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Review Article

Potential Use of Sustainable Industrial Waste Byproducts in Fired and Unfired Brick Production

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Use of bricks and their manufacturing process plays an important role in the construction sector. Despite its various methods of manufacturing, still large quantities of bricks are used in the building construction. Manufacturing of bricks consumes large quantities of natural resources, and it is energy intensive. Similarly, due to rapid industrialization large quantities of waste industrial byproducts are generated and causes handling and disposal challenges of these wastes. This review work attempts the possibilities and potential use of various types of waste industrial byproducts in fired and unfired bricks. This study also highlights the importance of waste and its usage guidelines in bricks manufacturing to enhance the strength and durability properties. To overcome the challenges associated with bricks manufacturing, firing is still considered as the most preferred method of making bricks. Use of industrial waste byproducts to the mix matrix of fire and unfired bricks will overcome the disposal challenges and reduce the depletion of natural resources. Since sustainability is a key factor that is considered when it comes to making bricks, innovative methods are needed to produce them using sustainable materials. The production and application of bricks and their usage guidelines are reviewed further in various aspects such as environment, social, economic, and technology to meet global standards and policies of the local government for sustainable development.

1. Introduction

Bricks have been used as a major building component since ancient times. The first known use of dried-clay bricks was around 8000 BC, while the earliest known use of fired-clay bricks dates to around 4500 BC. The global production of bricks is estimated to be around 1,391 billion units yearly, and the demand for them is expected to keep on rising due to rapid growth in the infrastructure sector [1, 2]. Portland cement and ordinary clay bricks are usually produced using a high-temperature kiln firing process [3, 4]. In addition to being energy-intensive, quarrying operations for the clay can also have a negative impact on the environment. The kiln firing process leads to the release of greenhouse gases [5–7]. Compared to the other building materials, such as concrete, bricks are known to have an embodied energy (equivalent to 2.0 KWhr) and a carbon dioxide emissions rate of around 0.41 kg/unit. Due to the scarcity of clay in various regions of the world, countries like China and India have started to limit the usage of clay bricks. The production of concrete bricks using ordinary Portland cement (OPC) is very energy intensive [8, 9]. It is known that the process of making 1 kg of this product uses around 1.5 KWhr of electricity. In addition, the release of CO_2 into the atmosphere is estimated to be around 1 kg. The production of OPC cement globally accounts for around 7% of the world's total CO_2 emissions. This means that the process of making concrete bricks consumes a huge amount of energy. In addition, aggregates produced through

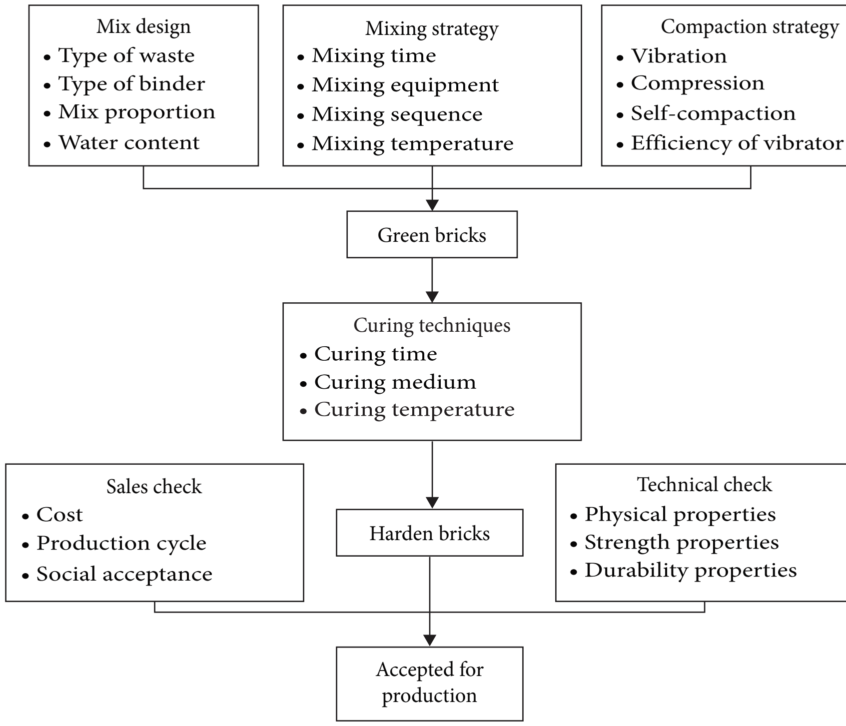


Figure 1: Manufacturing process of bricks using industrial waste byproducts.

quarrying are also known to have the same issues as clay [10, 11]. Researchers [12, 13] have been studying the various waste materials that can be used to make bricks to find ways to reduce the energy consumption of the production process. Some of these include fly ash (FA), mine tailings, pulp production residue, cotton waste, paper production residue, construction and demolition waste, cement kiln dust, cigarette butts, and rice husk ash, etc. [14, 15]. Use of various industrial byproducts in making bricks proved in improving the strength, durability, and performance [16–18]. Similarly, this will reduce the challenges associated with disposal, landfilling and handling of waste industrial byproducts [19–21]. To meet the demands for sustainable and energy-efficient bricks, this critical evaluation primarily focuses on the availability of various types of waste materials and their application in manufacturing sustainable bricks [22–24]. Development of the building envelope is a primary concern nowadays due to green initiatives concerning energy saving and to make economically friendly houses [25, 26]. Primarily it focuses on the thermal conductivity and specific heat of the whole building envelope [27–29]. Building façade needs to be studied based on development of new type of bricks made from local available waste material [30, 31]. Researchers have been taking steps forward, meticulously analyzing the incorporation of binary use of mixed wastes that can improve thermal performance without compromising the various functional performance parameters [29, 32, 33]. This paper reviews the current research on the different approaches utilized to produce bricks using various types of industrial byproducts. It also provides an extensive analysis of the disadvantages and advantages of using different methods. The overall methodology followed for bricks manufacturing using industrial waste byproducts is presented in Figure 1.

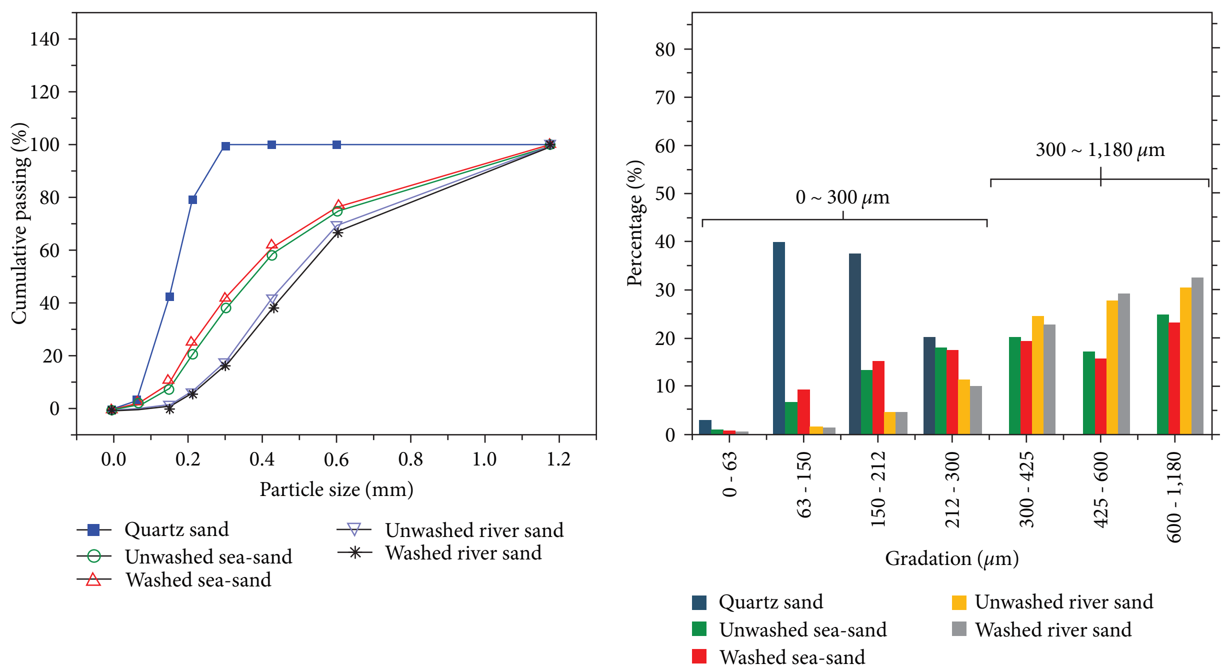
2. Literature Review on Utilization of Waste-Based Industrial Byproducts to Produce Bricks

