Valorization of steel slag in clay: Thermophysical study and energy simulation in Oujda (Morocco)

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Abstract. The valorization of industrial by-products is key to sustainable construction. This study investigates the use of Steel Slag Aggregate (SSA), a waste product from the Moroccan steel industry, as a partial replacement for clay in unfired bricks. Clay-soil from the Alouana region was mixed with SSA at proportions of 0, 10, 20, and 30 wt%. A detailed thermophysical characterization of the composites was conducted, and the obtained data were integrated into a dynamic energy simulation of a standard building in Oujda, Morocco, using TRNSYS. The results demonstrate that incorporating 30% SSA leads to a significant improvement in thermal performance: thermal conductivity decreases from 1.127 W/m·K to 0.88 W/m·K (a 21.9% reduction), thermal diffusivity drops by 34.4%, and specific heat capacity increases by 7.47%. The density also increased by 10.13%, suggesting enhanced compactness. The energy simulation for a semi-arid climate revealed that using clay bricks with 30% SSA can reduce the annual cooling energy demand by 13.62%, the heating demand by 8.29%, leading to a total annual energy saving of 12.80%. This research conclusively demonstrates that SSA is a highly effective additive for producing eco-friendly clay bricks with superior insulating properties, contributing to energy efficiency and waste recycling within a circular economy framework.

1 Introduction

Considering the urgent need to reduce the environmental impact of the construction sector while promoting the recovery of industrial waste, the development of sustainable, local, and high-performance construction materials has become a pressing challenge [1]. Among these waste materials, steel slag a major by-product of the steel industry stands out due to its high content of silicates, calcium, and iron oxides, making it a promising candidate for construction applications [2]. Although chemically stable, this residue remains underutilized, particularly in developing countries, where it is generally stored or landfilled, creating environmental risks [3]. In Morocco, for instance, the Sonasid steel plant in El Jadida generates approximately 150,000 tonnes of steel slag annually from a production of 650,000 tonnes of steel. According to recent studies, only about 29.5% of this slag is effectively reused, while the remainder is mostly stockpiled or landfilled, highlighting the urgent need

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for innovative valorization strategies [4]. Meanwhile, clay an abundant and traditional building material in Morocco demonstrates encouraging thermal performance, yet offers considerable room for improvement [5]. The country possesses extensive clay deposits spread across regions such as Taza, Taourirt, Oujda, Marrakech, and Fès, with annual production amounting to several thousand tonnes mainly used in conventional construction [6]. The excessive consumption of clay resources has gradually led to their depletion, highlighting the need for alternative and sustainable solutions. Integrating clay with industrial by-products represents an effective approach within the framework of a circular economy, aiming to preserve natural resources and develop eco-friendly construction materials that combine low environmental impact with improved thermal efficiency [7]. Among these solutions, the combination of clay and steel slag stands out as a promising pathway for designing construction materials with enhanced thermal performance, reduced energy consumption, and strong alignment with sustainable development and environmental protection goals.

Recent studies have demonstrated the potential of incorporating steel slag, a by-product of the steel industry, into clay-based materials to improve their thermal and mechanical performance. Among them, Wang et al. [8] showed that adding steel slag to clay significantly enhances its thermal conductivity, especially under varying temperature and moisture conditions. In structural applications, Islam et al. [9] found that integrating steel slag into clay bricks improved compressive strength and reduced water absorption, making them more durable. Liu et al. [10] went further by using steel slag as a matrix for phase change materials, demonstrating high thermal storage capacity and stability. Despite these encouraging results, most studies have focused on isolated material properties or energy storage potential, without integrating these materials into full-scale building envelopes. This highlights a clear research gap, the need to evaluate the impact of clay steel slag composites on the energy consumption of buildings, particularly in semi-arid regions such as Oujda, Morocco. The present study addresses this gap by coupling experimental thermophysical characterization with dynamic energy simulation, aiming to quantify the energy-saving potential of such eco-efficient construction materials.

