

Article

Development of Limestone Calcined Clay Cement-Based Lightweight Bricks Incorporating Waste Rockwool: A Step into Leading the Way in Low-Carbon Bricks

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Abstract: This study aimed to develop eco-friendly limestone calcined clay cement (LC3)-based lightweight bricks by reusing waste rockwool (RW) with the improvement of technical performances such as thermo-physical and mechanical, including fire-resistance performances. LC3 binder was blended with expanded clay (EC) aggregates at a ratio of binder-to-aggregate of 1:1.5 (vol%). EC was substituted by waste RW at different percentages, ranging from 5 to 15 vol%. Several technical properties such as density, compressive strength, total porosity, water absorption, thermal conductivity, and thermal diffusivity were investigated after 7 days of curing. The fire-resistance performance of the developed bricks was determined by assessing the residual compressive strength after exposure to standard fire for up to an hour. With dry bulk densities ranging from 1200 to 1360 kg/m³ and compressive strengths (>8.60 MPa), the developed brick met the acceptance criteria for non-load-bearing applications. Even at the highest dosage of RW, the results demonstrated a thermal conductivity as low as 0.36 W/mK, indicating that the developed brick is suitable for hot weather zones, as it reduces the heat flow into buildings. The partial replacement of EC by RW is very beneficial in enhancing the fire-resistance performance, and a residual strength of about 89.7% has been maintained by the bricks incorporating 5% waste RW after 1 h of fire exposure (employing a maximum applied temperature of 927 °C). Lifecycle assessment results indicated that up to 13% lower carbon emissions are associated with LC3-based lightweight bricks designed to reuse a higher amount of waste RW.

Keywords: compressive strength; fire resistance; lifecycle assessment lightweight bricks; thermal conductivity; waste reuse



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1. Introduction

Since thousands of years ago, fired clay bricks (FCBs) have been synthesized and used as traditional load-bearing building units [1]. These bricks are characterized by acceptable strength and high firing resistivity [2,3]. Over the years, after the discovery of Portland cement (PC), a new type of building block known as concrete block (CB), in which PC is the sole binder, was synthesized with higher strength [4,5]. However, both fired clay bricks and concrete blocks are still being used in construction projects. CB is synthesized

by mixing aggregate with PC, followed by compaction, to produce a hardened material with considerable mechanical properties [6]. Unlike traditional structural concrete, CB is fabricated using lower cement content [7]. The high CO₂ emissions and high energy demand are the main disadvantages of CB manufacturing [8–10]. Approximately one tonne of CO₂ is produced during the manufacturing of one tonne of PC [11,12]. PC manufacturing is responsible for around 8% of the total global CO₂ emissions [12,13]. Additionally, the manufacturing of one tonne of PC consumes 2.8–3.0 GJ/tonne [14,15].

Many attempts have been made to mitigate the CO₂ emissions produced from PC manufacturing and to decrease the energy demand [16–18]. One efficient approach to producing an alternative binder with low CO₂ emissions and energy demand is to replace PC with calcined clay and limestone powder [19]. PC can be replaced with 40 wt% calcined clay and 20% limestone powder to produce limestone calcined clay cement (LC3) [20]. LC3 is utilized in the preparation of cement mortar [21], concrete [20], and soil stabilization [22]. Different grades (25, 32, and 45 MPa) of concrete can be fabricated using LC3 [23]. The key hydration products inside LC3 are calcium silicate hydrate and monocarboaluminate [24–27]. Previous works have also proven that LC3-based building products exhibit higher resistance to aggressive environments, such as alkali–silica reaction, carbonation, long-term reinforcement corrosion, sulphate resistance, and firing, compared to neat PC [24,27–29]. There are many benefits of producing and using lightweight building materials, such as reducing the building load, enhancing handleability, minimizing transportation costs, and facilitating their application in various construction sectors.

Lightweight bricks can be synthesized by using lightweight aggregate [30,31] and/or the application of a foaming process [32,33] during manufacturing. Recently, Zhou et al. [34] synthesized lightweight LC3-based composites by replacing silica sand with fly ash cenospheres. These composites exhibited higher ductility, slightly lower strength, and also lower strengths compared to composites containing neat PC. LC3-based lightweight mortar was formulated by using autoclaved aerated concrete aggregate, with volume percentages of 25, 50, and 75% [21]. The mortar containing 75% autoclaved aerated concrete achieved a 28-day bulk density of 1280 kg/m³, compressive strength of 13 MPa, and thermal conductivity of 0.21 W/mK. Furthermore, it exhibited outstanding properties under thermal load. The utilization of waste RW for improving the mechanical and thermal performances of LC3-based mortars made with natural aggregates [35,36], recycled aggregates [35], and lightweight aggregates [36] was recently studied, in which the RW was added at small percentages ranging from 1 to 5% by weight of LC3 binder. Despite many studies focusing on the preparation and performance of OPC-based lightweight composites [5], no studies have addressed the production of lightweight bricks containing LC3 as the sole binder. Therefore, this study aims to focus on the fabrication of lightweight bricks containing LC3 as a binder and expanded clay (EC) as aggregate. The study presents an attempt to substitute the EC with the waste RW lumps at various volume percentages up to 15%.

