimen and the trough. Water was poured for 50 mm above the roof tile and the water in the trough was allowed to remain for 48 h allowing the water penetration to be visually inspected.

2.5.3. Acid and alkaline resistance

Sulphuric acid solution was prepared by adding distilled water in the ratio of 1:7 (Acid: water). Three specimens (50 mm × 50 mm) were cut from the relevant samples without cracking the tile. Then the cut specimens were weighed (W_i) and immersed in the acid solution at room temperature for 10 days. The specimens were dried in an oven at 100^0 C for 16 h and later the specimens were cooled. Then the specimens were washed with water, dried in an oven, and weighed (W_f), as per the procedure explained by the Bureau of Indian standards [44].

$$\text{Weight } increase = \frac{Wf - Wi}{Wi} \tag{1}$$

The tile specimens were weighed and kept immersed in 3.5 % sodium chloride for 28 days and the evaporation was avoided by closing the tank. The specimens were taken out, kept on wire mesh to drain and then weighed. Percentage of weight increase was determined using Eq. 1.

2.5.4. Thermal performance

Thermal performance of the clay roof tiles was analysed by using the setup developed by [9] (Fig. 2(b)). An insulating material was used to cover the all sides of the tiles specimens except the top surface. Saw dust was used to fill in the gap between the tile and the insulating material to prevent transferring heat from the sides other than the top surface. For each tile, two thermocouples were placed; one at the top surface; other one at the bottom surfaces. There were eight number of type K thermocouples, connected to a heat flow data logger (LR 8432), to monitor the temperature simultaneously for four tiles: a conventional tile and three waste added tiles. The specimens were placed in the sun and temperature readings were recorded for 10 sunny hours in 10 min intervals. For each tile, the temperature of the bottom surface was compared with that of the conventional tile.

2.5.5. Water quality of run-off water

The runoff water was collected by exposing the roof tiles to the rain. The runoff water through four different types of roof tiles and rain water were collected using the experimental set up shown in Fig. 3. The procedure was repeated for three rainy days which had at least two dry days in between. The runoff water was analysed for water quality parameters: pH value and total solid concentration as per ASTM D 5907 [45].

2.5.6. Statistical analysis

If the waste content level had a statistically significant effect on tile properties was investigated by conducting analysis of variance (ANOVA). The F test in the ANOVA analysis determined whether the differences between the' mean values of load- extension curves and temperature of the tiles had been significantly affected by the level of waste content.

Fig. 3. Roof structure to collect runoff water.

3. Results and discussion

3.1. Raw materials and mixtures

3.1.1. Particle size distribution

Fig. 4 compares the particle size distribution of raw materials. From No 200 sieve (0.075 mico-meter), the passing percentage of waste RHA, CS and clay were 10 %, 60 % and 75 %, respectively, indicating that clay are finer than other two materials. Clay consists of large number of micro particles which would help the effective mixing of the raw materials. The particle size distribution of soil used in the manufacturing of ceramic products is very important to the strength gain during firing, which would affect the product's durability [3].

3.1.2. Specific gravity and bulk density

Specific gravity of waste RHA, CS and clay were found to be 2.08, 2.24, and 2.50, respectively (Table 2), aligning with the previously reported values of 2.11 [3,46] and 2.06 [47] for RHA, and 2.23 [9] for CS. A bulk density of 337, 1277, and 1295 kg/m^{3,} were found for waste RHA, CS and clay, respectively, which was similar to the values reported previously: 339 kg/m^3 for waste RHA [8], 1198 kg/m^3 for CS and 1312 kg/m^3 for clay [6]. Among the raw materials used to produce the roof tile, waste RHA had the lowest bulk density, while CS had the bulk density less than that of the clay. CS and waste RHA, which have been used as clay replacements, had lower specific gravity and bulk density compared to clay, promising a light weight fired clay roof tile. The light weight roof tiles reduce the total load on the roof structure and make the tiles for easy handling, subsequently reducing material and labor costs in construction.

3.1.3. Chemical composition

Table 2 compares the chemical compositions of raw materials. Waste RHA mainly comprised SiO_2 (84.14 %), along with a discrete amount of other oxides such as Al_2O_3 (4.08 %), Fe_2O_3 (1.15 %). The summation of $SiO_{2,}$ Al_2O_3 and Fe_2O_3 was greater than 70 %, satisfies ASTM C618 [48], proving that waste RHA is a pozzolan material. The XRD pattern of the waste RHA showed a broad halo at around 22^0 two theta angle (Fig. 5(a)), proving that the silica presence in waste RHA is in the amorphous form.

