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Thermal insulation and mechanical characteristics of cement mortar reinforced with mineral wool and rice straw fibers

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ABSTRACT

Building insulation is an essential requirement for buildings located in areas of varying temperature conditions. However, the conventional building insulation techniques accrue high cost and consume resources. This work aimed to evaluate the use of mineral wool and rice straw to improve Portland cement mortar's thermal insulating properties. Samples of 40x40x160 mm mortar were produced with cement and sand, but varying mineral wool and rice straw constituents from 0 to 50% in weight. Water absorption, flexural and compressive strengths, thermal conductivity were performed in samples with and without mineral wool and rice straw addition. The microstructure of mortars was analyzed using scanning electron microscopy (SEM). It was observed that reinforcing mortars with mineral wool and rice straw fibers yielded a significant drop in the mortar's thermal conductivity, improving their insulative abilities. Although the addition of fibers, in turn, deferred the mechanical performance in some mixes, however, it was not too significant or below workable standards. The performed tests prove the feasibility of adopting the selected fibers for insulating Portland cement mortars.

1. Introduction

The need for thermal insulation against high solar radiation in building structures has been a conversant and growing topic in construction. Generally, thermal insulation is one of the major methods of reducing energy losses, especially in residential and commercial structures. Thermal insulation is vital in buildings for achieving thermal comfort to their occupants. High temperatures in buildings can affect the general well-being of their occupants. Heat loss or gain is prevented by insulation and can decrease energy consumption from heating and cooling systems [1,2].

Cao, Dai, and Liu [3] reported that most people currently spend 90% of their lives indoors, using mechanical heating and air conditioning, making buildings the largest energy consumers worldwide. These authors also reported an increase of 7.4% in energy consumption in the USA. International Energy Agency (IEA) [4] 2021 report showed that about 46% of the total energy consumed worldwide in 2018 was from the heat and cool buildings. Also, IEA data between 2009 and 2019 revealed that regions in the Middle East and North Africa record about 71% of the total carbon emissions in the world. In France, for example, the building sector

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consumed approximately 51% of the final energy consumption [4,5], over the building sector consumption of energy worldwide (50%) [4,6]. In hot and humid climates, a lot of energy is given to cooling the house, and in colder temperate seasons, energy, in turn, is used to keep homes warm. Therefore, more feasible and sustainable building insulation methods are necessary to reduce energy consumption and costs.

Studies have shown that residential structures in sub-Saharan African nations such as Nigeria occupants use mechanical cooling and operable windows, fans, and air conditioning, for thermal comfort. These mechanical cooling systems consume about 53.3% of the electricity generated in Nigeria [7]. Most of these mechanical cooling systems are powered by fuel generators. Nigeria is reputable for large fuel consumption from these petrol generators and high imposed electricity tariffs. Petrol generators are mostly used due to the unreliability of electrical generation and distribution from the National grid. These generators emit carbon monoxide (CO), a poisonous, colorless, and odorless gas that is very deadly and can kill persons trapped in enclosed spaces with it.

Unfortunately, due to the lack of a constant power supply from the national grid, these mechanical cooling systems cannot always be depended on [8]. Lower-income citizens rely on open-air ventilation. The continuous running of these mechanical systems proves not to be cost-effective, especially for low-income home citizens.

Since lots of insulation materials are used commercially, cost-efficiency is needed. These materials can be classified as inorganic, organic, combined, and advanced materials and are found in several forms, such as porous, blanket or batt form, rigid, natural form, and reflective form [9]. Commonly used insulation materials in the construction industry are polymer-based products such as polystyrene (PS), polyurethane (PU), and polyisocyanurate (PIR) foams due to their characteristics such as low thermal conductivity and low cost. Although these materials have good performance, they are synthetic polymers and toxic for health and the environment [9,10]. There has been a range of development on sustainable thermal insulation materials focused on using cheaper renewable resources and waste that still possess good insulation properties, besides lower environmental impact [2,5,10–13].