Several lifecycle assessment (LCA) studies were conducted to evaluate the environmental impacts of clay brick and concrete block production with alternative materials and techniques. For example, Dabaieh et al. [37] demonstrated that fired clay bricks are associated with substantial environmental impacts. Compared to traditional clay bricks, about 15–20% (depending on the indicators) of the lower environmental impacts were found for bricks produced with organic waste [38]. Similar environmental benefits were also reported for producing organic waste-incorporated porous bricks, by Bories et al. [39]. Compared to conventional concrete blocks, eco-blocks produced with waste materials and a certain percentage of alternative cementitious materials reduce about 20% of the total carbon emission [40]. Thus, it is well established that incorporating waste materials into the brick and block production can significantly reduce environmental impacts. However, no LCA study has been found for producing lightweight bricks containing LC3 with partial replacement of EC by waste RW. The integration of industrial waste and lightweight aggregate into a green low-cement binder for the production of eco-friendly bricks with improved thermal performance, fire resistance, and mechanical strength reveals the innovation of this study.

2. Materials and Methods

2.1. Materials

2.1.1. Binder

In this study, a green LC3 ternary blended binder was created by replacing 60 wt% of Ordinary Portland Cement (OPC, CEM I 42.5N) with a combination of limestone powder (LS) and metakaolin (MK) in a 1:2 weight ratio of limestone to metakaolin. This blend was chosen for its excellent cementing performance, nearly matching that of 52.5N-grade OPC, and its ability to reduce CO₂ emissions by approximately 30% [35,36]. The MK was produced by activating kaolinite clay (42% kaolinite content) at 750 °C for two hours. The physical properties and the chemical composition of the ingredients of LC3 are illustrated in Table 1. The sum of percentages of pozzolanic oxides including silica, alumina, and iron oxide is 91%, which is higher than the minimum threshold specified by ASTM C618 [41] for pozzolanic materials.

Table 1. Chemical composition (wt%) and physical properties of the ingredients of LC3.

Material	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	Na ₂ O	SO ₃	L.O.I.	Specific Gravity	Surface Area, m ² /g
Ordinary Portland cement (OPC)	21.32	6.20	3.18	63.60	0.58	0.12	2.69	2.59	3.16	0.33
Metakaolin (MK)	52.15	39.00	0.18	0.43	0.030	0.08	0.03	8	3.10	11
Limestone powder (LS)	0.22	0.09	0.02	57.71	0.20	0.09	0.04	41.63	2.56	0.54

2.1.2. Aggregate

Expanded clay (EC) aggregate was used for producing lightweight bricks because of its low density and thermal conductivity. In rockwool production, waste materials like fiber lumps and fine dust are typically disposed of in landfills. However, the waste fiber lumps can serve as a replacement for coarse and fine aggregates, as demonstrated in a prior study [1]. Sieve analysis has been conducted for the as-received RW lumps to insure that the grading meets the requirements of ASTM C33 [42] for fine aggregates.

Table 2 presents the physical characteristics of EC and waste rockwool (RW), while Figure 1 displays the grain size distributions for both waste RW and EC.

Table 2. Comparative physical properties of aggregates used in this study.

Property	EC	Waste RW
Color	Brown	Yellow
Moisture Content, % max	0.39	0.21
Specific Gravity	0.28	0.24
Thermal Conductivity, W/mK	0.071	0.047

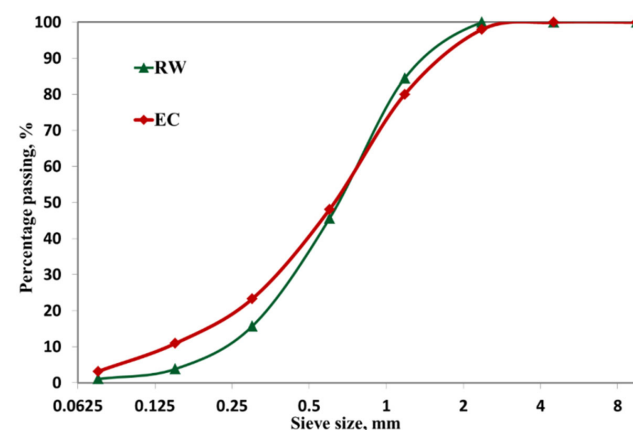


Figure 1. Grain size distributions of EC and waste RW.