Clay material comprised SiO_2 of 61.99 %, Al_2O_3 of 17.98 %, and Fe_2O_3 of 6.03 %, whereas CS had SiO_2 of 66.83 %, Al_2O_3 of 16.84 % and Fe_2O_3 of 1.06 %, along with a discrete amount of other oxides(Na_2O, K_2O, and SO_3). SiO_2 content was observed to be higher for ceramic sludge and waste RHA compared to laterite clay, which may contribute to strength gain in combined waste added clay roof tiles. The mineralogical content of CS determined from XRD are shown in Fig. 5(b). Quartz, calcite and mullite were observed as the main mineral phases in CS (Fig. 5(b)).

3.1.4. Atterberg limits

Atterberg limits varied with varying waste content in the mixtures as shown in Table 3. Liquid limit of mixture without any CS was 66 %, while the liquid limit decreased from 66 % to 54 % with increasing CS content from 10 % to 20 % at 10 % waste RHA. Liquid limit means the flow of clay mixture in the presence of water. Clay content in the soil influences the liquid limit and the plastic limit of the mixture.The increment of more active particle would decrease the size of micro scales and the flow has been controlled, resulting to the reduction of the liquid limit. Plastic limit shows an increment with the addition ceramic sludge at 10 % RHA, possibly due to the mica (silicate minerals) content in the mixture: Liquid and plastic limits exhibited a linear, monotonically increasing trend with increase in mica content [49], as a result, plasticity index decreases with increasing CS content. Variations in the liquid limits and plastic limits in the current study confirm to the limits found for waste RHA added clay roof tile mixtures [8] and CS added clay roof tile mixtures [9].

Linear shrinkage was reduced from 2.90 % to 2.79 % with the addition of waste RHA and CS, aligning with the results obtained previously in [8,9]. Lower shrinkage would reduce the cracking, warping and other defects which would reduce the durability in the roof tile.

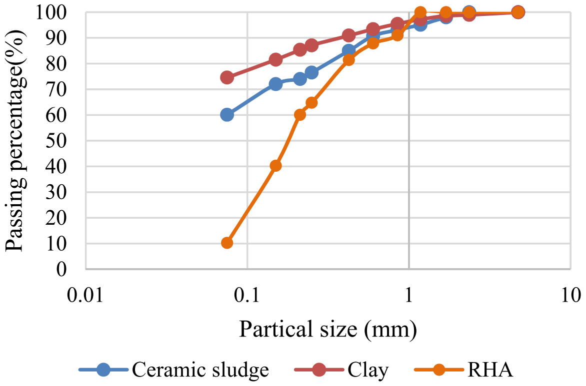

Fig. 4. Distribution of particle sizes of raw materials.

Table 2
Physical properties and chemical composition of raw materials.

Property	Waste RHA	CS	Laterite clay
Physical properties			
Finesse modulus	1.72	1.05	0.41
Specific gravity	2.08	2.24	2.50
Bulk density (kg/m^3)	336.9	1276.8	1294.5
Chemical composition			
SiO_2 (%)	84.14	66.83	61.99
Al_2O_3(%)	4.08	16.84	17.98
Fe_2O_3(%)	1.15	1.06	6.03
CaO(%)	0.97	2.08	1.78
MgO(%)	0.44	1.83	0.54
SO_3(%)	0.05	0.08	0.04
K_2O(%)	1.34	1.52	1.87
Na_2O(%)	1.69	0.55	1.36
LOI(%)	6.13	9.2	8.40