2.1. Previous Research/Review Studies on Use of Various Categories of Industrial Waste in Bricks. Previous studies by Praburanganathan et al. [34–38] carried out extensive research on using various categories of waste materials in making bricks. Limited studies focus on overall performance on the use of agro-industrial and municipal solid wastes with limited focus on thermal enhancement and life cycle energy. This comprehensive review mainly focused on, Source category of waste (industrial, agro, and municipal solid waste, etc.) as suggested by Murmu and Patel [15], Methods of manufacturing, physical and strength properties include specific gravity, water absorption, density, compressive and bending strength, etc. and impact and material characterization of wastes used in preparation [39, 40].

Sarkar et al. [41], have differentiated material wastes based on processes of brick production: burning, cementing and Geopolymerization. The review study examined the use of waste materials in relation to the requirements for producing bricks, as well as the analysis of test findings. Another review of compressive strength, binder, and molding water content for making a brick by using different types of wastes for brick production is studied by researchers Murmu and Patel [15]. In continuation, the review paper further elaborates discussion of some of the key issues regarding the utilization of waste materials in the commercial process of brick production is not up to mark. Figure 2 presents the modular and non-modular bricks prepared with FA, lime and paper mill waste, respectively.

(a) (b)

Figure 2: (a) Modular bricks using fly ash and lime and (b) nonmodular bricks using paper mill waste [41].



(a) (b)

Figure 3: (a) Particle size distribution and (b) gradation of various types sand used in brick production [45].

Study conducted by Azad and Samarakoon [42] explored the thermal properties of modular bricks prepared with and without FA and its effect is compared. Additionally, the study compared several parameters including physical, mechanical, and thermal were examined. Similarly, one of the study conducted by Bories et al. [43] reviewed the physio-mechanical characteristics of industrial wastes combined with additives to produce geopolymer material and their impact on unfired bricks. Use of FA, municipal sewage sludge, organic wastes, and inorganic residue where the four categories into which additives were divided in order to determine the effects of the exploitation of wastes based on their nature [17, 44]. Particle size distribution and gradation of various types of industrial waste as a fine aggregate in brick production is present in Figure 3.

2.2. Physio-Mechanical and Thermal Properties of Bricks Containing Industrial Waste. Researchers around the world are using various source and all types of waste materials especially, agricultural, and industrial, for bricks manufacturing [46, 47]. However, the focus of this review work is to develop an insulated building material that can improve the mechanical and thermal performance by incorporating various sources of waste in bricks production. Studies by Boom Cárcamo and Peñabaena-Niebles [48], Koul et al. [49], and Arslan et al. [50] have tested municipal solid waste, agriculture, and industrial waste in bricks by adopting various production methods. As a part of sustainable practices, studies should also focus on the life cycle energy of the buildings by improving thermal comfort in an effectively insulated wall system. But few limited studies focused on the physical, mechanical, and thermal properties of the bricks [51, 52]. Basically, bricks are manufactured using two methods like fired and unfired. In a detailed sense, use of recycled waste in bricks can lead to a higher sustainability and reduces carbon emissions to save mother earth [53, 54].

2.2.1. Studies on the Production of Fired Bricks Incorporating Waste Material. Excavated clay will give perfect bonding and strength due to the present rice alumina and silica content, after being fired to high temperatures between 700 and 1,100°C. According to a study conducted by Karaman et al. [55], an increase in strength is mostly caused by firing time and temperature causes decrease in water absorption and porosity. During firing, clay bricks change its mineralogical properties and texture hence, improvement in strength are noticed. It is also observed that burnt clay bricks are energy intensive and emit green house gas (GHG) in large amounts, which is hazardous to the environment and causes air pollution. From an environmental point of view, many researchers studied the pros and cons of bricks to reduce the carbon emissions of fired brick by incorporating various types of waste. Some researchers have taken one step further and attempted to improve investigations into mechanical, physical, and thermal characteristics of the burnt bricks. Table 1 presents the strength and thermal properties of bricks prepared with various sources of waste industrial byproducts.

The study conducted by researchers Adebakin et al. [79] investigated the effect of sawdust and wood ash as admixtures by changing proportions to develop a burnt laterite-clay brick. By using percentage ratios (0%, 2.5%, 5%, 7.5%, and 10%) of sawdust and (10%, 7.5%, 5%, 2.5%, amd 0%) wood ash, the density is reduced to 1,512 from 1,578 kg/m^3. The wood ash and sawdust were combusted at an oven temperature of 600°C. The findings concern the effects of using 10% wood ash in bricks increases the compressive strength and reduce water absorption to a certain extent. It is concluded that an increase in the percentages of sawdust used in bricks results in quick setting of final product.

Researcher Shibib [67], studied the effect of utilization of waste paper on mechanical and thermal properties of fired clay brick. The specimens were oven dried at a temperature of 105°–115°C till it enhances the constant weight. The various mix proportions ratio (1 : 10, 2 : 10, 6 : 10, and 10 : 10) of wastepaper by weight and wet clay to meet the standards of severe weather conditions were obtained to improve durability and compressive strength. Thermal and mechanical properties are enhanced by 29% by incorporating municipal paper waste projecting as a sustainable material. In addition, it will minimize the burden on atmospheric pollution and reduce the challenges of waste disposal. The visual presentation of bricks manufactured using wastepaper is highlighted in Figure 4.

Researchers Riaz et al. [80] used brick kiln dust (BKD) in replacement percentages of 0%, 5%, 10%, 15%, 20%, and 25% as a sustainable. The firing temperature was maintained at 800°C for about 36 hr to enhance the strength properties. The presence of calcite and quartz in BKD helped in improving the thermal and mechanical properties of bricks. Since, BKD is a waste material that can be used for resistance to any weather and acts as building insulation materials. XRD analysis of BKD and clay is highlighted in Figure 5. Similarly, SEM analysis of BKD at 0%, 10%, and 25% is highlighted in Figure 6.