In advancing research relating to thermal insulation, new materials (emanating from solid wastes) are also considered as potential application in composite development. The focus in this current study is on combined use of rice straw (an agricultural waste) and mineral wool (a conventional material) for cementitious mortar development, and this could be a good choice among many thermal insulation materials. Mineral wool exhibits good thermal insulation properties, but it is essential to explore the performance of mineral wool with rice straw in a cementitious mixture. The carbon emissions during production of mineral wool is 1471.77 kgCO2eq/t, and it is among the highest of all green building materials [14]. Thus, incorporating the materials in a cementitious mixture can help mitigate the potential environmental effects. Miskinis et al. [15] studied the influence of expanded polystyrene (EPS), mineral wool and plaster layers on sound and thermal insulation and reported that thermal insulation of basic wall increases with the addition of a mineral wool layer. It is worthy of note that mineral wool is used in several applications; such as designing insulation-filled masonry blocks [16,17], or applying it as ETICS [18,19]. Overall, appreciable performance in terms of insulation characteristics of mineral wool was recorded with masonry blocks and ETICS. Tran *et* al. [20] developed an aerogel from rice straw and polyvinyl alcohol (PVA) with low densities, high porosities, low thermal conductivities, and good mechanical properties. Ramírez et al. [21] recorded a drop in thermal conductivity of mortars incorporated with both rock wool and glass fiber when compared the control mortar. Likewise, Hareedy, Nasr, and Sadek [22] also observed a drop in thermal conductivity in cement bounded boards when rice straw was used to replace fines partially. These results prove that fibrous materials such as mineral wool and rice straw are efficient insulative materials.

The compressive strength of most materials dropped when fibrous materials were incorporated. Ramírez et al. [23] observed a drop in compressive strength in mortars with increasing addition of fibrous materials were included when compared to the control mortar. Although there were cases where compressive strength increased with some addition, it dropped with increasing addition. This was observed in Gorlenko et al. [24] research, which used basaltic fibers in concrete. It is important to note that although the compressive strength recorded was lower than control mortars; it did not go below the approved working standards.

In the case of flexural strength, it was observed that the addition of fibrous materials favorably increased the material's resistance to bending. Ramírez et al. [23] reviewed a positive increase in bending resistance when rock wool and rice straw were incorporated in mortars. Hareedy, Nasr, and Sadek [22], who researched incorporating rice straw into cement bounded boarded also observed an increase in flexural strength, but flexural strength deteriorated with increasing addition. Other studies [23–26] have also dwelt on the thermal insulation properties of rice straw and mineral wool. Also, some applications of fibrous materials in mortar production have been reported [27–30]. The studies noted that fibers enhanced the stiffness properties of mortar pastes.

Mineral wool materials such as rock wool, glass wool, and slag wool are inorganic fibrous materials. Mineral wools are used as materials for filling cavities and spaces like roofs. Studies have shown that mineral wools and rice straw independently have thermal conductivities ranging between 0.030 and 0.050 W/mK [9,31], and 0.051–0.053 W/mK [32], respectively, thus, making them good insulation materials. The typical thermal conductivity of wools is dependent on temperature and moisture content. Sulphur copolymers and tannin-based foam, which have one of the lowest thermal conductivities for an inorganic cellular material, prove to be useful building insulation and fire protection. Tannin-based foam is an alternative to replacing petroleum-based foams.

Although rice straw and mineral wool can be used individually as thermal insulators [33–36], their combined use for mortars are not reported yet. This way, this work aimed to evaluate the use of mineral wool fiber (MWF) and rice straw fiber (RSF) to reduce thermal conductivity in Portland cement mortar (PCM).

2. Materials and methods

2.1. Raw materials and samples

The raw materials used in this study include cement, river sand, mineral wool (rock wool), rice straw, and potable water. Ordinary Portland Cement (OPC), Grade 42.5, was used. Processed rock wool fiber was sourced from a local production plant in Lagos State, Nigeria. Rice straw was harvested from H-Might farms limited, Oyo State, Nigeria. River sand with particles that passed through 0.075 mm size was utilized as fine aggregate for mortar production. Fig. 1 shows the raw materials used for mortar production.

The processed rock wool fiber was washed with clean water to remove impurities, dried in open-air conditions (at average weather conditions of 29 °C temperature and 86% humidity), and chopped into 10 mm particle lengths with a cutter for mortar specimens' size without deterring the mortar significantly. Rice straw (RS) was filtered and washed with clean water until washing water became clean. After, RS was dried for a day in open-air conditions (at average weather conditions of 29 °C temperature and 86% humidity). RSFs were also cut/ground by cutters to size 10 mm, suitable for the mortar specimens. The mix proportion for mortars is shown in Table 1. MWF and RSF were mixed with cement, ranging from 0 to 50%. Four test specimens are considered: (a) mortars without any MWF and/or RSF addition, that is, control mortar (CT); (b) mortars with MWF addition (CT-MF); (c) mortars with RSF addition (CT-RS); and (d) mortars with both MWF and RSF addition.