The micro-morphology and pore structure of EC and waste RW, respectively, were analyzed by SEM, as introduced in our previous studies [35,43]. EC showed a porous structure with spherical and elongated-shaped pores. In addition, the high closed-cell content is obvious. With an average size of about 1–2.5 mm, the RW exhibited fiber lumps/agglomerates. In addition, the XRD pattern revealed its fully amorphous structure, i.e., resembling active pozzolan, as illustrated in our previous study [35].

2.2. Sample Preparation, Testing and Analysis

First, a mechanical mixer was used to blend 40 wt% OPC, 40 wt% MK, and 20 wt% LS for 5 min to produce the LC3 binder, as described previously. This LC3 binder was combined with expanded clay (EC) lightweight aggregate, making up 60% of the aggregate volume. Water was then added (with a water-to-binder ratio of 0.5) to form the reference LC3-based lightweight brick, labeled “Ref” in this study, for comparison purposes. Three groups of lightweight bricks, each containing three specimens, were also produced. In these groups, waste rockwool (RW) partially replaced EC at volume percentages of 5%, 10%, and 15%, labeled as M1, M2, and M3, respectively, as shown in Table 3. Dry materials, including the LC3 binder, EC aggregates, and waste RW, were mixed at a slow speed of 50 rpm until a uniform mixture was achieved. Water was then added according to the specified water-to-binder ratio, to maintain consistent workability across RW-blended LC3 bricks. The ratios were set at 0.5 for Ref, 0.53 for M1, 0.55 for M2, and 0.59 for M3. These variations in water ratios are attributed to the higher fineness of the RW as compared to the EC grains. The increased water content may result in increasing the porosity, and this is helpful in reducing the bulk density and hence thermal conductivity.

Table 3. Mixture proportions of the developed bricks (kg/m³).

Mix	Binder			Aggregate Type		Water
	OPC	MK	LS	EC	RW	
Ref	232.5	232.5	116.25	565	0	290.63
M1	232.5	232.5	116.25	0	555	308.08
M2	232.5	232.5	116.25	0	500	319.72
M3	232.5	232.5	116.25	0	380	342.96

Additionally, 1% superplasticizer (by binder weight) was incorporated into each mixture. The fresh mixtures were poured into wooden molds with dimensions of 190 × 90 × 50 mm to create brick samples, which were then stored at 25 °C and 50% relative humidity for 24 h. The samples were demolded and water-cured for 7 days. Figure 2 presents a photograph of several prepared LC3-based lightweight bricks. After curing, their mechanical properties, such as compressive strength, were assessed following ASTM C67 [44]. Bulk density, apparent porosity, and water absorption were evaluated according to ASTM C20 [45], while thermal conductivity and thermal diffusivity were measured per ASTM D5334 [46]. Finally, the microstructural characteristics of freshly fractured brick specimens were analyzed using a scanning electron microscope (SEM).

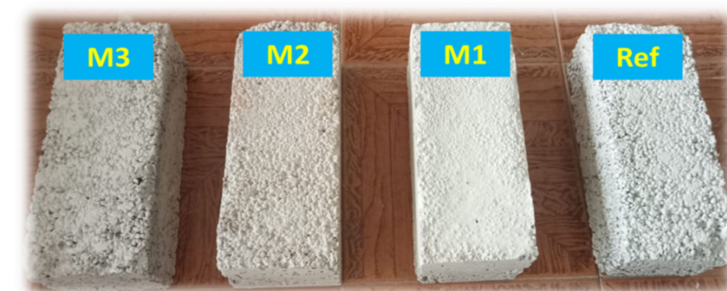


Figure 2. Photograph of some of the prepared brick specimens.

In order to examine the fire-resistance performance, the 28-day compressive strength was determined for brick samples exposed to standard fire up to one complete hour (1 h), according to the temperature–time curve of ISO 8340 [47], employing a maximum applied temperature of 927 °C, as shown in Figure 3 [48], and the residual strength was calculated relative to the initial compressive strength before fire exposure.

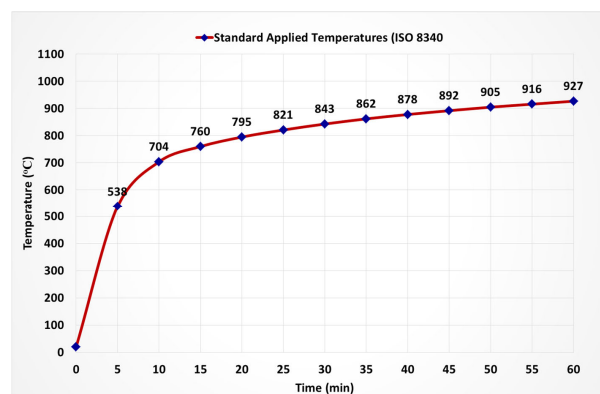


Figure 3. Temperature–time curve according to ISO 8340.

