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Rubber Crumbs in Alkali Activated Clay Roof Tiles at Low Temperature

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***Abstract*—**The continuous increase in vehicle uptake escalates the number of rubber tyres waste which need to be managed to avoid landfilling and stockpiling. The present research focused on the sustainable use of crumb rubber in clay roof tiles. The properties of roof tiles composed of clay, crumb rubber, NaOH, and Na_2SiO_3 with 10 wt.% alkaline activator were studied. Tile samples were fabricated by heating the compacted mixtures at 50 °C for 72 hours, followed by a higher heating temperature of 200 °C for 24 hours. The effect of crumb rubber aggregates as a substitution for the raw clay materials were investigated by varying their concentration from 0 wt.% to 2.5 wt.%. X-ray diffraction (XRD) and scanning electron microscopy (SEM) analyses have been conducted to study the phases and microstructures of the samples. It was found that the optimum rubber crumbs concentration was at 0.5 wt.% and 1 wt.%, while cracks and larger porosity were found at higher crumbs concentration. Water absorption, and compressive strength test results demonstrated that rubber crumbs and clay satisfied the standard requirement for the roof tiles.

***Keywords*—** Crumb rubber, clay, roof tiles, alkaline activators.

I. Introduction

CLAY is considered a primary element for building materials. The discovery of the first fired clay bricks was dated back to 4500 BCE [1]. Dalkilic and Nabikoglu [2] suggested the traditional approach of brick making was still a popular and common technique in many countries. The traditional methods of making bricks require higher temperatures at the kiln, significantly increasing carbon emissions. Dabaieh et al. [3] studied the usage of sun-dried bricks and fired clay bricks and suggested that sun-dried bricks were better options than the fired clay bricks since it saves 5907 kg of CO_2 emission for every thousand bricks and have lower production cost. Lourenco et al. [4] reviewed the properties of clay materials, and a comparison was made between old bricks and new bricks. The results for the old clay bricks exhibited a higher porosity and higher absorption percentage of 29.1% and 17.7%, respectively. On the other hand, the new clay bricks with different chemical compositions achieved a lower porosity of 20.7% and a lower water absorption rate of 11.2%.

Roof tiles are used in the construction sector widely [5]. The glazed roof tiles used in the China museum were constructed in 1406 AD which had an exquisite waterproofing [6]. The roof tiles are mainly used to prevent the interior space from extreme weather conditions [7]. The physical and mechanical properties of roof tiles from recycled materials have previously been explored [8]-[12]. Zakira et al. [8] experimented with roof tile using recycled materials such as polyurethane foam and shredded automobile tyres. Polyurethane foam acts as an insulating agent. The suitable ratio was 33% shredded automobile tyres and 67% polyurethane foam, and the thermal insulation K - factor achieved was 0.1633 W/m°C. The 100% polyester foam showed the highest thermal insulation of 0.592 W/m°C.

Herbudiman and Saptaji [9] investigated recycled tile powder in self-compacting concrete. A slump flow test was used to determine the characteristics of the material and showed no damage in segregation. The roof tile powder percentages illustrated were 0 wt.%, 10 wt.%, 20 wt.% and 30 wt.%. The increase in the roof tile powder percentage also increases the mechanical properties of the samples and can be used up to 20 wt.%. The highest compressive and tensile strength was 44.11 MPa and 3.25 MPa, respectively achieved with 20 wt.% roof tile powder. The roof tile powder of 30 wt.% in concrete achieved a lower compressive strength of 37.13 MPa. Muhamad et al. [10] experimented with roof tiles using partial replacement of cement and rice husk ash (RHA). The percentage of RHA investigated was 5 wt.%, 10 wt.%, 15 wt.% and 20 wt.%, respectively. The incorporation of 20 wt.% of RHA in roof tile failed to satisfy the water absorption percentage as it only reached 15.19%.