The fibers were first suspended in water for 24 h before use for producing the mortars, with posterior cement addition. The mixing of constituents was done manually. The mix was kneaded for 15 s before it was mixed. Fine aggregates were then added and mixed for 75 s. A water/cement (W/C) ratio of 0.6 was used to mix all fiber-reinforced mortars. Molds of 40x40x160 mm were prepared for all mortar specimens. For each mix, two specimens were produced and an average result of tests was taken for each. The mold was lubricated, and the mix was poured into it. The samples were cured by immersion in water at a temperature of 20 °C. After a regime of curing (7, 14, and 28 days), the mortars were removed from the mold and placed in a curing tank. Thus, mortars were left to cure at specific day intervals depending on what they were to be tested for. Experimental tests on mortars were evaluated according to BS EN 1015–11:2019 [37] and BS EN 1015–18:2002 [38] standards. Samples of freshly produced mortars are shown in Fig. 2.

2.2. *Thermal conductivity test on mortars*

This test was performed on cylindrical cement mortar specimens with diameter of 30 mm and thickness of 18 mm after curing of 28 days to determine the thermal conductivity. The mortars were subjected to a constant heat of 40 W according to BS EN 1745:2020 [39]. Fig. 3(a) shows the thermal conductivity testing apparatus, while Fig. 3(b) shows samples used in this experiment. Two specimens each were prepared from each mix for the test. Test samples' average temperature and moisture content were 23 °C and 5.3%, respectively.

A smooth smaller cross-sectional surface was placed on the testing apparatus, and the insulating cover was placed on the sample before heating started on the hot plate. The thermal conductivity reading was repeated until temperature and consumption became stable. Thermal conductivity was determined according to Eq. (1).

$$k = \frac{\mathrm{Q} \cdot \mathrm{L}}{\mathrm{A} \cdot \Delta \mathrm{T}} \tag{1}$$

where k is the thermal conductivity per area (W/m·K), A is the surface area of the specimen (m^2), Q is the amount of heat transferred through the specimen (J/s), ΔT is the temperature difference (K).

2.3. *Flexural and compressive strengths tests*

Flexural strength test was performed on a 40x40x160 mm cement mortar beam specimen after 28 days. This beam is usually subjected to a bending load until failure was achieved [40]. As indicated in the previous section, for each mix, two specimens were produced and an average result of tests was taken for each. A three-point loading technique was used for the flexural strength test. For this arrangement, support rollers are 100 mm apart, and the loading roller is located above the prism sample at its midspan. The adopted loading rate was 0.005 mm/s on a 200 kN capacity three-point flexural strength testing machine.

The experimental setup showing the tested sample is shown in Fig. 4. The flexural strength was determined using Eq. (2).

$$f = 1.5 \cdot \frac{\mathrm{F} \cdot \mathrm{L}}{\mathrm{b} \cdot \mathrm{d}^2} \tag{2}$$

where f is the flexural strength (MPa), L is the distance between the support rollers (mm), b is the width of specimen (mm) and d is the depth of the specimen (mm); b and d were taken from the mold dimensions. Results are presented by the average and standard deviation of three tested specimens.

Fig. 1. Raw materials used for mortar production: (a) rice straw; (b) rock wool; and (c) river sand.

Table 1
Mix proportion of raw materials.

MIX ID	Cement (wt%)	Mineral Wool (wt%)	Rice Straw (wt%)	Sand (wt%)
CT	100	0.00	0.00	100
CT-MF/10	100	10.00	0.00	100
CT-MF/30	100	30.00	0.00	100
CT-MF/50	100	50.00	0.00	100
CT-RS/10	100	0.00	10.00	100
CT-RS/30	100	0.00	30.00	100
CT-RS/50	100	0.00	50.00	100
CT-MF-RS/10	100	5.00	5.00	100
CT-MF-RS/30	100	15.00	15.00	100
CT-MF-RS/50	100	25.00	25.00	100

Fig. 2. Samples of produced mortars.