2.3. Lifecycle Assessment of LC3-Based Lightweight Brick Production

To address key environmental concerns, the carbon emissions (expressed in CO₂ equivalents) for mixtures containing varying proportions of waste rockwool (RW) and conventional mixtures (without RW) were evaluated using standardized lifecycle assessment (LCA) techniques, following ISO guidelines. This study applied a “cradle-to-gate” system boundary with 1 m³ of lightweight brick production as the functional unit. Due to the lack of localized lifecycle inventory (LCI) data for Egypt, the LCI was developed using various sources, including the scientific literature, environmental product declarations (EPD), and databases. For example, data for OPC production were sourced from Vanderborght et al. [49]; emission factors for metakaolin, limestone powder, expanded clay, and waste rockwool were derived from Maddalena et al. [50], Kim et al. [51], Uceda-Rodríguez et al. [52], and an EPD within the Egyptian context [53], respectively. Waste rockwool was used in designing the lightweight bricks in this study, and only end-of-life processing of waste rockwool was considered (e.g., transport and reuse processing). LCI data for superplasticizer production were sourced from MPA (2009) [54] and calculated based on Hossain et al. [55]. The brick production process was excluded from the assessment, since it remained constant across mixtures, ensuring it did not affect the comparative results. Similarly, emissions from water usage and transportation were excluded, as these factors were consistent across all scenarios and would not impact the comparative analysis.

3. Results

3.1. Technical Performance

The 28-day compressive strengths of LC3-based lightweight bricks incorporating various percentages of waste RW as volume replacements for EC aggregates before and after fire exposure are shown in Figure 4. A significant increase in compressive strength has been obtained with increasing RW percentages up to 10 vol%. Enhancements of about 34.88 and 42.44%, relative to the reference brick, have been obtained for the bricks incorporating 5 and 10 vol% of waste RW, respectively. Although increasing the RW content to 15 vol% led to a slight decrease in the compressive strength, 15% RW-blended bricks possessed a relatively higher strength than the reference brick (without RW). The improved compressive strength is attributed to the unique features of RW in terms of pozzolanic reactivity and fiber-like morphology, which help in improving the physical packing of the LC3 host matrix. Due to its high amorphous silica content, RW effectively participates in the pozzolanic reaction and creates additional cementitious hydrates that

fill the interstitial spaces between the matrix and EC aggregate [56–58]. In addition, due to its ultra-fineness, the fiber-like RW uniformly distributes throughout the skeleton of the cementitious matrix and provides matrix reinforcement. Previous studies affirmed the considerable improvement in compressive strength of cement-based composites by the addition of waste RW for the substitute of natural aggregates [56,57]. These studies assigned the significant increase in compressive strength with the increase in replacement percentages and curing age to the extreme fineness of RW waste, which helped enhance the pozzolanic properties and particle packing density of cement. Moreover, another study affirmed that RW fibers can arrest cracks in cement-based structures, inhibiting internal crack propagation and hence improving strength [56]. The degradation of strength with 15% RW is attributed to the agglomeration of RW fiber and hence the associated difficulties in attaining uniform distribution. Fire exposure can significantly affect the physical and mechanical properties of cement-based structures [58]. As can be seen from Figure 4, the waste RW has significantly influenced the residual compressive strength of LC3-based lightweight bricks after standard fire exposure for an hour. The reference brick without RW has attained the lowest residual strength; it maintained about 70% of its initial strength after fire exposure. The maximum residual strength of about 90% has been achieved by the bricks incorporating 5% waste RW; i.e., an enhancement of residual strength by about 20% has been achieved, relative to the reference brick without RW. This significant enhancement points out the effective role of RW in enhancing the fire-resistance performance. The enhanced fire-resistance performance is attributed to the superior thermal resistance of RW [51]. A previous study assigned the enhanced residual strength to the thermal compatibility between EC aggregates and the LC3 host matrix, in addition to the unique structural quality of the interfacial transition zone (ITZ) [42]. The increased packing of the bricks, incorporating 10% of RW, is responsible for the slightly reduced residual strength after fire exposure. This is because, in compact or dense cement-based structures, the releases of water vapor upon the dehydration of the binder cause internal stresses and create a high number of microcracks in the structure [21].