In this context, the objective of this study is twofold. On the one hand, it aims to characterize the thermophysical properties (thermal conductivity, heat capacity, density) of a composite material made of clay composed of steel slag aggregate (SSA) in different proportions 0 to 30%. On the other hand, it aims to integrate these data into an energy simulation model of a typical building located in Oujda (Morocco), to evaluate the impact of this new material on annual energy consumption for heating and air conditioning. This work is thus part of an applied research approach combining the recovery of industrial waste, the development of local construction materials, and the energy optimization of buildings.

Fig. 1. Steel slag aggregate (SSA)

2 Materials and sample preparation

2.1 Materials

The clayey soil used in this study was sourced from the Alouana region, located in Taourirt Province, Morocco (33°58'48.5"N, 3°07'25.2"W), an area well known for its traditional use in pottery and construction. The characterization of the soil was conducted at the laboratory scale through a series of tests, including particle size distribution analysis, Atterberg limits determination, and mineralogical and identification using X-ray diffraction (XRD).

The steel slag (Fig. 1) used in this study is an industrial by-product obtained from a mineral processing plant operated by the Sonasid steel company, located in the Jorf Lasfar industrial zone near El Jadida, Morocco (33.1369° N, 8.6037° W). This site is one of the largest steel production facilities in the country, generating substantial quantities of slag during the steelmaking process. The slag was collected in its raw state and subsequently crushed to a particle size of 2.5–5.0 mm. To assess its suitability as an additive in construction materials, the slag was characterized using both X-ray diffraction (XRD) analyses.

2.2 Sample preparation

To ensure consistency in sample preparation, as detailed in Fig. 2 and reliable comparison between formulations, the following protocol was adopted for all specimens:

- A fixed water-to-clay ratio (w/c) of 0.33 was maintained for all mixtures.
- SSA was used as a partial replacement for clay at for substitution levels ranging from 0% ,10% ,20% and 30% by weight were selected to systematically evaluate the effect of SSA content on the thermophysical properties of the clay composite, covering a range from a pure clay reference to a high dosage of industrial waste as detailed in Table 1.
- The dry materials (clay and SSA) were thoroughly homogenized through mechanical mixing to ensure uniformity.
- Water was gradually added to the dry mixture to form a cohesive and workable paste.
- The paste was cast into steel molds with dimensions of $5 \times 5 \times 5$ cm³.
- Specimens were manually compacted to reduce entrapped air and improve density.

After 96 hours, the samples were demolded and subjected to a seven-day air-curing period under ambient indoor conditions (average temperature: 25 ± 3°C; relative humidity: 50 ± 10%) before testing. No binding agents were used in the sample preparation. The structural integrity of the unfired bricks was achieved solely through the natural cohesion of the clay and the mechanical compaction process, consistent with traditional earth construction techniques.

Fig. 2 Schematic diagram of the sample preparation process and the composition of the clay-SSA mixtures (Table 1).

Table 1. Composition of clay brick samples with SSA (CSSA).

Specimen Identification	C (Clay brick)		SSA	
CSSA	Wt%	g	Wt%	g
CSSA $_{0}$	100	200	0	0
CSSA $_{10}$	90	180	10	20
CSSA $_{20}$	80	160	20	40
CSSA $_{30}$	70	140	30	60

3 Method

3.1 Granulometric analysis of sediments.

The soil's particle size distribution was determined by the sedimentation method following NF P 49-057 [11], which estimates particle proportions based on their settling speed in liquid. Density readings at set times allow calculation of equivalent mesh sizes related to mean particle diameters.

3.2 Limits of Atterberg

The Atterberg limits define the water content thresholds that distinguish the liquid, plastic, and solid states of fine-grained soils. In this study, the tests were conducted on the mortar fraction (particles < 0.4 mm) in accordance with the French standard NF P 94-051 [12].The liquid limit (WL) and plastic limit (WP) were determined to calculate the plasticity index (Ip = WL – WP), which characterizes the range of water content within which the soil remains workable and moldable.

3.3 X-ray diffraction (XRD)

The clay minerals and SSA, which occur in very fine crystalline forms, were identified using X-ray diffraction (XRD). The analysis was performed with a SHIMADZU XRD-6000 diffractometer operating at 40 kV and 30 mA, using Cu Kα radiation with a wavelength of 0.154 nm. The scanning was carried out over a 2θ range of 5° to 60°, at a step size of 0.02°/min.