The study conducted by Kadir et al. [68] claimed that, the influence of crumb rubber (CB) waste of various percentages (0%–10%) in fired clay bricks reduces the strength, density, and water absorption. Reduction of thermal conductivity was observed at 51% and 58% for cigarette butts' content of 5% and 10%. Leaching tests were performed to determine heavy metals' toxicity characteristics during clay-fired brick production. Results are extremely insignificant and well below the acceptable levels. The lowest thermal conductivity observed at 10% replacement of CB was 0.45 W/m K.

The researcher Aramide [71] studied the effect of using sawdust as a mineral admixture on fired clay bricks. The clay and sawdust were burnt at a temperature of 1,000°C. Thermal performance of 0.05 W/m K was obtained with 30% of sawdust. The results exhibited that using sawdust of 10%–15% was recommended for optimum compressive strength.

Researcher Ozturk et al. [72] studied the influence of addition of tea waste on specific gravity, porosity, strength, and thermal conductivity properties of fired clay brick. Study concluded that use of tea waste in fired clay bricks decreases the compressive strength with an increase in firing temperature of 950° and 1,050°C. As per the code provisions, the minimum strength that needs to be obtained at the usage of 10% tea waste is 9.3 at 950 and 10.7 MPa at 1,050°C, and by increasing the tea waste up to 12.5%, porosity increases about 58.5% affect the mechanical properties of the brick. At 12.5% tea waste, the results state the decrease in thermal conductivity, and exhibits 42% of energy savings.

Researcher Muñoz et al. [73] studied the effect of particle size and grapevine shoot replacement rates as a forming agent in burned clay bricks at firing temperature 900°C. The particle size (up to 0.5 mm, between 0.5 and 1.5 mm, above 1.5 mm) and percentage replacement of additive (5%, 10% and 15%) are critical factors that directly affect the properties of mechanical and thermal of the brick. The results exhibit that optimum compressive strength and water absorption were obtained at 10% replacement. At this percentage, thermal performance was reduced by 50%, i.e., no effect on the particle size.

Researcher, Munir et al. [38] studied on use of marble waste to achieve energy-efficient fired clay bricks. Various dosages of replacement of marble waste sludge (5%, 10%, 15%, 20%, and 25% by mass of clay) were considered to replace clay at a temperature 800°C for 36 hr and removed after 45 days. Test results showed that minimum compressive strength and corresponding thermal conductivity were obtained at 15% replacement of waste. The study concluded that the increase in porosity and water absorption was due to an increase in percentage content of marble waste sludge which will improve the thermal enhancement of the bricks. Test results of study conducted by researcher, Munir et al. [38] is presented in Figure 7.

The influence of agricultural biomass wastes (WS, SSC, and OSF) as additives in fired clay bricks with different particle sizes and compositions was studied by Bories et al. [43]. The bending strength and thermal conductivity decrease

Table 1: Physical, mechanical, and thermal properties of bricks prepared using various types of industrial waste.

Type of brick	Materials used	Compressive strength (MPa)	Flexural strength (MPa)	Density (Kg/m^3)	Water absorption (%)	Thermal conductivity (W/m K)	Specific heat	References
Alkali activated brick (unfired)	Blended ash and stone dust	4.88–14.85	–	1,180–1,606	6–14	0.4	–	[56]
Geopolymer brick (unfired)	FA, copper slag, and crusher dust	68.9	7.2	2,234	5.89	0.942	1,186	[57]
Geopolymer brick (unfired)	FA, crusher dust	45.6	4.1	1,975	7.67	0.973	1,237	
Geopolymer brick (unfired)	FA, copper slag, foaming agent	3.78	–	592	13.4	0.13	881	[58]
Fly ash brick (unfired)	FA, corncob ash, cement, and sand	5.1–5.4	–	–	10–14	0.25–0.4	–	[59]
Geopolymer brick (unfired)	FA, cement, lime, aluminum powder, and GGBS	5.8–13.5	–	870–1,370	14.11–16.25	0.34–0.43	–	[60]
Clay brick (fired)	Clay, brick Kiln dust	9.13–5.95	1.73–1.3	–	21.95–24.31	–	–	[61]
Cement brick (unfired)	FA, and pebble lime	35.5 MPa		–	–	–	–	[62]
Geopolymer brick (unfired)	Electric arc furnace slag, FA, and foundry sand	18.93–25.76		–	–	–	–	[63]
Cement brick (unfired)	Waste glass powder, cement, crusher dust, and oil palm fibers	35.56–50.15		–	21.7–52.15	0.59–0.8	–	[37]
Geopolymer brick (unfired)	GGBS and M-sand	5.1–23.8		–	5.5–21.8	–	–	[64]
Geopolymer brick (unfired)	FA, rice husk ash, and bottom ash	31.33–41.49	2.89–4.31	1,150–1,900	6.5–9.0	–	–	[65]
Composite brick (unfired)	Crumb rubber (CR), cement, and sand	4.1–22.6	1.88–4.87	2,090–1,490	3.01–7.02	–	–	[66]
Clay brick (fired)	Wet clay and wastepaper	23–33	–	1006.2–1264.8	–	0.39–0.52	598–678	[67]
Clay brick (fired)	Silty clayey sand and CB	3–25.65	1.24–1.97	1,482–2,118	5–18	0.45–1.08	–	[68]
Cement brick (unfired)	Lime, FA, glass powder and crusher dust	6.48–13.85	–	1407.36–1616.81	11.48–18.22	0.389–0.536	–	[69]
Clay brick (fired)	Cement, sand, Co-fired blended ash, sawdust, and coal	2.2–8	–	1,690–1,075	20–35	0.53	–	[70]
Clay brick (fired)	Dried sawdust and Ifon clay	14.71	–	500–2,500	20–80	0.05–0.225	–	[71]
Clay brick (fired)	Clay and tea waste	7–34	–	1,400–1,900	15–48	0.4–0.72	–	[72]
Clay brick (fired)	Clay and grapevine shoots	2–35	–	1,000–1,660	17–42	0.22–0.68	–	[73]
Clay brick (fired)	Clay, dry sand, and marble waste	4–8	–	1,150–1,300	16–24	0.4–0.51	–	[38]
Clay brick (fired)	Clay, wheat straw, olive stone flour, sunflower seed	5.3–10.8	–	1,460–1,690	17.8–30	0.2–0.38	–	[43]
Geopolymer brick (unfired)	Soil and rice straw ash	0.65–2.10		–	8.30–25.80	0.46–0.83		[70]
Mud brick (unfired)	Red soil, FA, bagasse ash, groundnut shell ash and GGBS	10–30.20	–	–	3–12	–	–	[62]
Geopolymer brick (unfired)	Solid waste	2.5–75	–	–	10–16	–	–	[74]
Geopolymer brick (unfired)	Ceramic tile waste and slaked lime	2.4–9	–	–	20–31	–	–	[75]
geopolymer brick (unfired)	Ferrosilicon slag, and alumina waste	5.5–10.9		710.22–1598.93	15.8–29.3	0.28–0.59	–	[76]
Geopolymer brick (unfired)	GGBS, waste brick, and sand	38.51–89.1	3.12–6.94	–	–	–	–	[77]
Foamed geopolymer brick (unfired)	FA, glass powder, and crusher dust	CS- 10–52.27	1.5–6.78	1,000–1,500	9–33	0.43–1.02	–	[78]

Figure 4: Final shape of bricks produced with waste paper [67].