Sultana et al. [11] demonstrated an experiment using hard rock dust and red clay in the roof tiles with the firing temperature at 850°C to 1100°C. The increase in the firing temperature caused a decrease in the water absorption percentages for all the samples. The highest water absorption of 8% was recorded for the rock dust sample of 30 wt.% fired at 850°C. Compressive strength for all the samples was found to decrease with an increase in rock dust percentages. The rock dust of 20 wt.% fired at 1100°C achieved the highest compressive strength of 53 MPa. Costa et al. [12] reported clay roof tiles using glass cullet. The various firing temperatures were conducted between 800°C to 1200°C. Two particle sizes of glass cullet were used and named as alpha (0.088 to 0.125 mm) and beta (0.037 to 0.088 mm). The glass percentages exhibited was 0 wt.%, 5 wt.%, 8 wt.% and 10%. The highest flexural strength of 17.2 MPa and 12.5 MPa was achieved for the alpha and beta glass cullet percentage of 10 wt.%, and the firing temperature was recorded at 1200°C.

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In this modern era, the construction sector is primarily focused on eco-friendly practices. During the production process, reducing the material cost can potentially improve energy conservation [13]. Liu et al. [14] illustrated that crumb rubber production generally involves removing steel and fibres from the tyres. The ambient shredding can reduce the size of rubber particles. Tsang [15] explored scrap tyres and suggested numerous ways to reuse the material (energy recovery, recycling, retreading). The demand for the tyres is increasing every day, and the annual usage of rubber tyres worldwide was 1.5 billion [16]. According to the tyre manufacturing association from the USA reported that 300 million tyres are scrapped annually. Of this, 36.8% of the scrapped tyres contribute to tyre-derived fuel, 24.4% is ground rubber, land disposal holds 14.3%, and civil engineering applications comprise of 5.1% [17]. Various researchers [18]-[20] conducted studies on rubber materials. Tang et al. [18] explored the material properties of brick clay powder and styrene-butadiene rubber. The silane coupling agent mixed with brick clay powder acts as a filler for the styrene-butadiene rubber. The highest tensile strength of 3.6 MPa and 3.4 MPa were achieved for the modified and unmodified rubber content of 50%.

Jena et al. [19] experimented with epoxy and waste tyre rubber crumbs followed by different percentages (10 wt.%, 20 wt.%, 30 wt.%, 40 wt.% and 50 wt.%). The water absorption percentage for all the samples was increased due to the incorporation of crumb rubber percentages. The waste tyre crumb rubber of 50 wt.% exhibited the maximum water absorption of 0.254%. The highest elongation percentage showed a result of 7.33% for the sample containing crumb rubber percentage of 40 wt.%. Sodupe-Ortega et al. [20] examined the properties of crumb rubber aggregates and cement in hollow bricks. Curing days for the sample exhibited were 7 days and 28 days. The water-cement ratio of 0.8 achieved the highest compressive strength of 20 MPa and 25 MPa for 7 days and 28 days, respectively. The appearance of the crumb rubber was elastic and non-brittle in nature. The matrix between rubber aggregates and cement showed poor adhesion and larger voids in the compression loading. The failure rate in the compressive strength for the hollow bricks using rubber crumbs was reported due to the excessive water and cement ratio of 0.9.

While many review papers on crumb rubber applications in concrete are available, no investigation has been conducted on incorporating crumb rubber in clay roof tiles at low temperatures. The crumb rubber materials are less economical [21]. The study conducted by Wang et al. [22] mentioned that rubber particles have low unit weight. The recycling of crumb rubber is a challenging aspect, mainly due to its increase in toxicity when the heating temperature increases [23]. Crumb rubber has been dumped into landfills over the past few years; hence, the use of crumb rubber in roof tiles and other geotechnical applications are promising.

The present work investigated the properties of crumb rubber and clay using alkaline activation in roof tiles. Based on the previous study [40], it was found that the acceptable percentage of alkaline activators in this study was 10 wt.%. XRD, SEM, water absorption, and compressive strength tests were carried out to characterise the sample and determine the mechanical properties.

II. Methodology

A. Materials

The materials used in the study for making the roof tiles samples were crumb rubber, clay, distilled water, and alkaline activators (NaOH, Na_2SiO_3). The chemical composition of clay materials is presented in Table I.

TABLE I
CHEMICAL COMPOSITION OF CLAY MATERIALS [40]

Chemical compositions	Weight (%)
Na_2O	<0.02%
MgO	1.35%
Al_2O_3	16.92%
SiO_2	65.90%
P_2O_5	0.07%
SO_3	0.04%
K_2O	3.49%
CaO	0.08%
TiO_2	0.90%
MnO	0.02%
Fe_2O_3	4.02%
Loss of ignition (LOI)	6.89%
Norm. Factor	1.07%

The sodium hydroxide powder of 160 grams was dissolved in 500 grams of water to achieve a sodium hydroxide solution. The clay, and crumb rubber were sourced from a local recycling plant in Melbourne, Australia. Table II presents the physical properties and chemical composition of crumb rubber.