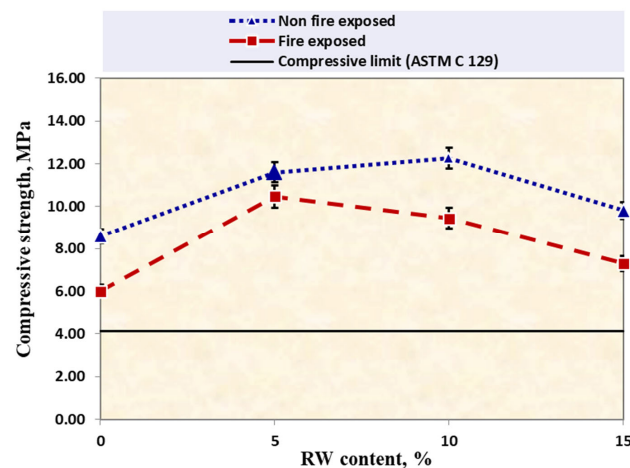


Figure 4. Compressive strength of the fire and non-fire exposed lightweight bricks cured for 7 days, along with relative strength (ASTM C 129).

3.2. Density and Thermal Performance

The variations in thermal conductivity (K) and thermal diffusivity (D) with dry bulk density of the newly developed LC3-based lightweight bricks incorporating various amounts of RW are presented in Figure 5. The lowest density of 1200 kg/m^3 was obtained for the control/reference brick, and the brick with 15 vol% RW possessed the highest density, of 1360 kg/m^3 . The increase in density points to the improved physical packing caused by the dispersion and uniform distribution of RW fibers through the LC3-host matrix. The newly developed LC3-based bricks possessed densities below the density limit

prescribed for lightweight cement bricks (1680 kg/m^3), as per ASTM C 129 [59]. A slight increase in both the conductivity and thermal diffusivity has been found with the increase in RW content in the prepared bricks, since the higher percentage of RW contributes to better packing and hence higher density, thermal conductivity, and diffusivity. Although, RW is superior insulating material, the slight increase in thermal conductivity is attributed to the relatively higher K-value of RW relative to the static air enclosed in voids [60,61]. It is well known that, as the thermal diffusivity increases, the rate of temperature change as heat passes through the structure increases. Therefore, the increased thermal diffusivity confirms the improved packing by RW addition. Although the RW-blended bricks possessed higher thermal conductivity, their thermal conductivity values are still lower than those reported in previous studies for lime, cement, clay, and stabilized soil-based lightweight bricks, as summarized in Table 4 [62–66]. In addition, other studies on sintered clay-based bricks reported relatively lesser thermal conductivities; however, these types of bricks are intensive energy consumers, due to the thermal treatment at high temperatures of $900\text{--}1000^\circ\text{C}$ [67,68]. The low thermal conductivities of the newly developed LC3-based lightweight bricks incorporating EC and RW are attributed to the inferior thermal conductivity of EC (as low as 0.071 W/mK [58]) assigned to its porous structure. In addition, RW is one of the most effective thermal insulation materials [55].

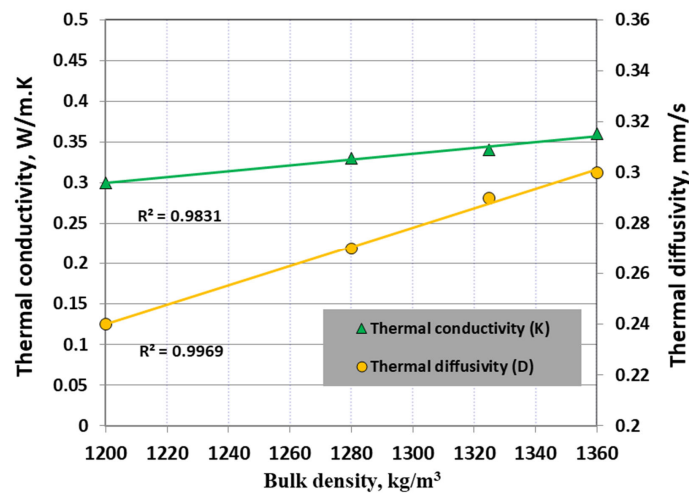


Figure 5. Relationship of thermal conductivity and thermal diffusivity with density for the designed LC3-bricks.

Table 4. Density and thermal conductivity of various lightweight bricks incorporating various additives.