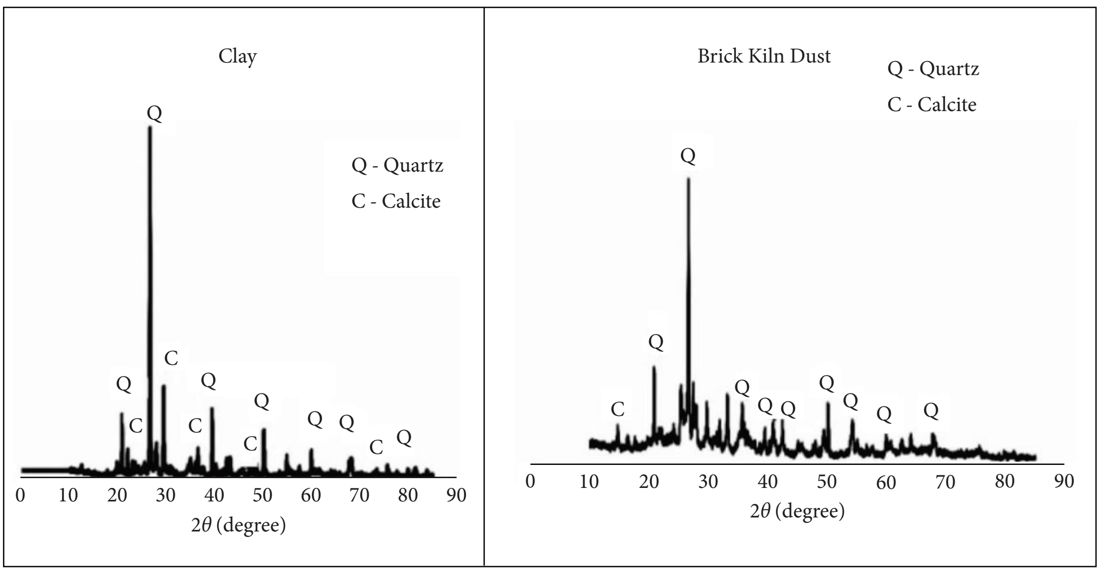


Figure 5: XRD analysis of BKD and clay [80].

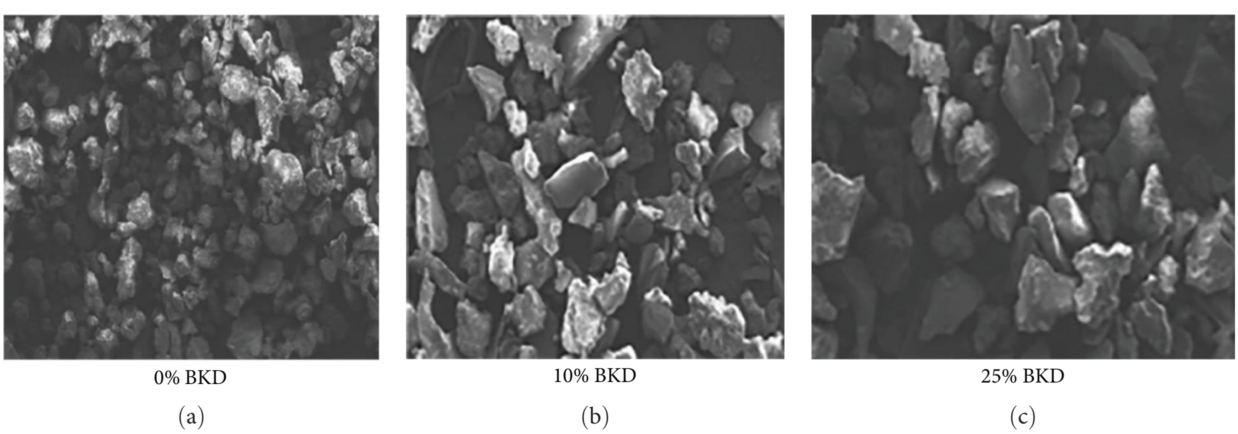


Figure 6: SEM analysis bricks prepared with BKD [80].

with an increasing percentage of additive of WS and OSF and vice versa for SSC. The studies concluded that minimum bending strength and thermal performance were obtained for the best composite additive SSF at 4% based on the smallest particle size with an increase in porosity of 23% by mass.

2.2.2. Studies on Production of Unfired Bricks by Incorporating Waste Material. Production of sustainable unfired bricks does not require a process of firing. It mainly relies on cementing properties waste raw material used as binders [81]. Significant studies are performed by using industrial and agricultural

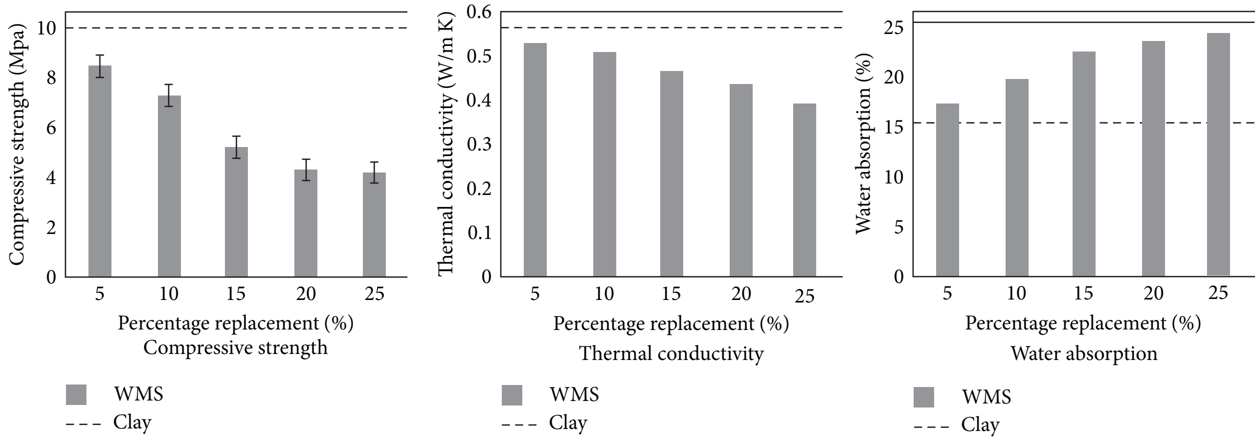


Figure 7: Test results of compressive strength, thermal conductivity and water absorption incorporating waste marble sludge [38].

wastes to produce bricks with all qualitative parameters to meet the requirements of conventional building materials [82, 83]. Generally, the preparation of unfired bricks is based on the process of the heat of hydration similar to cement to form bonds such as calcium–silicate–hydrate (C–S–H) and calcium–silicate–alumina–hydrate (C–S–A–H) gels in order to contribute the strength [84]. Cement is a commonly used binding material in the production of unfired bricks. It produces carbon emissions during the process of manufacturing, and it is energy intensive. Use of waste industrial byproducts in cementitious bricks can reduce the release of GHG and embodied energy of brick to a certain extent [53]. Researchers Rajwade and Netam [59] studied the physical and mechanical properties of FA bricks using corncob ash. The study concluded that, up to 10% of cement by corncob ash and 30% FA is optimum to improve the mechanical and thermal properties of bricks.