TABLE II
PHYSICAL AND CHEMICAL PROPERTIES OF RUBBER CRUMBS [41]

Properties	Percentage
Density (g/cm^3)	1.15
Moisture content (%)	0.45
Fibre content (%)	0.55
Ash content (%)	4.6
Acetone extract (%)	15
Carbon black content (%)	32

B. Preparation of Samples

During the initial phase of the study, clay materials were not sieved using particle size distribution. Instead, the untreated clay materials were mixed with crumb rubber and alkaline solution, resulting in severe cracks and uneven heating inside the samples. After that initial phase, the modification for the clay was introduced and sieved at a size of 4.75 mm [24], [25], resulting in the particle size distribution highlighted in Fig. 1.

The moisture content of the clay was eliminated by heating it at a low temperature of 110 °C for 24 hours [12]. The roof tiles samples were prepared using a steel mould with the size of 230 x 110 x 35 mm^3. The preparation of clay and crumb rubber involved making three batches of samples per mix. Initially, the clay and crumb rubber were placed in a bowl, and dry mixing was performed for 2 minutes. The ratio of the alkaline activators was 1:1 between sodium hydroxide and sodium silicate. The activator solutions were mixed with crumb rubber and clay for 2.5 minutes. The samples were compressed and compacted in the mould using a universal testing machine (UTM). The compacted mixture was then heated at 50 °C for 72 hours and continued heating at 200 °C for 24 hours. The samples with different percentages of crumb rubber aggregates are listed as: 0 wt.%RC, 0.5 wt.%RC, 1 wt.%RC, 1.5 wt.%RC, 2 wt.%RC, and 2.5 wt.%RC where RC is denoted as rubber crumbs.

Fig. 1 Particle size distribution of clay

C. Characterisation of Samples

The samples were examined using various testing methods to determine the physical and mechanical properties. The laboratory testings performed in the study were XRD, SEM, water absorption, linear shrinkage, and compressive strength.

1. X-Ray Diffraction

The identification of minerals presented in the sample was determined through powder XRD method [26], [27], [29]. The Bruker AXS–D8 diffractometer utilising Cu Kα radiation (1.54178 Å) operating at 40 kV and 30 mA was used to scan the sample from 5° to 80° (2θ) at a rate of 0.02° per 1.5 s time step. The samples were crushed into fine powders prior to the analysis.

2. Scanning Electron Microscopy

The microstructure properties of different crumb rubber percentages were analysed using SEM. Initially, the samples were tested using mechanical loading, and the values were observed from the compressive strength [28], [31]. The crushed samples were collected, and a gold sputter coating was applied to the samples prior to SEM analysis.

3. Water Absorption

The initial weight was measured after the samples were treated in the oven. The samples were then soaked in the water for 24 hours at a room temperature of 30 °C. The maximum limit for the water absorption in the clay roof tiles was 13% [30].

4. Compressive Strength

The compressive strength was conducted to evaluate the durability of the samples [31]. The samples undergo mechanical loading, and cracks would appear on the samples. The compressive strain rate for different rubber crumbs percentages was performed at 1 mm/min.

III. Results and Discussions

A. X-Ray Diffraction

The XRD patterns of the crushed samples with various rubber percentages ranging from 0.5 wt.% to 2.5 wt.% are presented in Fig. 2.

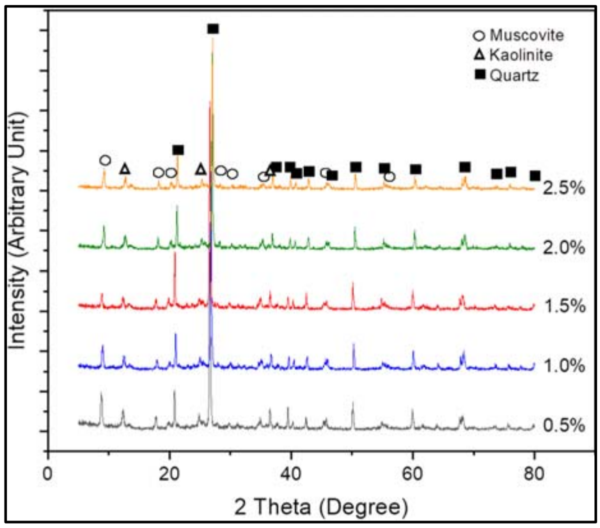

Fig. 2 The XRD pattern of samples with various crumb rubber percentages ranging from 0.5 wt.% to 2.5 wt.%