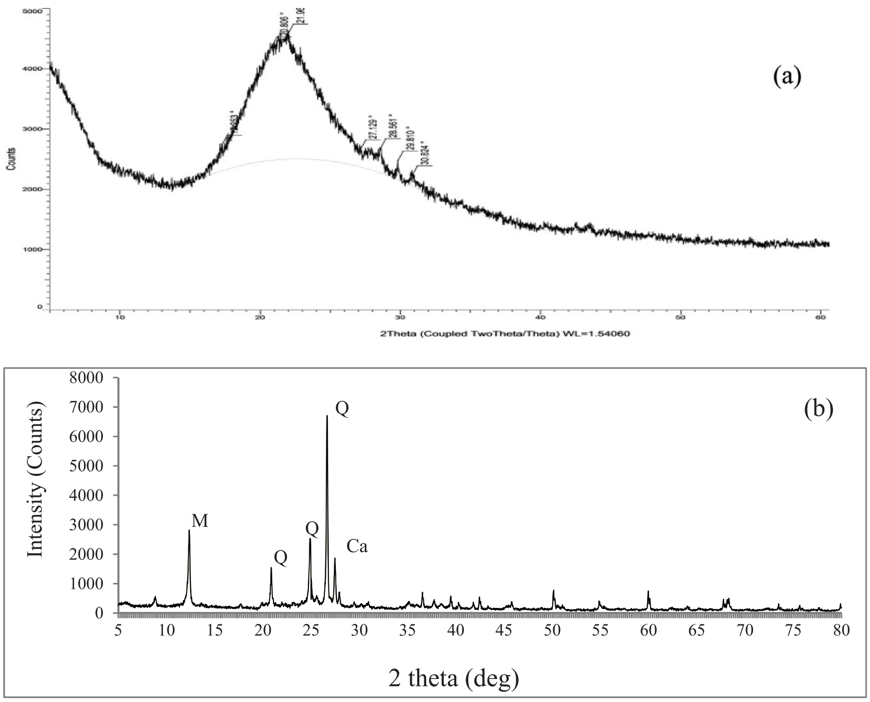

Fig. 5. XRD patterns of raw materials: (a) Waste RHA (b) CS, Q: quartz, Ca: calcite, M; mullite.

Table 3
Atterberg limits of mixtures.

Sample number	Liquid limit	Plastic limit	Linear shrinkage	Plasticity index
Control tile mixture				
10 % RHA 0 %CS	66	33	2.9	33
Waste added tile mixture				
10 % RHA 10 %CS	59	38	3.07	21
10 % RHA 15 %CS	57	42	2.93	15
10 % RHA 20 %CS	54	40	2.79	14

3.2. Fired clay roof tile properties

3.2.1. Structural properties

3.2.1.1. Transverse breaking load. Fig. 6 shows load–extension curves for tiles 10 % RHA and four different CS proportions. The

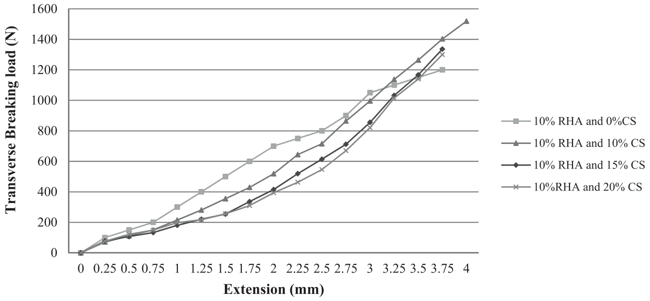

Fig. 6. Transverse breaking load of different mixtures.

transverse breaking strength of the tile was significantly affected by the clay replacement with waste RHA and CS (*p* value of the F-test 0.000 < 0.05). Maximum transverse breaking load of 1519 N was obtained for Mixture 2 (10 %RHA and 10 %CS) showing 26. 6% strength improvement by compared with 10 % RHA and 0 % CS. High amount of amorphous SiO_2 presence in RHA, and inert particles in the ceramic sludge may have contributed to the strength gain. Tile strength was increased with the clay replacement by high amount of amorphous SiO_2 presence in RHA [8], as well as with clay replacement by CS [9]. With 20 % clay replacement by combinations of two materials (i.e., 10 %RHA and 10 %CS), the transvers breaking load was 1519 N whereas with a single material of 20 % CS or 20 % waste RHA, it was 1427 N [9] and 622 N [8], respectively. This indicates that with 10 % RHA and 10 % CS, there was a further 6.5 % strength improvement, compared to 20 % CS achieved by clay replacement with combined two materials. Increased transverse loading was probably attributed by the strong bonding reflected in the uniformity of the matrix morphology and less cracking tendencies confirmed in SEM (Fig. 8(b)). Nevertheless, with 10 % RHA a large amount of CS addition to clay is not desired, similar to that observed in [9]. All tiles had a transverse breaking load greater than 890 N, satisfying the minimum requirement for type III roof tile as defined by ASTM C 1167 [41].

Linear behavior of the tile can be observed up to about 65 % of the ultimate failure load; beyond that, nonlinear behavior can be observed (Fig. 6). With an overall 20 % clay replacement (10 % by waste RHA and 10 % by CS), increased breaking load can be observed.