3.4 Hot disk method

Thermal conductivity, diffusivity, and heat capacity of the dried samples were measured using the Hot Disk TPS 2200 system equipped with a Kapton 5501 probe, following ISO 22007-2 standards. This transient plane source method, developed by Gustafsson, is widely used to characterize the thermal properties of solids, liquids, and powders [13]. The probe, which acts as both heat source and sensor, is positioned between two identical samples to ensure accurate measurement under the semi-infinite medium assumption.

4 Results and discussion

4.1 Geotechnical and mineralogical identification of soils

The particle size distribution curve in Fig. 3 shows that the soil sample consists predominantly of fine particles, with 45.8% clay (d < 2 µm) and 44.4% silt (2–50 µm), and only 9.8% sand (50 µm–10 mm). The graph confirms a steady increase in passing percentage with decreasing particle size, indicating that most particles are well below 50 µm. According to the Unified Soil Classification System (USCS) , this composition classifies the soil as clayey silt, suitable for applications requiring cohesive and plastic materials.

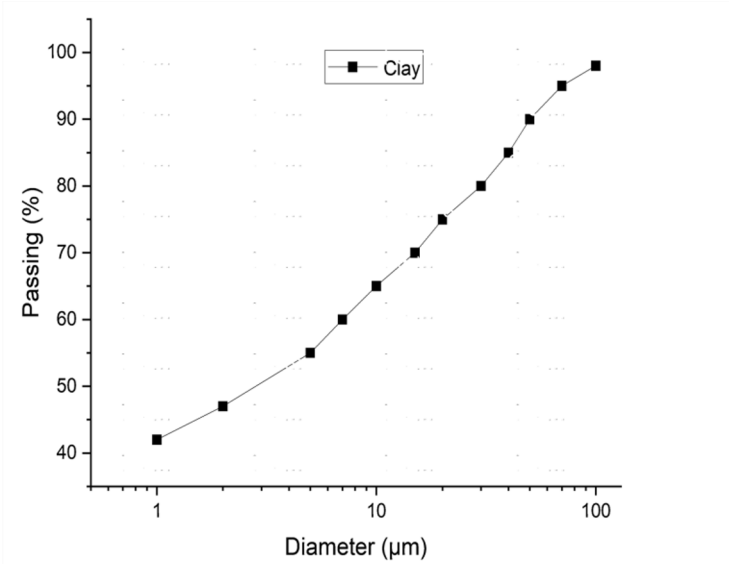

Fig. 3. Clay Soil Particle Size Curve.

The Atterberg limits namely the liquid limit, plastic limit, and plasticity index were determined using the Casagrande method, following the procedures outlined in the French standard NF P94-051 [12]. The results obtained in Table 2 reveal that the clay fraction

exhibits a high plasticity index, indicative of pronounced plastic behavior and a wide range of workable moisture content [14].

Table 2. Geotechnical properties of the clay soil (%).

Properties	**Value (%)**	
Atterberg limits	Liquid limit	43
	Plastic limit	21.3
	Plasticity index	22.6

The mineralogical composition of clay was determined through X-ray diffraction (XRD) analysis. As shown in **Fig. 4**, the samples comprise several minerals, predominantly quartz (Q), anatase (A), feldspar (F), and illite (I). The pronounced peak near $2\theta \approx 26°$ (I+Q) indicates a high concentration of quartz, with a minor contribution from illite. These results confirm that quartz is the dominant mineral phase in the soil. The dominance of quartz shows low plasticity and high dimensional stability, which are important for understanding the clay's behavior in construction applications [15]. As for mineralogical composition of SSA (Fig. 5), consists of calcium dis-silicate (Ca_2SiO_4) srebrodoskite ($Ca_2Fe_2O_5$), fayalite (Fe_2SiO_4), quartz (SiO_2), lime (CaO), dolomite ($CaMg(CO_3)_2$) and brownmillerite ($Ca_2(Al, Fe)_2O_5$). The dominant peaks of calcium silicate and srebrodoskite indicate a high content of silicate and ferrite phases, which are typical of basic oxygen furnace slags and contribute to the material's hydraulic and pozzolanic reactivity [16]. This makes it a valuable additive for construction materials, enhancing the mechanical strength and durability of concrete or stabilized soils while contributing to sustainable use of industrial by-products in building applications [17].