Reference	Brick Type	Additive		Firing Temperature, $^\circ\text{C}$	Density, kg/m^3	Thermal Conductivity, W/m.K
		Type	Percentage			
Current	LC3-based	Waste RW	15 vol%	unfired	1360	0.36
[62]	Lime-based	Oil palm fibers	1% wt	unfired	1338.7	0.39
[63]	Cement-stabilized earth block	--	--	unfired	1500	0.52
[64]	Earth bricks stabilized with cement	Wheat straw fiber	3 wt%	unfired	1357.7	0.39
		Barley straw	3 wt%	unfired	1139.9	0.365
[65]	Sintered clay brick	Hazelnut shell (HS) waste	10 wt%	900	1400	0.57
[66]	Sintered clay brick	Carbonation sludge	10 wt%	1000	1800	0.58
[67]	Sintered clay brick	Pomegranate peel waste (PPW)	12.5 wt%	1000	1230	0.20
[68]	Sintered clay brick	Expanded polystyrene (EPS)	2.5 wt%	1000	885	0.29
		Waste rubber tire powder (WRTP)	15 wt%	1000	1310	0.31

3.3. Porosity and Water Absorption

Figure 6 shows the variation in total porosity and water absorption of the bricks incorporating different amounts of RW. A direct relationship between water absorption values and apparent porosities has been obtained. The addition of RW led to a significant decrease in porosity and, hence, water absorption. The water absorption decreased from 15.8% for the reference brick to 13.1 and 12.7% for the bricks incorporating 5 and 10 vol% of RW, respectively. The decrease in water absorption is due to the improved packing density attained by RW-dispersed fibers. Although the increase of RW to 15 vol% led to increased porosity and water absorption, its performance against water absorption is still better than the reference brick. According to the technical requirements of ASTM C62 [69], all the produced bricks can be used for construction activities as severe weathering-resistive bricks with water absorption less than 17% [68]. The high closed-cell content of the used EC aggregate is responsible for these unique water absorption characteristics [56]. Referring to the maximum water absorption limit of bricks (20–30%) [70], all produced bricks have improved resistance to water ingress.

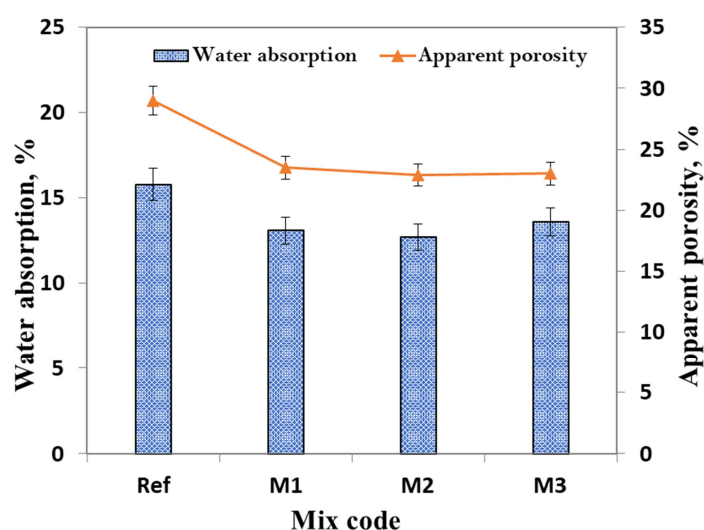


Figure 6. Water absorption and the total porosity for the developed bricks.

3.4. Microstructure Investigation

The microstructure characteristics of the newly developed LC3-based lightweight bricks are introduced in Figure 7a–h. The SEM micrograph of the reference brick revealed a compact structure and adequate bonding between the EC aggregate and the LC3 host matrix. After fire exposure, although relatively less bonding at ITZ has been observed due to the partial decomposition by fire action, the microstructure showed reasonable quality (see Figure 7b). This can be attributed to the porous structure, which facilitates the migration of water vapor without initiating microcracks by the internal stresses. The microstructure of M1 brick showed improved packing due to the distribution of RW fibers throughout the LC3 matrix. Although the waste RW was added as fiber lumps, the entangled fibers have dispersed upon mixing with water and blending. Even after fire exposure, the microstructure appeared quite dense, without considerable structural defects. This finding matches a previous study that revealed the crack-arresting and strengthening effects of RW fibers [35,36,56]. Increasing the RW content up to 10 vol% led to extremely enhanced packing, which adversely affected the fire-resistance performance. As the built-up pressure attained by the transformation of bound water into vapor inside the hardened skeleton reduces the structural integrity, it induces the formation of micro-cracks and causes cement paste–aggregate de-bonding, as can be seen from Figure 7f. Further increasing the RW content to 15 vol% resulted in fiber aggregation and non-uniform distribution, as shown in Figure 7g; in addition, with the increase in RW content, air gaps between fiber filaments were created.

Based on the microstructure analysis, the role of dispersed RW fibers in enhancing mechanical performance can be illustrated as follows: the strengthening mechanism is generally related to the interfacial bond between the embedded fibers and the LC3 host matrix. The SEM analysis revealed that the penetrating mode of fiber–matrix bonding is the predominant one. In addition, three-dimensional staggered networks have been seen, as in Figure 7e. The RW fibrous networks play a crucial role in supporting the applied load, improving the structural integrity and decreasing the stress concentration, and preventing the extension of cracks [61,71,72].