3.2.1.2. Dry mass. The replacement of clay with RHA and CS reduces the dry mass of the tile specimens, compared to the control tile specimen (10 % RHA and 0 % CS) (Fig. 7). This reduction of the dry mass with clay replacement by waste was statistically significant (*p* value of the F-test 0.001 < 0.05). The dry mass of the control tile was 2.79 kg (Fig. 7), whereas the dry mass of conventional tile was 2.88 kg [9]. The lowest dry mass was observed for Mixture 2 (10 % RHA and 10 % CS), which is 1.8 % reduction compared to the roof tile with 10 % RHA and 0 % CS, and 4.9 % reduction compared to the conventional roof tile. With 20 % clay replacement with CS alone a 3.95% reduction in the dry mass was achieved. When the 20 % clay replacement was achieved with 10 % RHA and 10 % CS, dry mass was further reduced from 3.95 % to 4.90 %, indicating that 20 % clay replacement with combined materials (i.e., 10 % RHA and 10 % CS) is more effective than with replacing by only one material (i.e., 20 % CS) for achieving a light weight roof tile. Lower specific gravity of RHA compared to CS might have contributed to further reduced dry mass, compared to that reported previously in [9]. Light weight roof tiles can further reduce the cost for transportation and labor in roof construction. In addition, light weight roof tiles promise further reduced structural and load flexibility, easy storing and handling with clay replacement with two combined materials. This will provide a more competition with other roofing tiles (i.e., concrete roof tiles, conventional clay roof tiles, only RHA added roof tiles, and only CS added roof tiles).

3.2.2. Micro structure

3.2.2.1. SEM analysis. SEM images of Sample (a), (b), (c) and (d) in secondary electron (SE) mode (Fig. 8) show a considerable number of pores (yellow arrows) in the microstructure. Generally good bonding between the different constituent components was

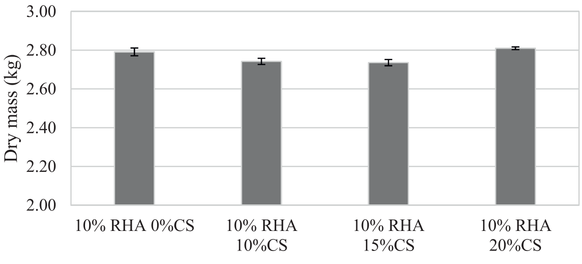

Fig. 7. Variation of dry mass for different specimens.

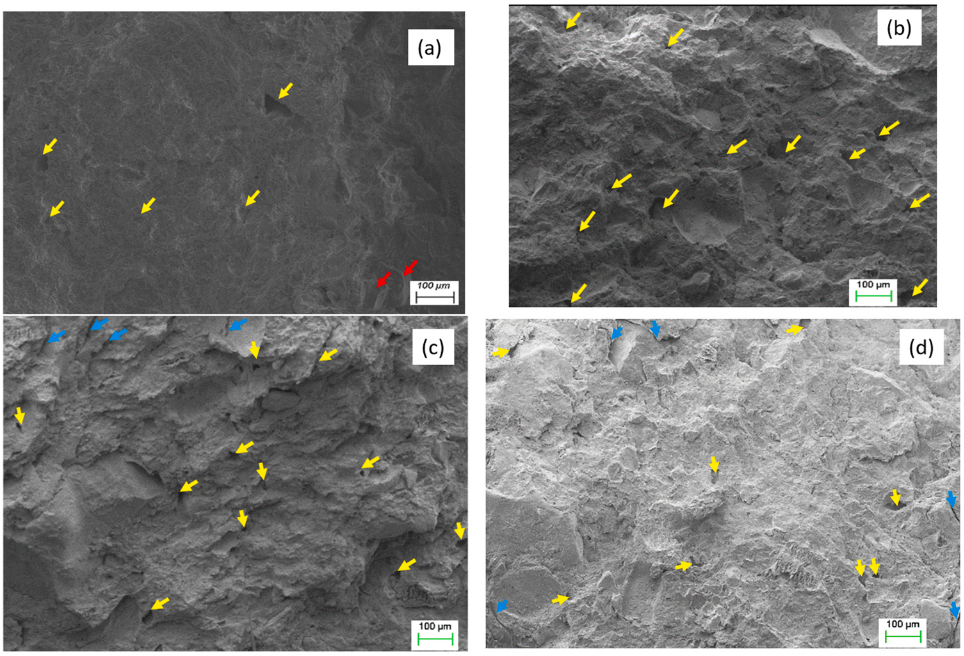

Fig. 8. SEM images of the sample taken from roof tiles with different mixtures: (a) 10 % RHA and 0 % CS, (b) 10 %RHA and 10 %CS, (c)10 %RHA and 15 %CS, (d) 10 %RHA and 20 %CS.