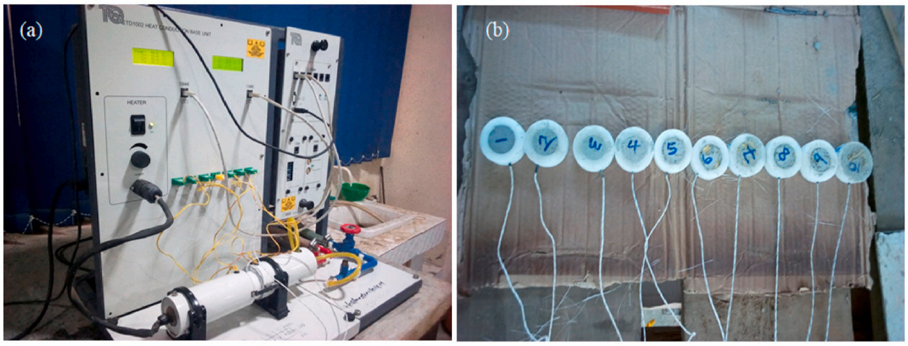

Fig. 3. (a) Thermal conductivity testing apparatus; (b) Mortars for thermal conductivity testing.

Compressive strength test was performed on 80x40x40 mm cement mortar specimen after 28 days. The samples used for this test were broken halves obtained from the flexural test, as recommended by BS EN 1015–11 [37]. The mortars were subjected to a compressive load usually from a hydraulic machine until failure was achieved. The compressive strength testing machine used and the mortar specimen are shown in Fig. 5. For compressive strength tests, three specimens were broken into two halves to provide six half specimens that were tested and the results were calculated according to Eq. (3), being presented by average and standard deviation. where σ is the compressive strength (MPa), F is the maximum load carried by the specimen (N), and A is the cross-sectional area of the bearing plate (mm^2).

2.4. Apparent density and porosity

The procedure of measuring density of mortars according to BS EN 1015–10 [41] was adopted in this study. Mass of mortar prisms were obtained by weighing on the mini digital scale. A consistent oven-drying of the mortars at constant temperature of approximately 60 °C was done until when a consecutive weight can be achieved within the space of 2 h. Finally, the average of the weights of similar mixes were obtained and divided by the volume of the prism to determine the density.

The apparent porosity of the mortar was obtained using equation (4) [42]:

Fig. 4. Flexural strength apparatus for tested mortars.

Fig. 5. Compressive strength of tested mortars.

$$\sigma = \frac{F}{A} \tag{3}$$

$$P_a = \frac{w_a \times \rho_a}{\rho_w \times 100} \tag{4}$$

Where P_a = apparent porosity in (%), w_a is water absorption in (%), ρ_a is apparent density in (kg/m^3), and ρ_w is the density of water in (kg/m^3).

2.5. Water absorption (WA) test

The water absorption coefficient due to the capillary action of mortars is measured at 20 °C. A face of a mortar specimen was immersed in 5–10 mm of water for a period of time until it was fully saturated [43]. Two specimens each were prepared from each mix for the test. Halves of 160x40x40 mm specimens used for the flexural test were used for the test. Water absorption was calculated using Eq. (5).

$$WA = \left(\frac{W_2 - W_1}{W_1}\right) \times 100 \quad (5)$$

where WA is water absorption (%), W_1 is the dried specimen weight (g), and W_2 is the weight of the moist specimen body (g).

2.6. Microstructural analysis

Following the mechanical and thermal conductivity tests on mortal samples, selected mortar mixes were examined using the Scanning Electron Microscopy (SEM). This test was necessary as it gives the inherent properties of the selected mortars, and moreover, the test aided the interpretation of the observed mechanical properties. Crumbs of samples from selected mixes were prepared for the test.

This study performed SEM in the second electron mode using a carbon coating in a SEM machine. Fig. 6 shows a Philips XL 30 SEM apparatus used for the material examination.

3. Results and discussion

3.1. Apparent density and porosity

The results of the apparent density and porosity is presented in Fig. 7. With this result, the performance of the mortars in terms of porosity, water absorption and density could be described. The density of all mortars was higher than the limit of 1300 kg/m^3 for normal weight mortars [44], which thus suggested that the fabricated mortars would suite the required applications in structural concrete. Generally, apparent density was higher and porosity was lower for most of the specimens, and it is deduced that mineral wool and rice straw additions contribute to the apparent density of the mortars, but there was no significant effect on porosity of mortars. This assertion is in agreement with the findings of a related study [45], where the effects of some selected supplementary cementitious materials on mortars have been investigated.