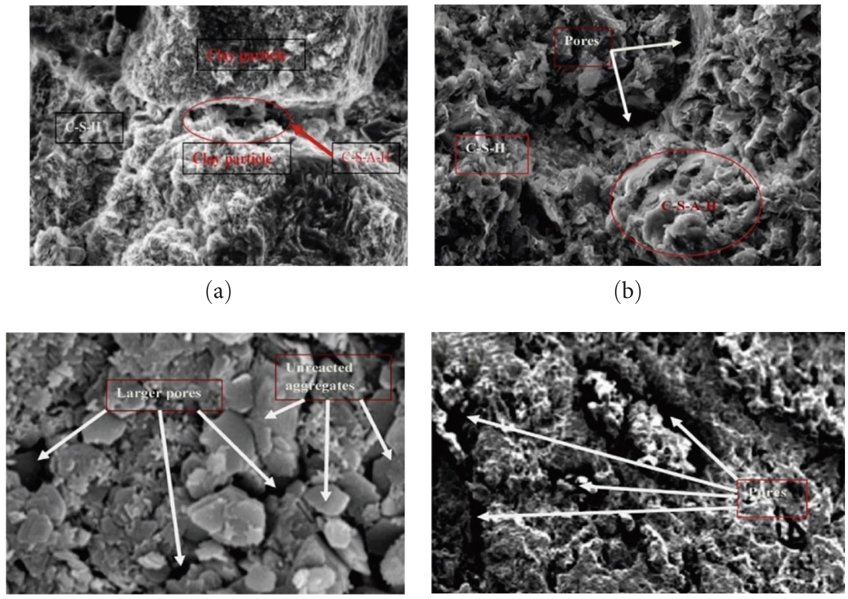
Jannat et al. [20] reviewed use of various types of agro and non-agro wastes across the globe in bricks manufacturing. Based on the findings, the percentage usage of waste varies from material to material based on the optimum strength and water absorption. Some industrial wastes have shown higher compressive and flexural strength, such as ceramic waste, FA, bottom ash, GGBS, Molybdenum tailing, etc., based on the usage. Few industrial wastes showed marginal thermal conductivity including GGBS, calcium carbide residue, recycled aggregate, and FA.

The study conducted by Raut and Gomez [37] presents that the use of oil palm fibers and glass powder reduces the energy consumption of the building due to thermal properties. The study performed properties of bricks like strength, water absorption, morphology, shrinkage, and porosity. Fibers were used in reinforced mortar mix in proportions of (0.5%, 1%, and 1.5%) by mass of the binder, while glass powder was added by replacing 10% and 20% of the OPC. The study concluded that compressive strength is reduced drastically by the addition of fibers. It is concluded that waste fibers can be used as a sustainable alternative for energy-efficient building.

Researcher Turgut and Yesilata [66]. Studied the various replacement percentages of crumb rubber (10%–70%) bricks with conventional sand. This study exhibits that the strength of brick reduced significantly with corresponding unit weight and increased porosity. Thermal performance is improved with an increase in crumb rubber from 5% to 11%. Thus, the kind of rubber-added bricks are an eco-friendly and unique lightweight building material. In an another study researcher Pradhan et al. [85] investigates the effect of using coal, co-fired blended ash and sawdust as waste to develop sustainable bricks. Ten percent cement is added to all the mixes to attain the required brick strength. Comparative analysis is studied between the newly developed sustainable bricks and conventional bricks, i.e., density is 15% and 26% lighter, and thermal conductivity is 58% and 50% lesser for burnt-coal bricks and FA. The developed bricks are used to build the load-bearing walls and have the capability to reduce the heat gained through walls.

The author Li et al. [86], studied the effect of sodium silicate, the ratio of water to fine FA, forming pressure and autoclaving time on water-permeable bricks using fine and granulated FA, pebbles, and lime. The best mass ratio for FA-based water-permeable brick was (fine FA: granulated FA: pebble: lime $= 30:25:42:3$), with 8% sodium silicate binder and a water/fine FA mass ratio of 0.15. The proportion of FA in the total mass of raw materials could exceed 50% by weight. The forming pressure was 10 MPa, the autoclaving temperature was 180°C, steam pressure was 0.8 MPa, and the autoclaving period was 8 hr. Under these conditions, compressive strength and coefficient of permeability reached the optimum value of 35.5 MPa and 1.044×10^{-4} m/s. The more significant water permeability coefficient is due to the linked pores in bricks. Similarly in an another study [69], optimization and development efficient thermal blocks using various percentages of GP, POFA, and OPF as admixtures using the process parameters. The optimum value of thermal conductivity is obtained for the ratios of GP (20%), POFA (35%), and OPF (1%) are 0.3765 ± 0.037 W/m K with a 90% confidence level. After investigating the addition of palm oil fibers, reducing the indoor temperature in terms of improving the thermal comfort of the building envelope leads to a direct and indirect effect on sustainability.

The study conducted by Kejkar et al. [60] on various mix proportions of nonaerated autoclaved geopolymer (NAAG)



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

Figure 8: SEM analysis of unfired clay bricks [87] (a–d).

blocks to increase compressive strength, durability and decrease water absorption, thermal conductivity, shrinkage, and cost. Heat curing results in higher compressive strength than water curing of blocks using aluminum powder as a forming agent for improving thermal comfort. Silica and alumina's reaction to forming a gel by using alkali activators adheres to good strength properties. The durability of blocks in acid resistance medium results in weight loss within accessible limits. Effect of cost and energy is compared with light weight NAAG, and conventional bricks will be the best alternative for sustainable construction.

The SEM analysis of the micrograph [87] of the mixtures B and C revealed that the glassy like films on the surface of mix B are formed by the presence of various cementitious substances, such as CSH and CAS as illustrated in Figure 8. This implies that the higher the cement's content, the stronger the mix. The interface between the particles is covered by these pozzolanic products. The surface becomes less homogeneous and dense when compared with the previous mix. The cracks and micropores found on the surface contribute to the lower compressive resistance of this mixture. The appearance of glassy films was lower on the surface of the aggregates compared to the CSAH and CSH development. The micrograph of the mixtures D and E shows the reduction in compaction, when compared to other mixes, which have 10% and 0% CC as partial replacements for cement, this one has a higher number of unreacted aggregates. This could also contribute to the reduced performance of some of the properties of this mix. The surface of mix E has a more prominent number of voids and micro pores. One of the main reasons why the cement did not perform well under various tests was due to the presence of calcium carbide. This finding shows that the higher the concentration of this substance, the more voids and pores will be formed. This will lead to a reduction in the performance of the cement.