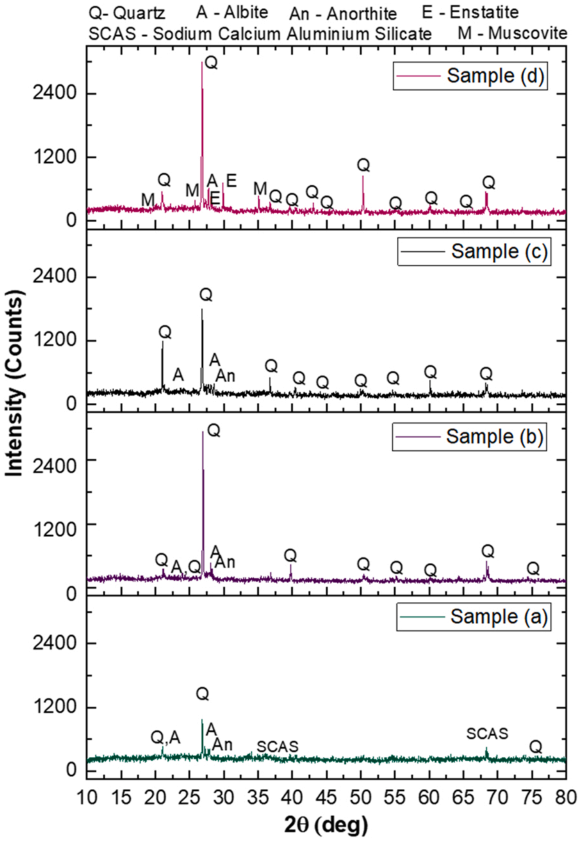

Fig. 9. XRD pattern: (a) 10 %RHA and 0 %CS, (b) 10 %RHA and 10 %CS, (c)10 %RHA and 15 %CS, (d) 10 %RHA and 20 %CS.

noted in all cases. Some quartz grains are bonded in the matrix in Sample (a) (red arrows). Moreover, while increasing of CS content from 0 % to 20 %, the number of pores in microstructure increased, resulting in enhanced porosity. Similar pattern has been observed in samples consisted of laterite clay and CS (0–25 %) [9]. According to the porosity test results (Fig. 10), the highest porosity in Sample (b) was in good agreement with SEM images where elevated number of pores were observed in Sample (b) compared with the other samples. Sample (b) had a relatively high porosity, as judged by the number of pores, while good bonding was reflected in the uniformity of the matrix morphology, as well as a lack of cracking tendency (blue arrows). Hence, the roof tiles made up of the composition in Sample (b) (i.e., 10 % RHA and 10 % CS) show lower water absorption and higher transverse bending strength compared with Samples (c) and (d). More brittleness is implied by the increased tendencies of the cracking in the cases of Samples (c) and (d). Increased porosity of the tile with 10 %RHA and 10 %CS would contribute to increasing the thermal performance of the tile.

3.2.2.2. XRD analysis. Fig. 9 shows XRD pattern of the samples taken from the roof tiles consisting of 10 % RHA together with varying CS levels (0 %, 10 %, 15 % and 20 %). The phase development of the samples was analysed after firing the roof tiles at 850^0 C. The main component of the samples is observed to be crystalline quartz. There is less amorphous silica content than crystalline quartz, implying non-excessive liquid phases at the firing temperature utilized, leading to the densification in the samples. Feldspars like albite and anorthite as well as micas like muscovite are detected. The feldspars appear to have been formed in solid solutions since some of the diffraction peaks were found to match with diverse feldspars such as sanidine, sodium-bearing anorthite, potassium-bearing albite, labradorite. In addition to quartz, Sample (a) consists of sodium calcium aluminium silicate ($NaCaAl_3Si_3O_{12}$) and albite ($NaAlSi_3O_8$). There is a significant increase in the proportion of quartz (SiO_2) when the percentage of CS in the samples increased while maintaining RHA at 10 % (Fig. 9). Feldspars such as albite are present in all the samples. In Sample (d), in addition to quartz and albite, muscovite ($KAl_2(AlSi_3O_{10})(OH)_2$) and enstatite ($Ca_{0.2}Mg_{1.8}Si_2O_6$) peaks were observed. Magnesium and calcium, the components of enstatite, are found at higher concentrations in the CS than in the RHA. The results of the phase composition analysis were consistent with mineralogical composition of RHA and CS used as raw materials (Fig. 5) and the XRF results given in Table 2. Moreover, Xu et al. [50] highlighted that formation of albite and anorthite can contribute to reduced water absorption as they become parts of the glassy phases filling voids. The diffraction peak intensities of albite and sodium-bearing anorthite ($Na_{0.5}Ca_{0.5}Al_{1.5}Si_{2.5}O_8$) are associated with Sample (b) resulting in lower water absorption and higher transverse breaking strength compared with Sample (c) and (d).