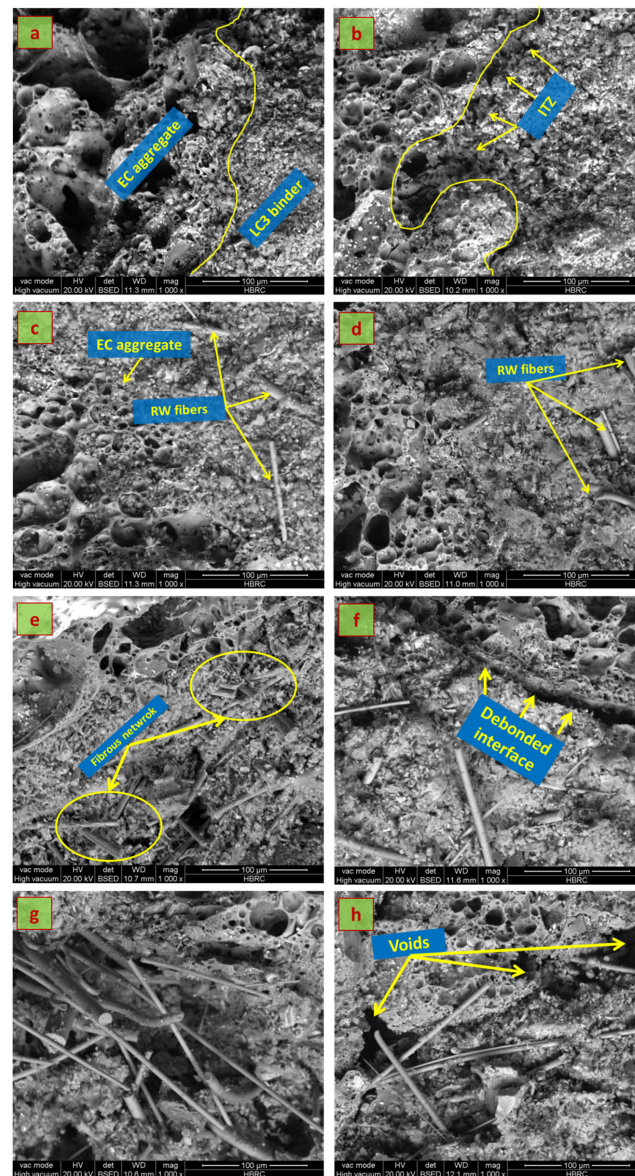


Figure 7. SEM micrographs of Ref, M1, M2, and M3 bricks (a,c,e,g) before fire exposure and (b,d,f,h) after fire exposure, respectively.

3.5. LCA of LC3-Based Lightweight Bricks

Based on the mix designs (in Table 3), carbon emissions for LC3-based lightweight brick production were evaluated based on the LCA techniques. As is clear in Figure 8, the results showed that about 458 kg CO₂ eq carbon emission is associated with the conventional LC3-based bricks where no waste RW is used (e.g., Ref). By adopting 5% waste RW (for expanded clay), mixture 1 (M1) is associated with 4% lower carbon emission. About 419 kg CO₂ eq and 400 kg CO₂ eq carbon emission is associated with M2 and M3, respectively,

which is 8% and 13% lower than Ref. The results indicated that replacing 10% and 15% EC with waste RW can save significant carbon emissions. The contribution to the total carbon emission by each material in all designs is shown in Figure 9. It can be seen that OPC has contributed the highest percentages in all designs (with a range of 55–63%), whereas the amount was 11–23% by EC, 17–19% by MK, 2–3% by LS, 3% by SP, and 0–1% by waste RW. EC has contributed considerably lower emissions in M3, as a considerably lower amount of EC is used, but in contrast, waste RW has contributed to only 1% of the total emission, even though a higher amount of RW is used. Therefore, it can be concluded that the M3 mixture is more environmentally friendly, as it incorporated more recycled materials and emitted a lower amount of carbon.

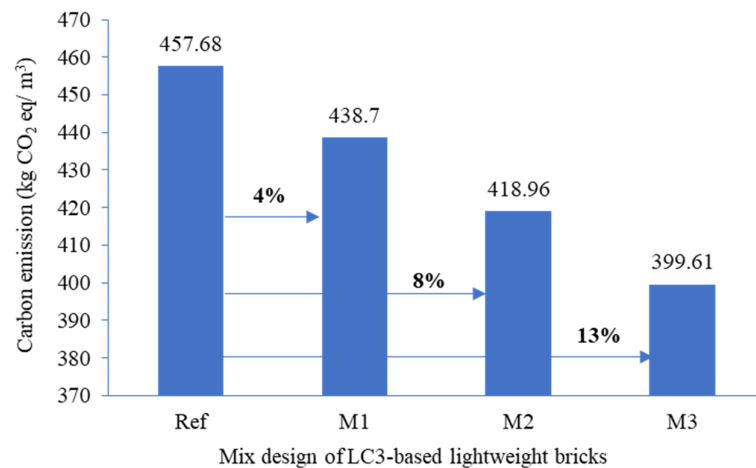


Figure 8. Carbon emissions of LC3-based lightweight brick production.