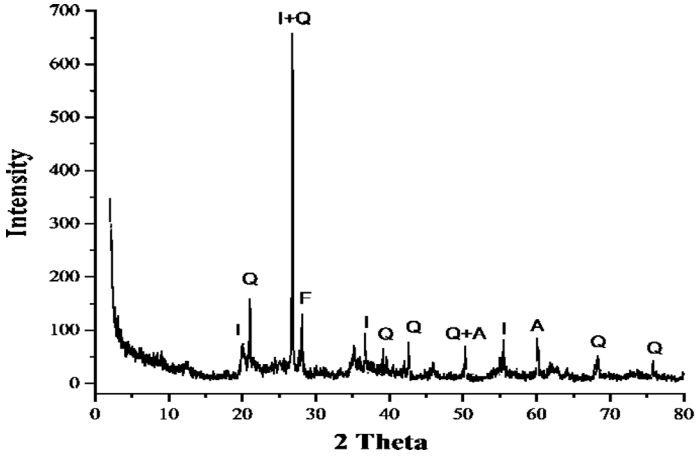

Fig. 4. XRD pattern of clay.

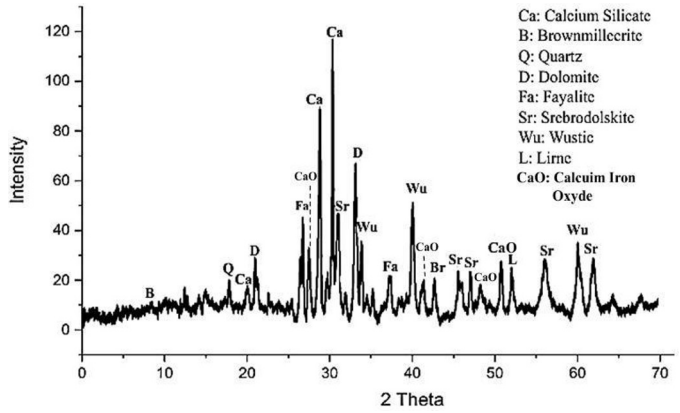

Fig. 5. XRD pattern of SSA.

4.2 Thermophysical properties of produced bricks

Fig. 6 shows that incorporating SSA into the clay matrix significantly reduces both thermal conductivity and diffusivity. Thermal conductivity decreases from 1.127 W/m·K (0% SSA) to 0.88 W/m·K (30% SSA), representing a reduction of 21.9%. This improvement is attributed to the presence of less conductive SSA particles and increased microstructural discontinuities that hinder heat flow [18]. Similarly, thermal diffusivity drops by 34.4%, from 0.61 to 0.40 mm²/s. This indicates that SSA not only improves insulation but also slows the material's thermal response, enhancing indoor thermal stability [19].