3.2.3. Durability properties

3.2.3.1. Water penetration, water absorption and porosity. With increasing CS content, water absorption increases (Fig. 10). Increasing the waste content had a statistically significant effect on water absorption (*p* value of the F-test $0.001 < 0.05$). Increased water absorption might be attributed to the increased porosity of the tile when increasing CS content (Fig. 10). The tile specimen cast with 30 % clay replacement with 10 % RHA and 20 % CS showed a maximum water absorption of 15.76 %, less than the 18 %, within the limits recommended in [41].

At 20 % clay replacement with 10 %CS and 10 %RHA, tile specimen showed the water absorption of 15.25 %, whereas the specimen with 10 % RHA and 0 % CS (i.e., the control specimen) showed the water absorption of 14.81%. In previous studies, water absorption of RHA incorporated tile increased from 14.2 % to 18.6 % when RHA content increased from 5 % to 20 % [8] while water absorption of CS incorporated tile increased from 9.8 % to 11.81 % when CS content increased from 5 % to 20 % [9]. This indicates that RHA contributed to increased water absorption more significantly than CS. With 20 % clay replacement by 20 % RHA showed water absorption of 18.55 % [8], where as 20 % clay replacement by combined materials (i.e., 10 % RHA and 10 % CS) showed the water absorption of 15.25 %. This indicates that potential of clay replacement with combined materials (i.e., RHA together with CS) in reduction of water absorption of RHA incorporated roof tiles. High water absorption is generally undesirable, because it causes more water to remain in the tile. This accelerates growing of moss species and tiny plants on the roof surface, reducing the durability performance and aesthetical aspects.

No tiles with any of the mixtures showed water penetration. Although adding of waste RHA and CS into the clay mixture makes the tile more porous, it is not sufficient to allow any penetration (or seepage) of water.

The determined porosity (Fig. 10) and the microstructure observed in Fig. 8, confirmed that porosity increased when clay

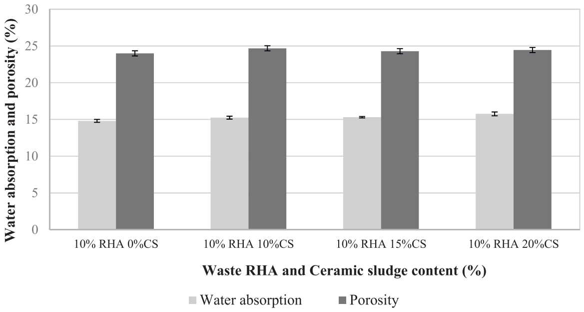

Fig. 10. Variation of water absorption and porosity for different mixtures.

replacement increased by up to 30 % (i.e.,with 10 %RHA and 20 %CS). This aligns with the increased porosity observed when the CS content increases in clay roof tiles [9], and clay bricks [6], possibly due to the replacing of finer clay particles with coarser CS particles. An increased number of pores might also have generated in the fired structure, due to decomposition of organic matter in the waste [51].

3.2.3.2. *Resistances to acid and alkaline exposures.*

Table 4 shows the tile resistance to acid and alkaline exposures. The weight gains reduces when the clay replacement increased with CS and RHA content, indicating that the increased acid and alkaline resistances were attributed by increased CS content in the waste added tiles, compared to the control roof tiles. For example, there was approximately 3.5 % weight gain in the control tile specimen but 3.3–3.0 % weight gain in the 10–20 % CS incorporated tiles, respectively (Table 4). Increased weight gain in the control specimen may be attributed by the partial filling the pores with sulphate crystals [3]. Higher sulphate resistivity was observed for the tile with 20 % of CS compared with the control tile specimen, indicating that the tiles with waste RHA and CS show better sulphate resistance compared to the control tiles for the same dose of H_2SO_4 for the same duration of immersion.