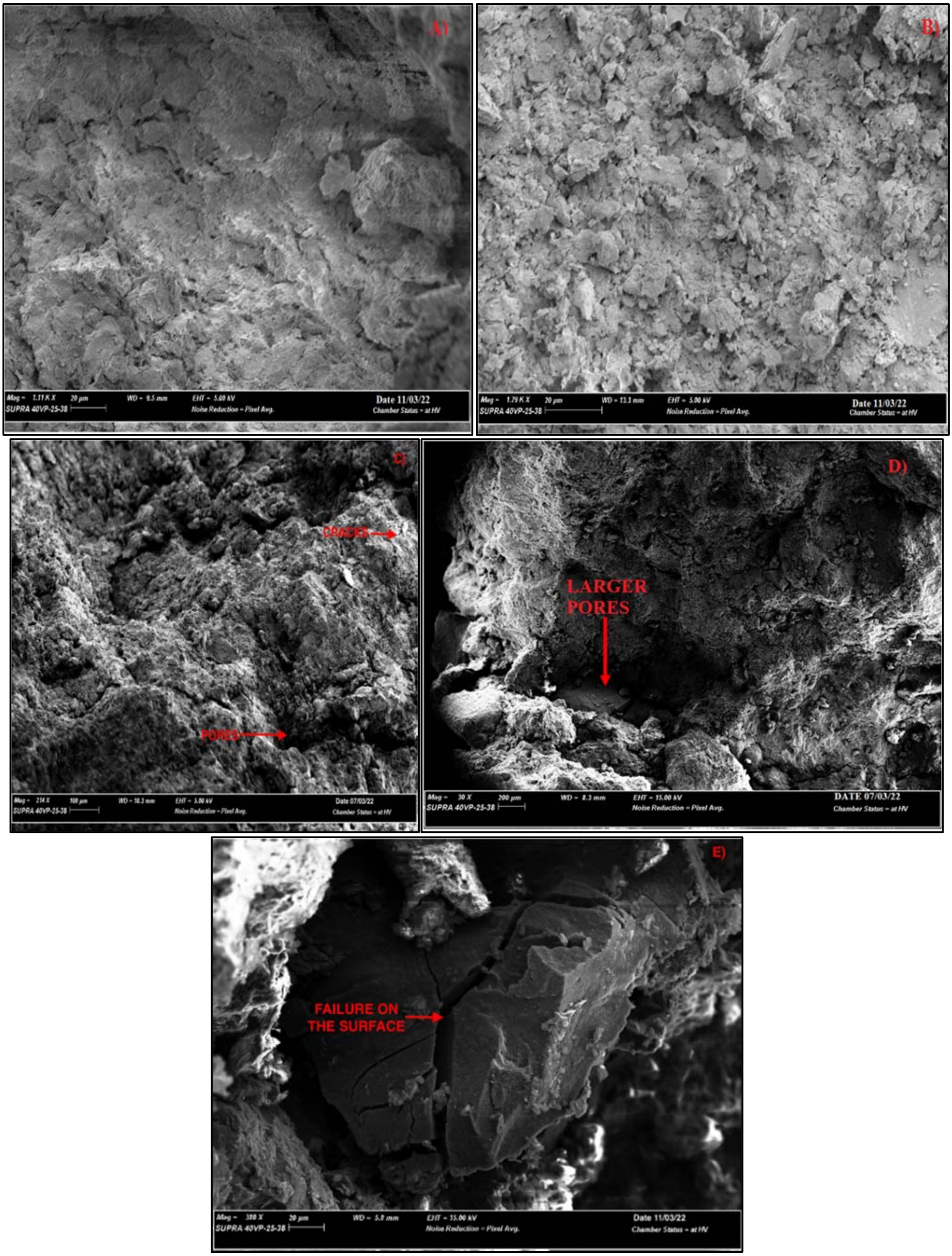

Fig. 3 SEM Microstructure of different rubber crumbs percentages: (a) 0.5 wt.%RC, (b) 1 wt.%RC, (c) 1.5 wt.%RC, (d) 2 wt.%RC, (e) 2.5 wt.%RC

It was found that three minerals, namely Kaolinite, Muscovite, and quartz are consistently present in all samples. In this study, the angles ranging from 5° to 80° of two thetas (2θ) were used to identify the intensity peak for the minerals. The mineralogical composition of quartz holds an intense peak, and the corresponding angles were positioned between 22° and 26°. The intensity peak for the kaolinite becomes very weak and narrower, with the corresponding angle between 39° to 80°. Therefore, kaolinite possessed the lowest intensity compared with quartz and muscovite.