The microstructure of USB samples was examined using SEM analysis [88]. The SEM images show the changes in the samples' characteristics. The cement hydration process resulted in the development of CAH and CSH gel structures. The bonding strength and compactness of soil particles were the determining factors that led to the strength gain of a cement-solidified DS. The CH plate was also observed in the USB samples, which supports the hydration product of cement. Compared to the USB with only 15% cement, the cement mixture with lime and FA exhibited a more compact microstructure. The effect of FA particles on the USB's micro-aggregate structure and the formation of CAH and CSH gels by the pozzolanic reaction enhanced its compactness. In Figure 9, the CSH gel structures were clearly visible on the soil particle surface. Some micro pores were visible in the USB samples when the L/FA rose to 3/7. This can be attributed to the expansion caused by the hydration process. The microstructure of the USB samples was modified by 1.5% and 0.5 NS, respectively. The compactness of the USB containing NS was also improved. The addition of NS also contributed to the development of additional CSH gel structures. These structures filled the micropores of the USB. The denser the structure of the USB with 1.5% NS, the more CSH gel it had. The findings support the previous statements about the compressive strength of the USB. It is believed that the consumption of $Ca(OH)_2$ by NS caused the additional CSH gel to form. The XRD analysis from Figure 10 revealed the crystal structures of USB samples. The mineral composition of the dredged sludge was revealed, such as quartz, illite, and kaolinite. The main hydration products of various types of cement, such as CSH, were also detected. These findings support the notion that the development of USB's strength can be attributed to its hydration process. The USB samples exhibited the crystallization phases

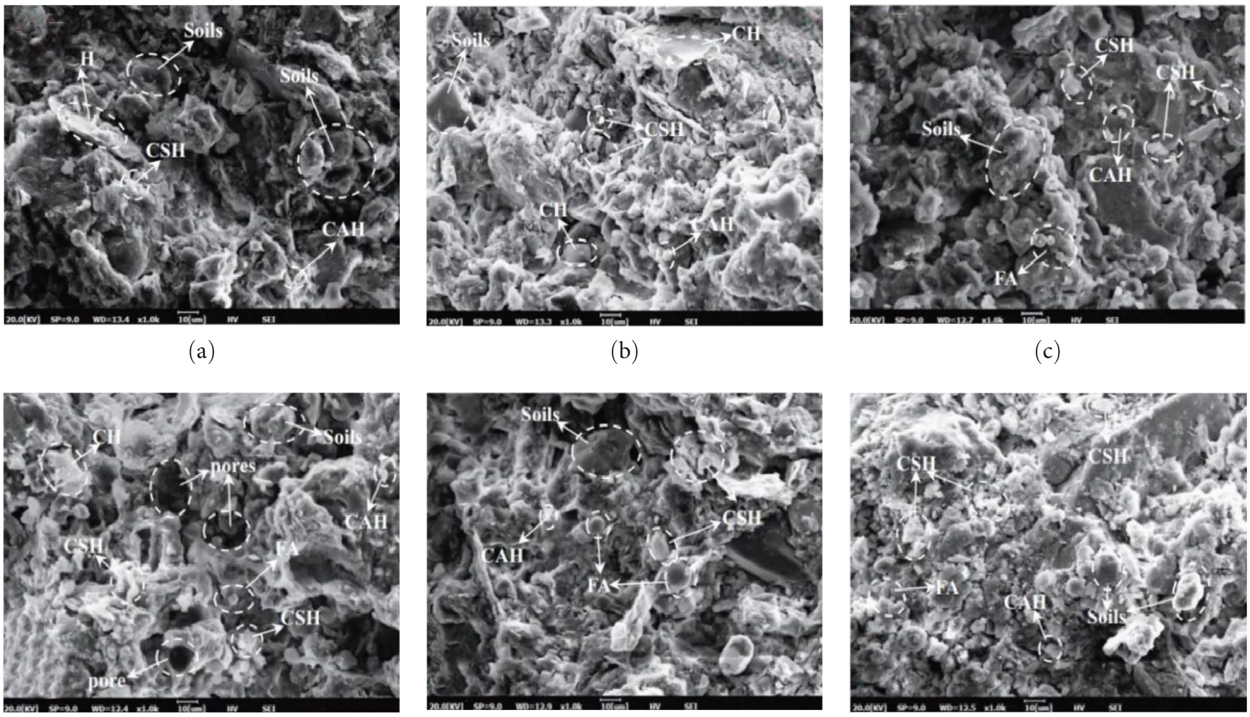


Figure 9: SEM micrographs of unfired bricks [88] (a–f).

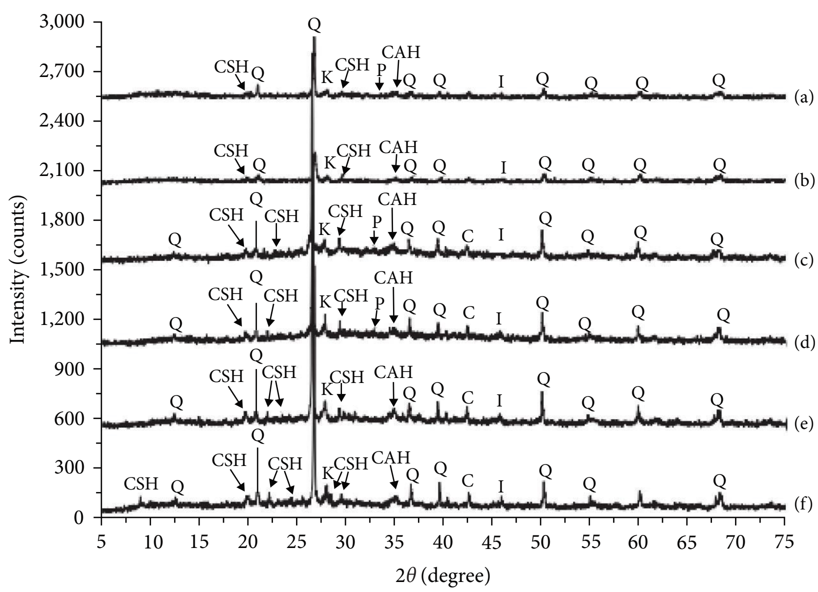


Figure 10: XRD patterns of unfired bricks [88].

with the help of FA and cement. It was observed that the different L/FA values did not influence the crystallization of the USB. In addition, the appearance of the $Ca(OH_2)$ and calcite ($CaCO_3$) in Figure 10 also suggested that the hydration process of cement and lime was responsible for this phenomenon. The results of the XRD tests revealed that the microcrack in the USB samples exhibited by SEM tests were caused by the presence of calcite. In the case of the USB containing 0.5% NS and CSH gel, the presence of the Portlandite was not detected. It was then inferred that the consumption of $Ca(OH)_2$ by the NS resulted in the production of additional CSH.

2.2.3. Studies on Production of Unfired Bricks through Process of Geopolymerization by Incorporating Waste Material. The production of bricks using various techniques such as high-temperature firing or cementing will overcome the drawbacks of high energy consumption and carbon emissions [89]. Few studies [90–92] have been reviewed on producing unfired bricks based on geopolymerization. Geopolymerization is a chemical reaction of rich in amorphous silica and alumina solids with a considerable amount of alkaline solution at various curing methods (ambient or steam or oven) from crystalline form to semicrystalline aluminosilicate inorganic polymer. Geopolymer has several additional advantages in terms of performance compared to firing and cementing; as such, it will improve mechanical and durability properties, resistance to chemical attack, thermal insulation, and reduce energy consumption and carbon emissions [93, 94]. These insights on features have significantly made geopolymer a unique material in terms of enhancing sustainability.

The significant observations from the study are using industrial copper and FA increases the ratio of sodium silicate (SS) (Na_2SiO_3) to sodium hydroxide (SH) (NaOH) and it results in a viscous solution by Khan et al. [57]. The author investigated strength characteristics of geopolymer bricks by increasing NaOH molarity and decreasing the curing temperature to a certain extent. Strength characteristics are analyzed for various design parameters based on 8, 10, 12, and 14 M at curing temperatures of 40, 50, 60, and 70°C. Optimum strength is predicted at SS/SH and curing temperature is 2.4 and 60°C. Thermal properties are studied between copper slag and FA-based geopolymer.