3.2. Thermal conductivity

The thermal conductivity test results on mortars are presented in Fig. 8. For samples with the addition of mineral wool fibers, the greater the amount of mineral wool, the lower the thermal conductivity; similar behavior can be seen for rice straw fibers addition. However, when both mineral wool and rice straw were added, the greater their amount, the greater the thermal conductivity, but still, thermal conductivity was less than that of control samples, an evidence that thermal insulation of modified mixtures has been enhanced. These results help to infer that both mineral wool and rice straw fibers are suitable for thermal insulation applications.

The 50 wt% RS mortar recorded the lowest thermal conductivity of all mortars. Compared with the 10 wt% RS and 30 wt% RS mortars, there is an observed decline in thermal conductivity with the increasing addition of rice straw fibers. This observation corroborates with Hareedy, Nasr, and Sadek [22] identifying improved insulation resistance with increased fibrous material, that is, palm oil fuel ash (POFA). Other similar study reported that POFA and polymer fiber addition of about 0.3 vol% reduced thermal conductivity of mortars [46]. Cellulose fiber has been reported to reduce the thermal conductivity of mortar [47]; and coconut fiber has also been noted to improve the thermal comfort in low-cost building [48]. Similarly, agricultural wastes such as fallen leave fibers and straws demonstrated substantial enhancement of the thermal insulation properties of mortar [49].

However, in this study, there was a slight inconsistency in thermal conductivity of the mortars, where the CT-MF-RS/50 mortar recorded a higher thermal conductivity than the CT-RS/30 mortars. This could be attributed to lower pore volume as observed in the water absorption test. From observation, rice straw fibers prove to be a better insulator in mortars when compared to mineral fibers. This could be attributed to their hollow structure [45]. The CT-MF/10 mortar recorded the test mortars' highest thermal conductivity, attributed to the lower pore volume.

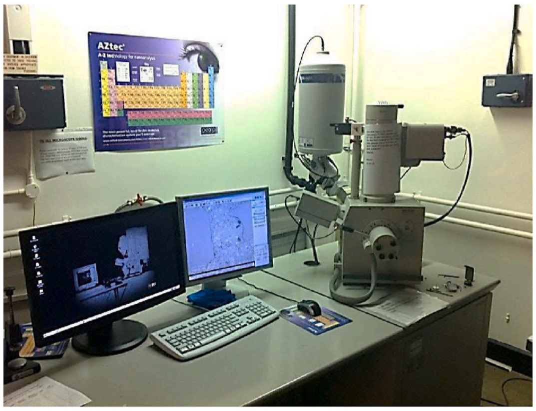

Fig. 6. SEM apparatus.

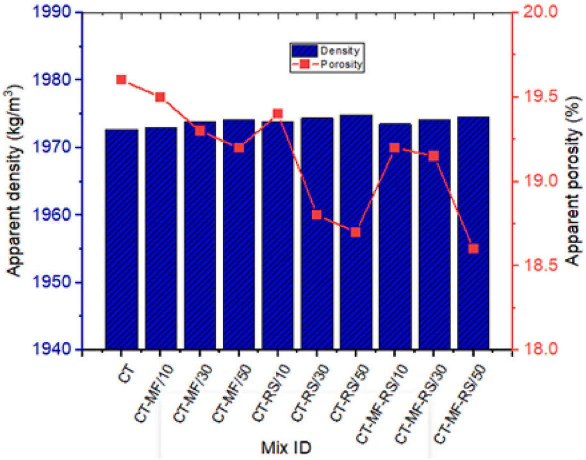

Fig. 7. Apparent density and porosity of mortar.

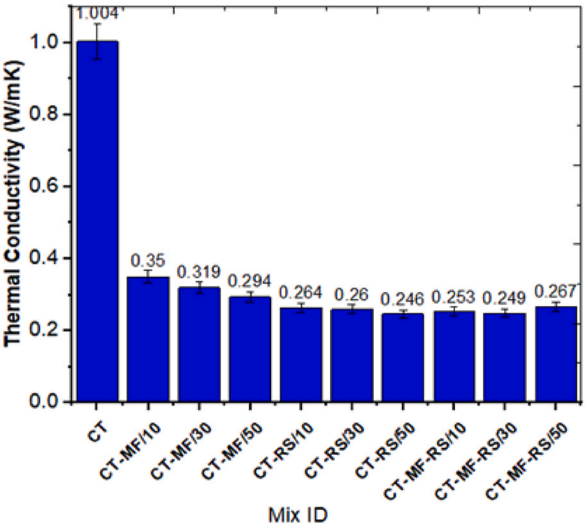

Fig. 8. Thermal conductivity of mortars.