The previous researchers [32], [33] made a comparison about the exploration of clay minerals. The study conducted by Hmeid et al. [32] revealed that kaolinite possessed the lowest percentage in the mineral composition. The angles to determine the position of minerals were identified at 0° to 80°. The phase of kaolinite falls between 0.10% to 1.49%. The previous study by Zanelli et al. [33] analysed that the mineral composition of the quartz falls between 30% and 39%. The amorphous phase of the mineral ranges from 24% to 57%. The increasing firing temperature improved the amorphous phase in the mineral composition for a particular batch.

B. SEM Analyses

SEM was used to evaluate the microstructural properties in the samples. The rubber crumbs with different percentages are depicted in Fig. 3. Initially, the crumb rubber of 0.5 wt.% and 1 wt.% were employed, and the sample microstructure was visually denser than the samples indicated in Figs. 3 (a) and (b).

Fig. 3 (c) shows cracks developed on the samples at a crumb rubber percentage of 1.5 wt.%. In Figs. 3 (d) and (e), the crumb rubber percentage of 2 wt.% and 2.5 wt.% showing larger voids and cracks, respectively. The cause of voids and cracks was the poor mixture of clay and crumb rubber. The micro-cracks in the samples started gradually, and eventually developed into larger pores as the percentage of crumb rubber increases (see Fig. 3 (e)). It can be observed from all the samples treated with 10 wt.% alkaline activator resulted in poor bonding, especially as the rubber crumbs percentage increases. It was observed that 0.5 wt.%RC and 1 wt.%RC exhibited the best results with minimal pores and crackings. Consequently, the crumb rubber percentage of 0.5 wt.% and 1 wt.% could be used as an aggregate for the roof tiles. The further increase in the percentage of crumb rubber to 1.5 wt.%, 2 wt.% and 2.5 wt.% showed pores and cracks failure incurred on the samples.

Similar studies were conducted by researchers [34]-[36] who investigated the properties of rubber with concrete. The study conducted by Eslami and Akbarimehr [34] analysed the microstructural properties of rubber grains and clay soil. Larger pores and rough surfaces on the samples were observed using rubber powder particles. The addition of clay soil percentages can improve the uneven surfaces of the rubber grains samples. Zhang et al. [35] examined the microstructure of cement materials with rubber powder. The surfaces were activated by using NaOH solutions. The 5 wt.% NaOH solutions were used along with rubber powder to treat the surface modification, and smaller holes were evident. Su et al. [36] investigated the microstructure of plastic rubber in cement. During the hydration stage, the cement paste and plastic rubber showed poor bonding, and eventually led to cracks in the sample.

C. Capillary Cold Water Absorption

The water penetration in the samples can be used to examine the pores' structure and apparent porosity is presented in Fig. 4.

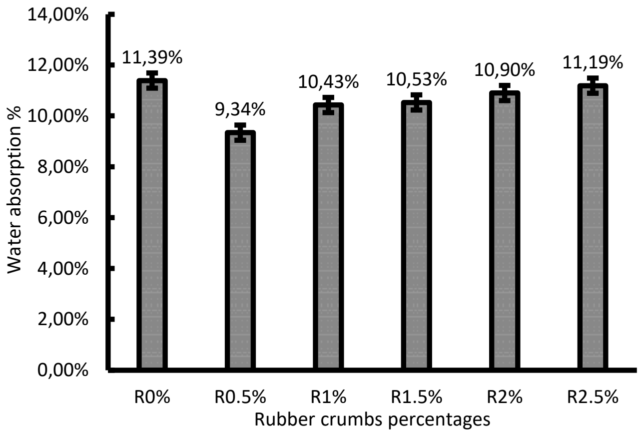

Fig. 4 Water absorption results

Initially, the failure occurred on the samples due to the low heating temperature at 50 °C. Based on this, the heating temperature was increased to 200 °C, which showed an improvement in the absorption rate. The water absorption rate for all the crumb rubber percentages is presented in Fig. 4. The absorption rate for all the samples increased proportional to the rise in rubber crumbs percentages. Moreover, the water absorption rate of 9.34% was achieved for 0.5 wt.%RC. Along with that, the crumb rubber increased slightly to 1 wt.%, and the absorption rate results exhibited a value of 10.43%.