The increase in the mass of the tiles is attributed by the formation of $Fe_2(SO)_4$ [52], from the chemical reaction between Fe_2O_3 and sulphuric acid produces $Fe_2(SO)_4$ [53].

$$Fe_2O_3 + 3H_2SO_4 \rightarrow Fe_2(SO)_4 + H_2O$$

The fact that there was more Fe_2O_3 in the clay compared to CS (Table 2), resulted in less Fe_2O_3 in the mixture when the CS content increased. The weight gain percentage of Mixture 1(control sample) was 3.5 % whereas that of Mixture 4 (tile specimen with 20 % CS) was 3.0 %. When CS content increased, there was comparatively low content of Fe_2O_3 in the mixture, contributing to less weight gain in Mixture 4 than Mixture 1.

The tile specimen with 20 % clay replacement by combined materials (i.e.,10 % RHA and 10 % CS) showed a weight gain of 3.3 %, whereas the tile specimen with 20 % clay replacement by single material (20 % CS) showed weight gain of 3.0 % [9], indicating that better performance of CS has been hindered by adding RHA. The higher amount of Fe_2O_3 presence in RHA (Table 2) might have contributed to weaker performance of the tile with combined materials (RHA and CS) compared to the CS incorporated tile.

In terms of alkaline exposures, weight gain of the tile specimen decreased when the CS content increased (Table 4), indicating the contribution of CS to increased alkaline resistance. When CS content increased from 10–20 %, the weight gain ranged from 2.1 % to 1.6 %. The lowest weight gain was observed for the tile with 10 %RHA and 20 % CS, indicating the highest alkaline resistance of combined waste incorporated tiles.

Clay replacement with combined waste (i.e.,CS and RHA) has benefit of a reduction in weight gain with exposure to salt solution. Clay has higher amount of alumina and iron compounds compared to CS and RHA (Table 2). Less aluminum chloride and iron chloride that could be formed due to less alumina and iron being present in CS and RHA [54], contributing to reduced weight gain in the tile specimen with combined waste.

3.2.4. *Thermal performance*

Temperature variations beneath the tile are compared in Fig. 11. The temperature beneath the tile is significantly affected by the clay replacement with waste RHA and CS (p value of the F-test $0.000 < 0.05$). The highest and lowest temperature values beneath the roof tiles were observed for conventional tiles and 10 %RHA and 20 %CS incorporated tile, respectively. At 12.30 p.m., the temperature was reduced from 56.8^0 C to 49.9^0 C for the conventional tile and the 10 %RHA and 15 %CS incorporated tile, respectively. This confirms that waste added tiles perform better in thermal performances. At 12:30 p.m., the tile with 10 %RHA and 10 %CS reduced the indoor temperature by 4.4°C, providing thermally comfortable indoor environment. The temperature at the top surface of the tile had no significant variation. The reduced thermal conductivity was attributed by the improved porosity of the tile by blending with RHA and CS (Figs. 8 and 10).

In previous studies, porous tiles and bricks were achieved with Waste RHA [4,8], and with CS, [6,9]. At 12:00 noon, a 3.6 °C temperature reduction was observed with 20 % RHA [8], whereas 3.5^0 C was observed with 20 % CS [9]. In the current study, 20 % clay replacement with combined materials (i.e., 10 % RHA and 10 % CS) achieved 4.4° C temperature reduction, indicating that clay replacement with combined material reduces temperature more effectively than a single material. Reduced thermal conductivity helps to maintain cooler indoor environment and, consequently, reduced expenses for synthetic cooling.

3.2.5. *Water quality of runoff*

3.2.5.1. *pH value and total solid concentration.*

Table 5 compares the average values of pH and the total solid concentration of the roof run-off water for all tile specimens and direct rainfall. The direct rain water sample showed the pH value of 7.52, confirming to the value previously reported in [8,9,55]. The pH value of direct rain water decreased to 7.22 for control roof tile, and to 6.49 with 10 % RHA and 20 % CS incorporated tile, indicating that the incorporation of RHA and CS into the clay mixtures had an effect on water quality of the run-off. In previous studies, with an RHA addition from 0 % to 10 % pH value reduced from 7.55 to 7.22, whereas with CS addition from 0 % to 10 %, pH value reduced from 7.51 to 7.41. It seems that, with combined materials (10 % RHA and 10 % CS) pH value is reduced significantly from 7.52 to 6.56, aligning previously reported pH value of run-off from roof [55].

The pH value, which is a measurement of how acidic or alkaline the water is, plays an important role in plant growth: irrigation water with a pH value outside the normal range may cause a nutritional imbalance or may contain a toxic ion. In the current study, pH

Table 4
Weight gain by acid and alkaline exposures.