3.3. Flexural and compressive strengths of mortars

Fig. 9 shows the trend in flexural strength of the tested mortars. With the addition of mineral wool fibers, the greater the content of mineral wool fibers, the less the flexural strength. Although works show that mineral wool fibers can increase mechanical strength [50–59] when replacing cement, sand or aggregate, they were added and mixed with cement and sand.

The flexural strength increased for all tested mortars. At 7 days, all mortars with the addition of mineral wool and rice straw fibers (individually or mixed) presented flexural strength higher than control mortar, but at 14 days and 28 days, only CT-MF/10 flexural strength was higher than control mortar.

The compressive strength results of tested mortars are shown in Fig. 10. At 7 days, mortars with the addition of mineral wool and rice straw fibers (individually or mixed) increased compressive strength when compared to control mortar. At 14 days, only CT-MF/10, CT-RS/10, CT-RS/30, and CT-RS/50 presented compressive strength higher than CT; however, at 28 days, none of the mortars with fibers presented results higher than CT. For mortars with RSF addition, the decrease in compressive strength of mortars at 7 days was similar to the work of Agwa et al. [60] for rice straw ash (RSA). These authors reported the pozzolanic behavior of RSA improved compressive strength and decreased porosity, but this behavior was not observed in this work.

3.4. Water absorption coefficient

It could be observed on Fig. 11 that the addition of MF and RS fibers increased the water absorption of mortars, when compared to the control mortar. This result verifies the observation of large pore volumes on the CT-MF-RS-30 mortar from the SEM micrograph. Zhang and Zong [57] noted that a high pore volume in a mortar would yield greater permeability which is a factor that affects a mortar’s resistance to penetration of water and thermal conductivity. Gebremariam et al. [61] added mineral wool fiber (0.5 wt%) as

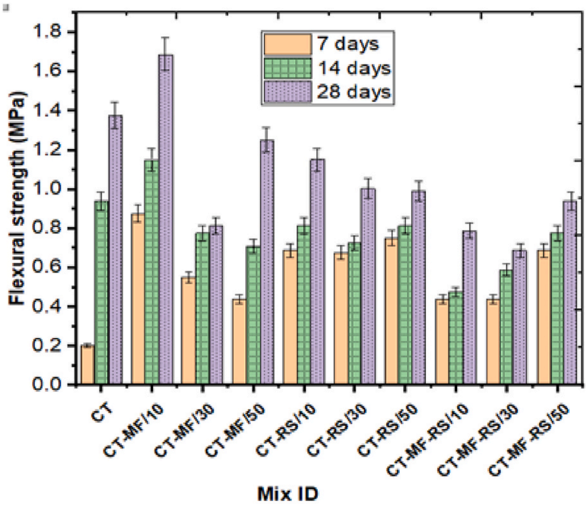

Fig. 9. Flexural strength of test mortars.

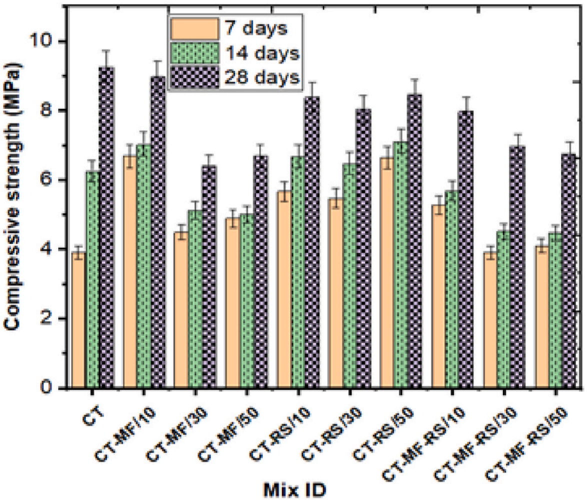

Fig. 10. Compressive strength of mortars.