The marginal increase in the absorption rate of 10.53% was determined for the 1.5 wt.% sample. As for the sample, 2 wt.% was experimented with, and the absorption rate attained was 10.90%. Apart from this, the further increase in crumb rubber to 2.5 wt.% and the water absorption rate achieved was 11.19%. Therefore, based on the results from Fig. 4, it can be classified that the roof tiles are considered second-class bricks, which can have a maximum water absorption of 20% [30]. On the other hand, the results obtained from the water absorption are compared with previous researcher [37]. Kazmi et al. [37] reported waste glass sludge in clay bricks. The water absorption percentages for the samples were reduced significantly due to the addition of waste glass sludge. The waste glass sludge of 5 wt.% used as a replacement for the clay recorded the highest water absorption percentage of 19%.

D. Compressive Strength

The compressive strength results of different rubber aggregates percentages are presented in Fig. 5.

The control sample of crumb rubber (0 wt.%) showed a compressive strength of 23.9 MPa. The crumb rubber of 0.5 wt.% were incorporated with clay, which achieved a strength of 17.6 MPa. Next, the incorporation of crumb rubber to 1 wt.% was attempted, and the strength exhibited was 19.2 MPa. The crumb rubber aggerates of 1.5 wt.% caused a decrease in compressive strength and attained 16.7 MPa. Furthermore, increasing the crumb rubber to 2 wt.% attained a strength of 14.5 MPa. The crumb rubber has been raised further to 2.5 wt.% and obtained a compressive strength of 13.9 MPa. The increase in water ratio caused poor bonding because of the segregation between crumb rubber and clay, resulting in poor workability. Therefore, the crumb rubber of 0.5 wt.% and 1 wt.% satisfied the specifications for the roof tiles. The compressive strength from the local standard was 17.2 MPa [30].

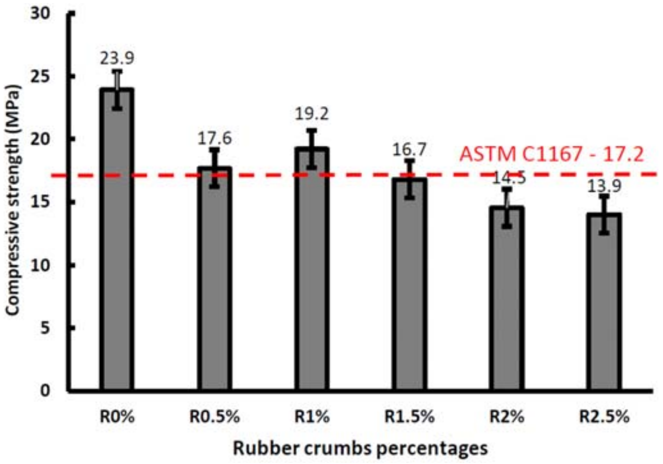

Fig. 5 Compressive strength results

So, the comparison was made from the earlier studies [38] employed to analyse rubber material properties. Faria and Manhaes [38] experimented using red ceramic and rubber tyre waste (RTW). The firing temperatures used for the samples were 850 °C and 950 °C. Compressive strength for the control sample RTW 0 wt.% showed 18 MPa at 850 °C and 18.5 MPa at 950 °C, and the decline in the strength was demonstrated for the samples RTW (0.5 wt.%, 1 wt.%, 1.5 wt.%). The improvement in the strength of the samples occurred for RTW 2 wt.%.

IV. Conclusion

A study on the activated rubber crumbs in clay roof tiles at a low temperature of 200 °C has been conducted. The findings from the microstructure revealed that no crack was observed on samples with crumb rubber of 0.5 wt.% and 1 wt.% owing to the crumb rubber amalgamated with clay. However, increasing the crumb rubber percentages (1.5 wt.%RC, 2 wt.%RC, and 2.5 wt.%) in the samples resulted in larger porosity and cracks, mainly due to the poor compatibility of the mixture. In addition, the water absorption rate for all different percentages of crumb rubber is considered as first-class brick since the water absorption rate was less than 13%.