This research interest in developing alkali-activated bricks can reduce the effective cooling load on the structure, cost, embodied energy, water absorption, and density as suggested by Gavali and Ralegaonkar [56]. Use of waste industrial byproduct helps to protect the environment and produces sustainable bricks. A comparative study predicts that existing and proposed buildings increase compressive strength and reduce material usage costs. Stability analysis of building is studied as per the Indian standards by comparing the proposed load-bearing structure (co-fired blended ash bricks) with a higher load carrying capacity compared to the conventional form of framed structure.

The heat transfer analysis and variation of temperature as being studied for walls such as foamed copper slag geopolymer (FCSG), conventional, aerated autoclaved concrete (AAC), and copper slag geopolymer in 2D isotherms from solid to fluid zone by Singh and Raut [58]. Outer door and indoor temperature are constant for analysis. Fluid temperature for the conventional system is beyond 302 K and traditional remains less than 300 K. Results validated that FCSG lowers thermal transmission than traditional systems because the foaming agent helps form pores in the material and helps to reduce the thermal properties and density of bricks. Specific heat for all the cases mainly depends on the weight and characteristics of the medium.

Effect of using geopolymer bricks using industrial waste such as FA, electric arc furnace slag, and waste foundry sand by Apithanyasai et al. [63]. The compressive strength for 28 days in ambient curing is a range of 18.93–25.76 MPa for various mixes with different ratios such as 70 : 30 : 0, 60 : 30 : 10, 50 : 30 : 20, and 40 : 30 : 30 with 8 M SH and 98% purity SS with a ratio of SS/8 M SH = 2.5. The study also analyzed the life cycle assessment using SimaPro software. Study exhibits that the impact on the environment is significantly reduced by using more and more industrial waste.

The effect of GGBS as industrial waste for making the geopolymer bricks mainly to minimize the cost of existing conventional bricks and to produce the first-class brick with compressive strength of more than 10 MPa from the study conducted by researcher Ganesh et al. [64]. Geopolymer bricks mainly depend on the raw materials, SH to SS ratio, and molarity. The CS is obtained by optimizing raw materials by considering the ratio of SS to SH is 1 : 25, GGBS is 20%–70% and M-sand is 30%–80%, respectively, for molarity of 10 for various mixes is 5.1–23.8 MPa. By varying the ratio of SS to SH of 1 : 0, 1 : 0.5,1 : 1, 1 : 1.5, 1 : 2, and 1 : 2.5 and ratio of molarity is 8, 10, 12, 13, 14, and 16 the compressive strength is 14.6–17.8 MPa and 15.2–19.8 MPa. The results highlight that the maximum compressive strength is 23.8 MPa for the 70% GGBS and 30% M-sand with ambient curing. The inclusion of calcium oxide (CaO) in GGBS accounts for the higher strength observed with greater GGBS content. Under economic conditions, of 40/60 GGBS/M-sand proportion gave the requisite CS. The maximum CS and least WA capacity were achieved with a 13-molarity sodium hydroxide solution.

Mechanical behavior of the geopolymer composites with rice husk ash (RHA) and bottom ash (BA) shows the formation of calcium/aluminum silicate hydrate gel which has a similar binding effect compared to other cementitious materials [95]. The results of this study [95] highlights that higher compressive strength is obtained for FA with BA as compared to FA with RHA. The reaction between silica and aluminates in the presence of a strong alkaline activator causes the geopolymer composite to gain strength. The intermolecular connection established due to continuous polymerization is responsible for the flexural strength. Due to its dense pore structure, BA on the other hand, is helpful in limiting water flow through the material. Using agro-industrial waste resources to generate a sustainable geopolymer product will provide an environmentally friendly option to the building sector in the future.

Effect of recycled rice straw ash leads to low-thermal conductivity and water-resistant geopolymer adobe bricks by Morsy et al. [70]. The rice straw ash used in various replacement (0%–20%) and SH contents of (2.5%–10%) after curing the composite for 28 days. The study concluded that increasing the percentage of rice straw ash and sodium hydroxide increases the CS and decreases thermal performance, and WA. The study concludes that optimum CS and thermal conductivity are 2.1 MPa and 0.46 W/m K at 20% rice straw ash and 10% SH. Thus, it is recommended that using this type of abode brick serves the purpose of minimizing energy consumption.

Influence of industrial (FA, GGBS) and agricultural wastes (Groundnut ash, Bagasse ash) on mud blocks using the process of geopolymerization by Vignesh et al. [62]. From the results of the test, it is observed that geopolymer (13.25%) is kept constants for all mixes, various percentages of red soil, and use of stabilizers (FA, groundnut ash, bagasse ash, and GGBS) increase in CS, FS and decrease with WA. Maximum strength and durability obtained for mix replacement of 45%–50% of GGBS to red Soil than other mix proportions. In another study, researcher Madani et al. [74] produced geopolymer bricks from solid waste using the process of alkaline activation. The study considers the influence of three parameters like molarity (4, 8 and 12 M) of sodium hydroxide, calcium hydroxide (10% to 30%) with an increase of 10%, curing temperature (70 and 105°C) for attaining the higher dry and wet compressive strength and other properties. This research investigated that increased calcium hydroxide showed a 75 MPa for dry compressive strength at 105°C and 36 MPa for wet compressive strength at 105°C due to the extensive incorporation of calcium hydroxide to form durable and stable brick with the formation of microstructure properties. Beyond 20%, calcium hydroxide showed lower physical and mechanical properties.

Effect of various percentages of calcium hydroxide and water content on geopolymer bricks using ceramic dust waste by Amin et al. [75]. These studies determined that obtained maximum CS at 28 days is 9 MPa at 10% Ca $(OH)_2$, 1% NaOH, and 38% water. The effect of increased curing time and temperature increase will increase the strength parameters to a certain extent and decrease the water transport properties. They concluded that the degree of polymerization would increase the strength and constituent decrease in porosity. Production cost will be reduced to a certain extent by substantial use of raw materials (except for NaOH). The study conducted by Ahmed et al. [76] investigated the effect of FS and AW to enhance thermal insulation of geopolymer bricks by using slag as a pore agent. The samples are prepared with different concentrations of NaOH solution (6, 8, 10, and 12 M), Si/Al ratio (0.5, 1, 2, 3, and 4), and alkali activated ratio is 2.5 is constant for all the mixes. The highest CS (10.9 MPa) was obtained for 8 M NaOH and (Si/Al ratio = 1) at 28 days. The effect of increased AW content decreases the thermal conductivity due to unreactive silica in FS. The optimum thermal conductivity is 0.33 W/m. K is marginal compared to conventional clay bricks.

Researcher Youssef et al. [77] investigated the effect of reuse of waste brick to produce the high-strength geopolymer bricks. The three main parameters considered for these studies are ratio of GGBS/WB, effect of NaOH molarity (6, 8, 10, 12, and 14), and different alkali activator ratios (1.5, 2, 2.5, and 3). From these results, compressive strength is 89.91 MPa, and flexural strength is 10.97 MPa. The study concluded that geopolymer bricks are more sustainable bricks than conventional bricks in protecting the environment and economic impact to attain durability.

The effect of a foaming agent on making FA-based geopolymer blocks using glass powder have achieved the lightweight, energy-efficient building material by increasing the foaming agent to reduce density and thermal properties by satisfying the strength parameters as per the code provisions by Singh et al. [78]. The results predicted that energy consumption is significantly saved by 8.94% and 10.47% during the operational stage by conducting energy simulation analysis using the eQuest simulation tool. Similarly, the fluid medium's average heat temperature is lower than 299 K in other cases using Open FOAM Software.