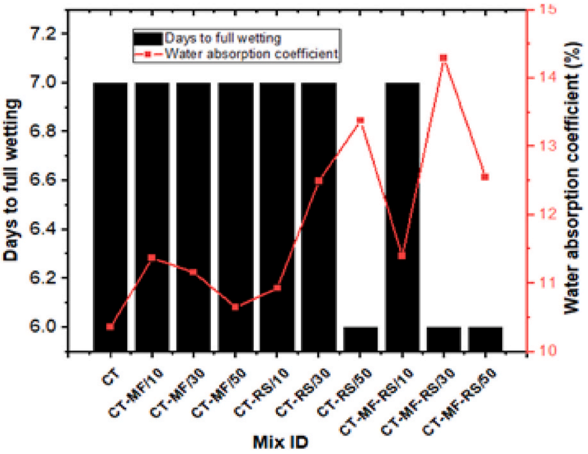

Fig. 11. Water absorption of mortars.

additive (limestone replacement) to evaluate their influence in concrete and noted that this addition increased the water absorption. Although Kubiliute, Kaminskas and Kazlauskaite [62] pointed out that 10–40 wt% of MWF decreases porosity, mortars where MWF was added absorbed more water than CT mortar; similar behavior was observed to mortars where RSF was added, probably due to fibers' shape.

3.5. SEM micrographs

In order to understand the water absorption and flexural and compressive strengths behaviors, scanning electron microscopy (SEM) was performed.

There was an observed orderliness in all samples when scanned at 1000× magnification. It can be seen in Fig. 12(a) that CT mortar shows a distinguished homogeneity, while CT-MF-10 (Fig. 12(b)) and CT-MF-RS-30 (Fig. 12(c)) show a rougher surface, indicating composite materials in mortar.

Considering the SEM of selected mixes at higher magnification control (Fig. 13(a)), 10% mix (Fig. 13(b)), and 30% mix (Fig. 13(c)), a cluster of fibers can be easily identified in CT-MF-30 mortar. The clusters indicate uneven distribution, causing inhomogeneity, which could be the primary reason for the low mechanical performance of this mix compared to other test mortars (Figs. 7 and 8). This behavior is similar to that of Ramírez et al. [23], who also indicated the drop in mechanical properties of mortars with recycled mineral fibers due to inhomogeneity caused by the uneven distribution of fibers. The Inhomogeneity of mortars with addition of MWF and RSF could be due to poor bonding of fibers with other constituents. The mortars with both MWF and RSF proved to be an inadequate adhesive reinforcement for mortars.

Analyzing CT mortar (Fig. 14(a)), it can be seen that there is low quantity of pores and/or cracks when compared to CT-MF-10 mortar (Fig. 14(b)) and CT-MF-RS-30 mortar (Fig. 14(c)). Comparing CT-MF-10 mortar and CT-MF-RS-30 mortar, it can be seen that CT-MF-10 presents a lower porosity than CT-MF-RS-30 mortar, which could be the key reason for the different mechanical performance of these mortars. It was also noticed that fibers could not be easily spotted. This could result from mineral fiber reinforcement having better homogeneity in mortars, causing a reduction in pore volume.

4. Conclusions

This study evaluated the influence of the addition (individually or mixed) of MWF and RSF on thermal insulation, flexural strength, compressive strength, and water absorption of Portland cement mortars. The following conclusions were drawn from the study:

- The study showed that both rice straw and mineral wool improved the thermal conductivity of mortars, and the same increased as the rice straw and mineral wool content were increased in the mix. Best insulation performance has been observed with rice straw than mineral wool fiber.
- The strength properties of the mortars (compressive and flexural strengths) increased with curing regimes, which conform with the general performance of cementitious composites. However, the control mix gave better strength than the modified mixture. Yet, the modified mixes are considered fit for wall application as their strength are within the range of building mortars based on BS EN 998–1. This result proves the feasibility of using mineral wool and rice straw mortars to improve the insulation of mortars and provides a gap to be breached in manufacturing construction materials in the industry.
- The water absorption properties of the mortars was somewhat inconsistent. However, the water absorption coefficient was genrall above 10% for all samples, which acceptable for building application. This performance was checked with the SEM micrographs, which showed pores' sparing presence in the matrix.

Authors statement

Paul O. Awoyera: Conceptualization, Investigation, Data curation, Formal analysis, Roles, Writing - original draft Writing – original draft. Ayomide D. Akinrinade: Investigation, Formal analysis, data analysis, Writing - review & editing Writing – review & editing. André Gustavo de Sousa Galdino, Fadi Althoey, Mehmet Serkan Kirgiz, and Bassam A. Tayeh: Writing – original draft, review, and resources.