The compressive strength of the sample on 0.5 wt.%RC and 1 wt.%RC samples satisfied the standard roof tiles requirement. The failure in the compressive strength was observed for the remaining sample percentages, i.e. 1.5 wt.%RC, 2 wt.%RC, and 2.5 wt.%RC; this is due to the natural tendency of the rubber, which is elastic, that causes the irregularity in the mixture composition. Further research needs to be conducted to treat the surface modification of crumb rubber. The crumb rubber has a characteristic of high durability and lesser permeability and can be used for commercial purposes such as pavements and floors.

Declaration of Competing Interest

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

CRediT Authorship Contribution Statement

Aswin Kumar Krishnan: Investigation, writing – reviewing, and editing. Yat Choy Wong: Writing – reviewing and editing. Reiza Mukhlis: writing – reviewing and editing. Zipeng Zhang: writing – reviewing, and editing. Arul Arulrajah: writing – reviewing, and editing

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References

[1] N. Yaseen, et al., Sustainable Development and Performance Assessment of Clay-Based Geopolymer Bricks Incorporating Fly Ash and Sugarcane Bagasse Ash. Journal of Materials in Civil Engineering, 34(4), p.04022036(2022).
[2] N. Dalkilic, and A. Nabikoğlu, Traditional manufacturing of clay brick used in the historical buildings of Diyarbakir (Turkey). Frontiers of Architectural Research, 6(3), pp.346-359(2017).
[3] M. Dabaieh, et al., A comparative study of life cycle carbon emissions and embodied energy between sun-dried bricks and fired clay bricks. Journal of Cleaner Production, 275, p.122998(2020).
[4] P.B. Loureco, et al., Handmade clay bricks: chemical, physical, and mechanical properties. International Journal of Architectural Heritage, 4(1), pp.38-58(2010).
[5] P. Chakartnarodom, et al., Properties and performance of the basalt-fiber reinforced texture roof tiles. Case Studies in Construction Materials, 13, p.e00444 (2020).
[6] N. Wang, et al., Autonomous damage segmentation and measurement of glazed tiles in historic buildings via deep learning. Computer-Aided Civil and Infrastructure Engineering, 35(3), pp.277-291(2020).
[7] S. Liu, et al., Effectiveness of the anti-erosion of an MICP coating on the surfaces of ancient clay roof tiles. Construction and Building Materials; 243:118202(2020).
[8] F. Zakaria, et al., Insulating material based on shredded useds and inexpensive polymers for different roofs. International Journal of Engineering and Technology (UAE), 7(4), pp.1983-1988(2018).
[9] B. Herbudiman, and A.M. Saptaji, Self-compacting concrete with recycled traditional roof tile powder, Procedia Engineering, 54, pp.805-816(2013).
[10] K. Muhamad, et al., April, Influence of rice husk ash (RHA) on performance of green concrete roof tile in application of green building, In IOP Conference Series: Earth and Environmental Science (Vol. 476, No. 1, p. 012038). IOP Publishing(2020).
[11] M.S. Sultana, et al., Utilisation of hard rock dust with red clay to produce roof tiles. Journal of Asian Ceramic Societies, 3(1), pp.22-26(2015).
[12] F.B. Costa, et al., Recycling of glass cullet as aggregate for clays used to produce roof tiles. Materia (Rio de Janeiro), 14(4), pp.1146-1153(2009).
[13] A.M. Radzi, et al., Water absorption, thickness swelling, and thermal properties of roselle/sugar palm fibre reinforced thermoplastic polyurethane hybrid composites. Journal of Materials Research and Technology, 8(5), pp.3988-3994(2019).
[14] J. Li, et al., Surface activation of scrap tire crumb rubber to improve compatibility of rubberised asphalt, Resources, Conservation and Recycling,169:105518(2021).
[15] H.H. Tsang, uses of scrap rubber tires, Rubber: Types, Properties and Uses; Nova Science Publisher: New York, NY, USA, 2013:477-91(2013).