Mixture	Weight gain by acid exposure (%)	Weight gain by alkaline exposure (%)
Control tile		
10 % RHA 0 %CS	3.5(±0.08)	2.2(±0.06)
Waste added tile		
10 % RHA 10 %CS	3.3(±0.03)	2.1 (±0.08)
10 % RHA 15 %CS	3.3(±0.02)	1.7(±0.05)
10 % RHA 20 %CS	3.0(±0.02)	1.6(±0.06)

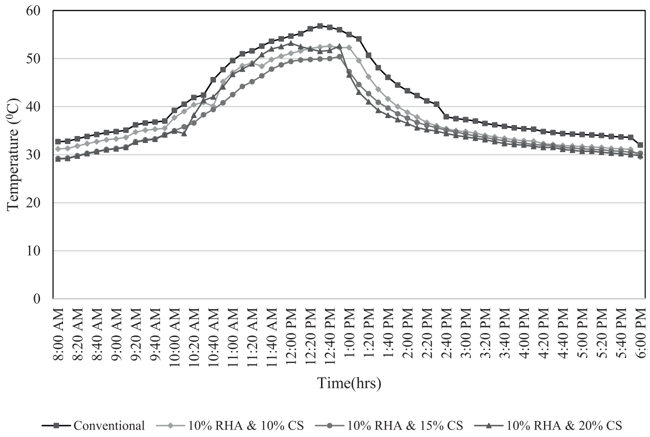

Fig. 11. Comparison of the temperature beneath tiles of different mixtures.

Table 5
Water quality properties of runoff.

Sample No.	pH	Total Solid Concentration (TS) (mg/l)
Direct rain	7.52(±0.06)	58 (±0.17)
10 % RHA 0 %CS (*control tile)*	7.22(±0.01)	118 (±1.9)
Waste added tiles		
10 % RHA 10 %CS	6.56(±0.03)	100 (±3.0)
10 % RHA 15 %CS	6.57(±0.05)	121(±2.1)
10 % RHA 20 %CS	6.49(±0.08)	139(±2.8)

value of the run-off from all tiles are in the most desirable ranges for agricultural purposes (i.e., 6.5–8.4) [56,57] and for irrigation (5.5–7.5) [58], ensuring that the collected run-off can be utilized as alternative water source for non-potable activities, such as paddy farming, irrigation purposes, gardening and washing.

Total solid (TS) concentration of rain water was 58 mg/l while that of the run-off from the control tile is 118 mg/l. TS for the run-off from waste added tiles varied in the range 100–139 mg/l (Table 5), aligning with the recommended value for agricultural purposes (i.e, 0–2000 mg/l [56]. With the addition of waste to clay mixtures, roughness of the roofing material might have changed, resulting in added pollutants into the run-off.

4. Conclusions

From this study the following conclusions can be drawn.

- For fired clay roof tiles, clay can be replaced with combined waste of 10 % waste rice husk ash (RHA) and 10 % ceramic sludge (CS), improving the strength, durability, and thermal performances, while achieving the recommended water quality of roof run-off for non-potable activities.
- Dry masses were found to have been reduced by 3.89 % and 4.9 % for the tiles with 20 % clay replacement with a single waste material (i.e.,20 %CS) and combined waste (10 % waste RHA and 10% CS) respectively, proving that a more light-weight roof tile can be achieved with clay replacement by combined waste.
- A roof tile with 10 % RHA and 10 % CS showed a transvers breaking load of 1519 N, whereas that of a 20 %CS tile showed 1427 N, indicating that 6.5 % further strength improvement can be achieved with clay replacement by combining two waste materials.

- Water absorption and, acidic and alkaline resistances can be enhanced by incorporating combined waste, especially CS, into the clay mixture.
- With 10 % RHA and 10 % CS, porous nature of the tile contributed to 4.4^0 C reduction in indoor temperature (confirmed by microstructure analysis) ensuring more comfortable indoor environment than that with conventional roof tiles.
- For run-off water from 10 % RHA and 20 % CS tile, there was 139 mg/l total solid concentration, and, 6.49 pH value, satisfying the recommended values favorable to harvesting the roof runoff, which can be utilized for non-potable activities.
- Combined waste added roof tiles are a sustainable product with enhanced strength, durability, thermal and run-off properties.

CRediT authorship contribution statement

G.H.M.J.Subashi De Silva: Conceptualization, Methodology, Investigation, Resources, Visualization, Supervision, Project administration, Funding acquisition. **T.H.F Aagani:** Methodology, Investigation. **Kidane F. Gebremariam, S.M. Samindi M.K Samarakoon:** Investigation, Resources, Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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