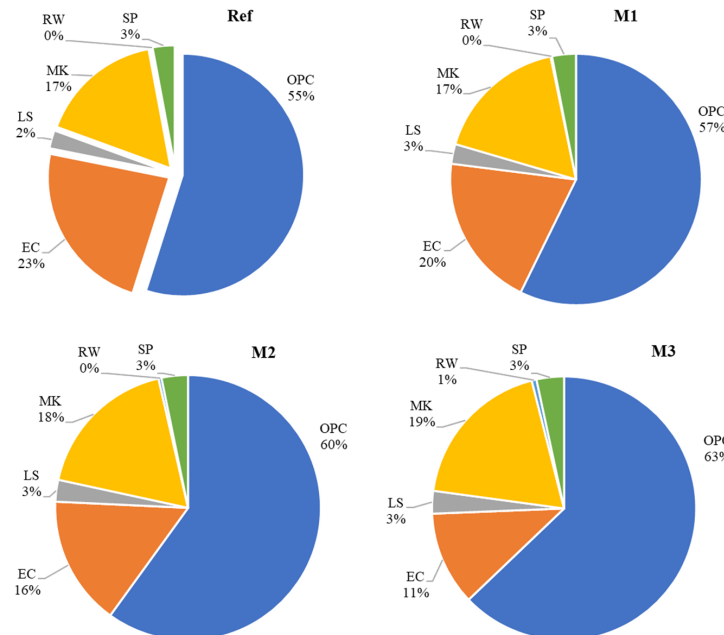


Figure 9. Contribution analysis for the designed LC3-based lightweight brick production.

Eco-friendly foam concrete was made with limestone calcined clay cement as a low-carbon cement candidate, and used engine oil (UEO) as a foam stabilizer. The results revealed that UEO notably enhanced compressive strength of 3.2 MPa and minimized the thermal conductivity of 0.16 W·m^{−1}K^{−1} [61]. Similarly, the mechanical, thermal and environmental performances of LC3-based lightweight bricks incorporating waste RW indicate that these have a high potential to replace conventional ones, decarbonize buildings, save virgin materials, and reuse waste materials. It should be noted that the results may be

associated with different uncertainties due to the lack of localized/regionalized LCI data. In addition, this study primarily focused on comparative carbon emissions evaluation. Thus, future studies should focus on comprehensive environmental evaluation with multiple impact indicators by utilizing more case-specific and localized data.

4. Conclusions

The development of lightweight green bricks for non-load-bearing wall applications with several competitive advantages over traditional bricks is the main research outcome of the current study. The produced bricks are associated with improved mechanical strength, thermal resistance and fire-resistance performance, and pave the way for sustainable disposal of industrial waste RW in the construction sector. The results can warrant the following conclusions:

- The combined use of waste RW and EC aggregate in the production of environmentally friendly LC3-based lightweight brick has technical feasibility, and can be used as an alternative to the existing energy-based fired clay brick.
- The partial replacement of EC with RW improves the physical packing, provides a strengthening effect, and contributes to the compressive strength development. A significant enhancement of about 42.4% of compressive strength has been achieved by replacing EC with 10% (by vol) waste RW.
- A slight increase in both thermal conductivity (K) and thermal diffusivity (D) has been obtained by increasing the RW content in the LC3-based bricks. Even with the highest content of 15% RW, the largest K and D values, of 0.36 W/m.k and 0.3 mm/s, indicate the improved thermal performance; i.e., this brick is helpful in reducing the heat flow into buildings in hot-weather zones.
- Owing to the improved structural integrity with the addition of RW, the developed bricks exhibit an enhanced resistance to fire exposure. The LC3-brick incorporating 5% (by vol) waste RW maintained about 90% of its initial strength after fire exposure for about an hour, i.e., an enhancement of more than 20% compared to the reference brick.
- With water absorption less than 17%, all the produced LC3-based lightweight bricks with or without RW can be used in construction as severe-weathering-resistant bricks.
- Based on the LCA results, LC3-based lightweight bricks with waste RW are more environmentally sustainable compared to those made only without waste RW. The brick with 15% RW provided a 13% reduction in carbon emissions compared to the reference brick without RW.

Future research can be conducted to assess the fire-resistance rating of a wall system made with the developed bricks, and to investigate their impact on energy efficiency in buildings. In addition, cost-effectiveness and comprehensive LCA require further attention in future studies.

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