[16] C. Karakurt, Microstructure properties of waste tire rubber composites: an overview. Journal of Material Cycles and Waste Management. 17(3):422-33(2015).
[17] Rubber Manufactures Association, US Scrap tire management summary 2019. Washington(2019).
[18] D. Tang, et al., The reuse of red brick powder as a filler in styrene-butadiene rubber, Journal of Cleaner Production, 10;261:120966(2020).
[19] B.P. Jena, et al., Physical & mechanical characterisation of composites from waste tire rubber crumb, Materials Today: Proceedings, 2020;26:1752-6(2020).
[20] E. Sodupe-Ortega, et al., Evaluation of crumb rubber as aggregate for automated manufacturing of rubberised long hollow blocks and bricks, Construction and Building materials;106:305-16(2016).
[21] J.K. Kim and J.W. Park, The biological and chemical desulfurization of crumb rubber for the rubber compounding. Journal of applied polymer science, 72(12), pp.1543-1549(1999).
[22] L. Wang, et al., Dynamic properties of the mucky clay improved with the steel slag and the rubber particles. Construction and Building Materials; 294:123489(2021).
[23] S.T. Pochron, et al., The response of earthworms (Eisenia fetida) and soil microbes to the crumb rubber material used in artificial turf fields. Chemosphere, 173, pp.557-562(2017).
[24] B.R. Phanikumar and T.V. Nagaraju, Swell and compressibility of GGBS–clay mixes in lumps and powders: effect of 4% lime. Indian Geotechnical Journal(2019).
[25] C.D. Shackelford and F. Javed, Large-scale laboratory permeability testing of a compacted clay soil. Geotechnical Testing Journal;14(2):171-9(1991).
[26] S. Wang, et al., Thermal behaviours of clay mixtures during brick firing: A combined study of in-situ XRD, TGA and thermal dilatometry. Construction and Building Materials; 299:1243192(2021).
[27] K. Khederlou, et al. A mathematical method for XRD pattern interpretation in clay containing nano composites. Applied surface science, 318, pp.90-94(2014).
[28] N. Golsanami, et al. Characterizing clay textures and their impact on the reservoir using deep learning and Lattice-Boltzmann simulation applied to SEM images. Energy, 240, p.122599(2022).
[29] C. Valantin, et al., SEM-EDX analysis and TOF-SIMS 3D imaging of a textile/rubber interface undergoing fatigue loading. Applied Surface Science, 360, pp.623-633(2016).
[30] ASTM C1167/2011, “Standard Specifications for clay roof tiles” (2017).
[31] L. Liu, et al., Evaluation of the compressive strength reducing behavior of concrete containing rubber aggregate. Cleaner Materials, p.100057(2022).
[32] H.A. Hmeid, et al., 2022. Preliminary characterisation and potential use of different clay materials from North-Eastern Morocco in the ceramic industry. Materials Today: Proceedings(2022).
[33] C. Zanelli, et al., Improving the frost resistance of roof tiles beyond current prediction schemes. Open Ceramics, p.100249(2022).
[34] A. Eslami, D. Akbarimehr, Failure analysis of clay soil-rubber waste mixture as a sustainable construction material. Construction and Building Materials, 310, p.125274(2021).
[35] R. Zhang, et al., Influences of different modification methods on surface activation of waste tire rubber powder applied in cement-based materials. Construction and Building Materials, 314, p.125191(2022).
[36] P. Su, et al., Investigation of the mechanical and shrinkage properties of plastic-rubber compound modified cement mortar with recycled tire steel fiber. Construction and Building Materials, 334, p.127391(2022).
[37] S.M.S. Kazmi, et al., Thermal performance evaluation of eco-friendly bricks incorporating waste glass sludge. Journal of Cleaner Production, *172*, 1867-1880(2018).
[38] N. Prasad, J. Sudha, An exploratory analysis on prejudice substitute of fine aggregate by glass powder and crumbed rubber on M30 concrete, Materials Today: Proceedings (2020).
[39] J.S. de Faria, et al., Incorporation of unserviceable tire waste in red ceramic. Journal of Materials Research and Technology;8(6):6041-50(2019).
[40] Z. Zhang, et al., Feasibility of producing non-fired compressed masonry units from brick clay mill residues by alkali activation. Journal of Cleaner Production, 306, p.126916.
[41] P. Li, et al., Analysis of physico-chemical properties for crumb rubber in process of asphalt modification. *Construction and Building Materials*, *138*, pp.418-426 (2017).