The study conducted by Teng et al. [45] investigates the effect of geopolymer foam on olive oil by using ceramic waste to improve the physical and mechanical properties. Different percentages of olive oil (0%–15%) affect the geopolymer pore formation and composites; as a result, an increase in WA and total porosity is inversely proportional to density and compressive strength decreases due to additive content.

3. Heat Transfer in Bricks Based on the Incorporation of Waste Material

From Table 1, it is perceived that various researchers have conducted several experimental studies to design sustainable bricks using industrial and municipal wastage. The new design was approved based on feasible thermophysical characteristics such as density, heat capacity, thermal conductivity, and other pertinent properties like WA and CS. Many bricks are not designed by considering both thermal and mechanical properties. Moreover, it is observed that most of the brick designs are approved on the purview of approaching the energy-efficient building [96]. The good aspect of the brick design is high-compressive strength to meet durability and low-thermal conductivity helpful for effective envelope design. On the other hand, brick weight can be reduced by maintaining low-water absorption and low density.

The heat transfer process through bricks mainly depends on porous morphology, adding additives, porosity, and preparation method [97]. Based on the literature studies, to decrease the rate at which heat moves through a material, pore structure formation and porosity are the crucial factors. Heat flowing through the pore structure medium is mainly attributed to geometry. The main goal of the thermally efficient bricks is to investigate the material's pore sizes and microstructure, which have a significant impact on how heat is transferred by convection, conduction, and radiation. The concepts governing heat transfer through building walls include steady-state heat flow, surface resistance, wall resistance, heat transfer by air infiltration, and variable-state heat flow. To study the radiation effect of heat transfer by Stefan–Boltzmann law and Fourier law. The heat transfer by conduction is given by

$$Q_{\text{cond}} = -kA\frac{dT}{dx}, \tag{1}$$

where Q_{cond} is the heat transfer rate,

A is the transversal area,

dT is the temperature difference on the distance dx,

k is the thermal conductivity.

The heat transfer by radiation is given by

$$Q_{\text{emit}}, \max = \sigma \varepsilon A T_s^4, \tag{2}$$

where Q_{emit}, max is the maximum radiation heat transfer,

σ is the Stefan–Boltzmann constant ($5.67 \times 10{-}8\ \text{W/m}^2\ \text{K}^4$),

Table 2: Criteria for selection of incorporation of waste material to develop thermally efficient, eco-friendly, and sustainable bricks.

Criteria	Input	Process	Output
Environmental	Optimum use of industrial and agro-waste and stainability	Lower embodied energy, reduction in waste during the process of operation	Reducing GHG emission, pollution control, and conservation natural resources
Socioeconomical	Lower use of fuel consumption in transportation of raw materials, affordability, and local existence of raw materials	Health and safety hazards, sustainable manufacturing, and easy process of raw materials	Cultural acceptance, skilled labor, lesser use of nonrenewable energy, and economical production
Technical	Particle size distribution, pozzolanic properties, nonvolatile and pore structure	Minimum usage of labors and ease in production processing procedures	Improvement in workability, strength, durability, and physical properties. Reduction in water absorption, bulk density, thermal conductivity, heat transfer, shrinkage, creep, resistance to wear and tear.

ε is the emissivity, and

T_s is the temperature of surface absolute Custodio-García et al. [98].

In general, inorganic and organic materials have been used as pore formation additives in burnt clay bricks. The process of firing during the production of bricks increases the thermal conductivity value, mainly due to the filling of the pores because of the densification of the matrix by glassy mass during the sintering stage. The impact caused due to firing bricks represents the major environmental issue that leads to global warming [99, 100]. Magnesium and calcium carbonates found in natural clay react during the firing process to produce calcium oxide as well as oxides of magnesium and calcium. Calcium oxide is highly reactive during the calcination process and can react with any other materials in the structure. Better thermal performance can be achieved by reusing residues and adding additives, Muñoz et al. [73]. Organic additives during combustion will release CO_2 and create voids responsible for enhancing the thermal properties of the fired clay brick. Therefore, an increase in additive content creates the pore-formation volume, minimizes the specimen's bulk density, and attains lower thermal conductivity.

In the case of unfired bricks through cementing process, thermal performance mainly depends on the porosity and bulk density of the constituent material properties. The lighter the self-weight of brick, the more pores will result in lower thermal conductivity values [101, 102]. Better use of natural organic materials represents a porous structure with lower density and a lower rate of heat transmission. The material consists of fibrous nature. Some industrial and agricultural fiber wastes can have a lower rate of heat conductivity. The air is entrapped within the enclosure and possesses a shallow heat transfer rate in a fibrous structure. Adding natural fibers (rice straw, oil palm, sawdust, etc.) lowers the overall thermal conductivity to a certain extent, according to the literature review. In supplementary cementitious materials, thermal values are partially related to the higher silica and alumina content. The effect of pore structure in aerated autoclaved concrete blocks is mainly due to varying the mixing time of aluminum powder, the dosage of aluminum powder, and foaming stabilizer [103, 104]. The thermal conductivity increases due to increased pore sizes and affects a few mechanical strengths, Chen et al. [105]. The process of hydration of cementitious blocks mainly generates smaller pores up to 0.34 mm. Thermal conductivity affects pore shapes and connectivity, Li et al. [106]. The characteristics are mostly influenced by the density of the material's packing and pore size. Thus, the importance of the microstructure of materials plays a crucial role in developing energy-efficient materials [107].

The unfired bricks developed through the geopolymerization process mainly influence the material composition and pore structure formation through the hydration process, causing various effects of vapor and chemical composition-based heating [108]. As a result of heat transfer mainly influences the pore pressure increase gradually upon pore structure, He et al. [109]. Criteria selection of thermally efficient bricks are presented in Table 2.

4. Conclusions

Based on the critical findings of the review on the manufacturing of masonry bricks from the incorporation of wastes for developing a thermally eco-friendly efficient brick, the following conclusions can be drawn:

(1) Use of industrial and agricultural wastes will overcome the challenges of waste disposal and help to develop eco-friendly sustainable bricks to achieve impact on minimization of operational energies in buildings. Not only operational energy, but this will also reduce the cost of the bricks production.

(2) After studying the different methods used to produce the bricks, the process of firing and cementing has some drawbacks, i.e., the release of carbon emissions, higher energy composition, and its effect on strength and durability parameters during the life cycle. The method of producing the bricks using the Geopolymerization process is a sustainable alternative in terms of environment, energy consumption, and life cycle cost.

(3) Some researchers have studied attaining thermally efficient bricks as promising building material, but they lack commercial attributes. The geopolymerization

process has the best microstructure behavior because pore structure and particle size can be the best alternative to firing and cementing. Not only microstructure, geopolymerization will also help in improving the strength and durability properties of bricks.

(4) For making bricks, studying microstructure is challenging due to the lack of composition of wastes and the mixing process. In sustainable bricks, the heat transfer process is low through the material, and it mainly depends on morphology. The results of the XRD and SEM tests revealed that the main cementitious substances found due to calcium-silicate and calcium-hydrate gel presence.

(5) The newly developed bricks are not acceptable to the government and industry without relevant standards. The utilization of waste to make bricks needs further research and development, not only in the socioeconomic, technical, and environmental aspects but also in policy implications and standard procedures.

Data Availability

Data supporting this research article are available from the corresponding author on request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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