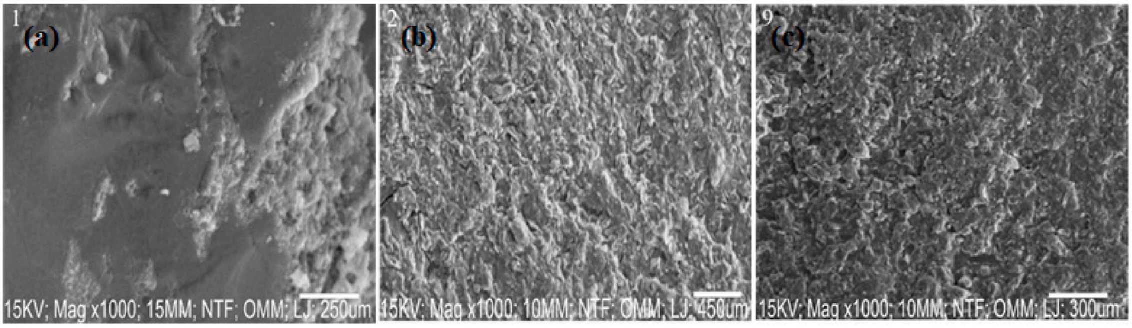

Fig. 12. SEM micrographs at 1000× magnification for: (a) CT mortar; (b) CT-MF-10 mortar; and (c) CT-MF-30 mortar.

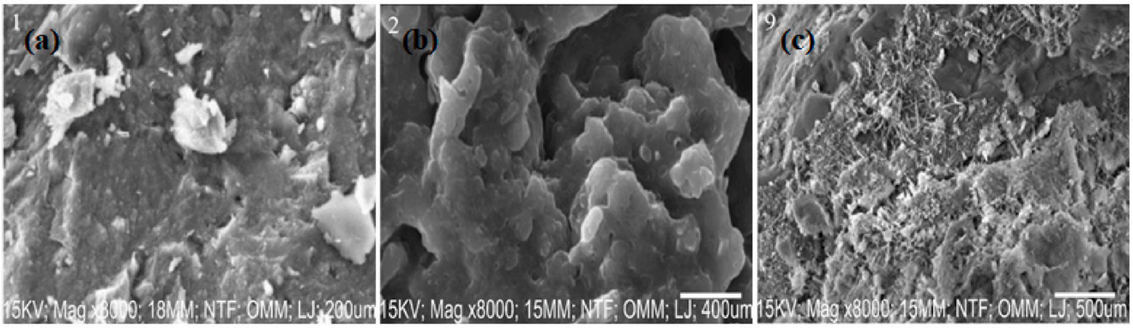

Fig. 13. SEM micrographs at 8000× magnification for: (a) CT mortar; (b) CT-MF-10 mortar; and (c) CT-MF-30 mortar.

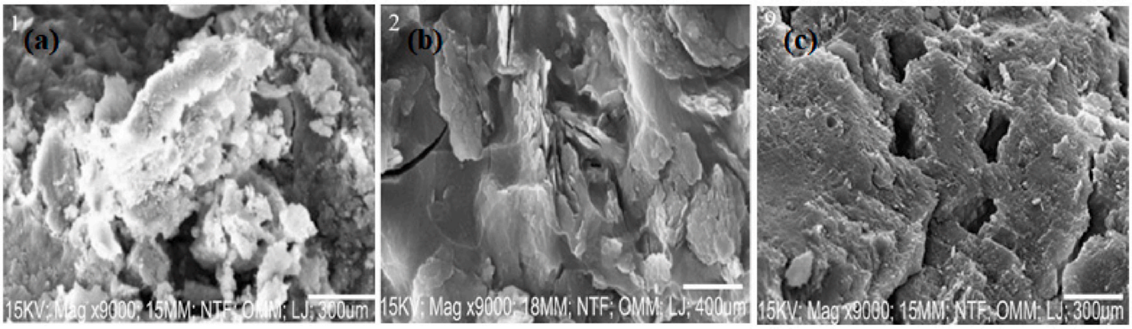

Fig. 14. SEM micrographs at 9000× magnification for: (a) CT mortar; (b) CT-MF-10 mortar; and (c) CT-MF-30 mortar.

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.

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