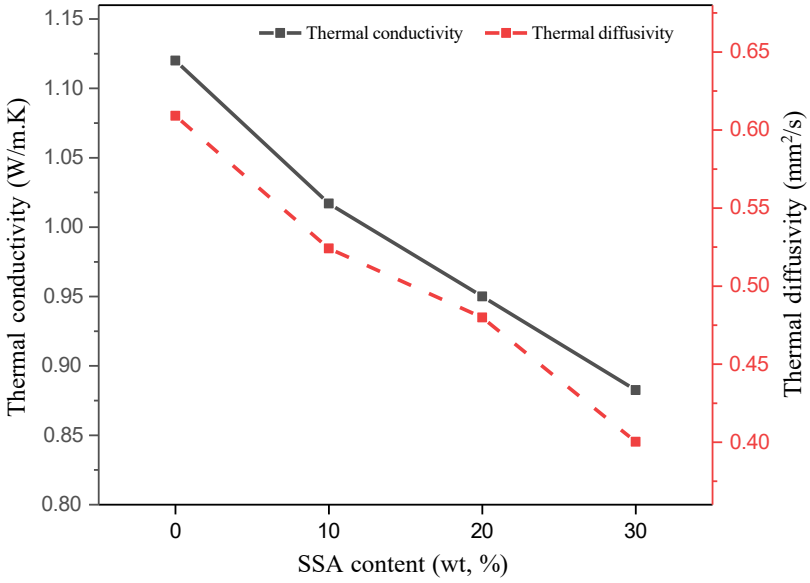

Fig. 6. Effect of SSA Content on Thermal Conductivity and Diffusivity of Clay Composites.

The incorporation of SSA into the composite matrix significantly influences both the specific heat capacity and density of the material, as shown in Fig. 7. As the SSA content increases from 0% to 30%, the specific heat capacity exhibits a steady increase, rising from approximately 1337 J/kg.K to about 1445 J/kg.K, an improvement of roughly 7.47%. This

enhancement may be attributed to the increased thermal storage capacity introduced by the SSA, which contributes to improving the material's thermal inertia. Such a property is particularly beneficial in thermal insulation applications, especially in buildings located in hot climates [20, 21]. On the other hand, the density also increases with the SSA content, from around 1375 kg/m^3 at 0% to nearly 1530 kg/m^3 at 30%, representing an approximate 10.13% increase. This rise is likely due to the higher specific gravity of SSA compared to the original matrix components, and possibly to the improved packing density resulting from the addition of finer SSA particles. While a higher density may slightly reduce the lightweight advantage of the material, it could enhance mechanical properties such as compressive strength and thermal conductivity, depending on the application requirements.

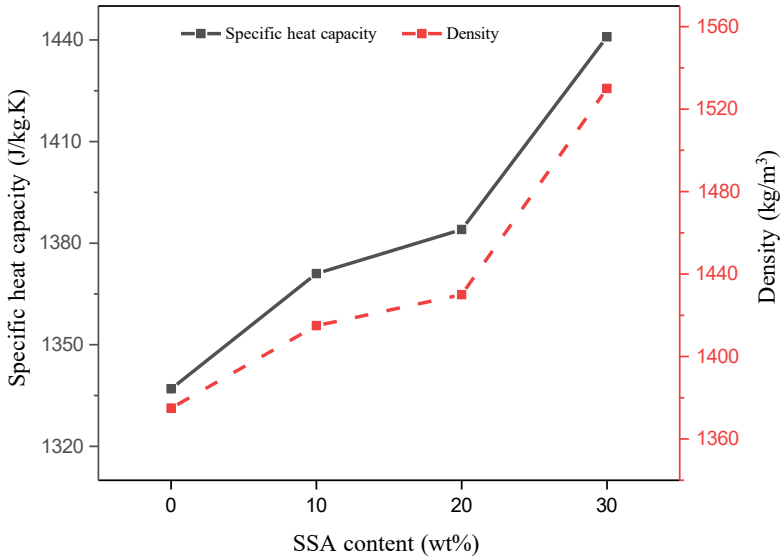

Fig. 7. Effect of SSA Content on the Specific Heat Capacity and Density of the Composite.

4.3 Dynamic thermal simulation (Annual Energy Consumption)

Dynamic thermal simulation was conducted using TRNSYS software to assess the annual energy demand of a standard room 32 m^3 (Fig. 8) located in Oujda (34° 41′ 12″ N, 1° 54′ 41″ W), a city with a semi-arid climate characterized by hot summers and moderately cold winters. The simulation considered different wall materials, including conventional clay bricks and clay bricks incorporating 30% (SSA), as detailed in Table 3. The local climatic conditions were defined using the Meteonorm weather file for Oujda.

Table 3. Details of the building materials and their thermal characteristics.

N°	Material	Thickness (m)	Thermal conductivity (W/mK)	Specific heat capacity (J/kgK)	Density (kg/m^3)	U-value (W/m^{2}K)
(a)	Clay	0.50	1.127	1337	1375	1.630
(b)	Clay with 30% SSA	0.50	0.882	1440.9	1530	1.358

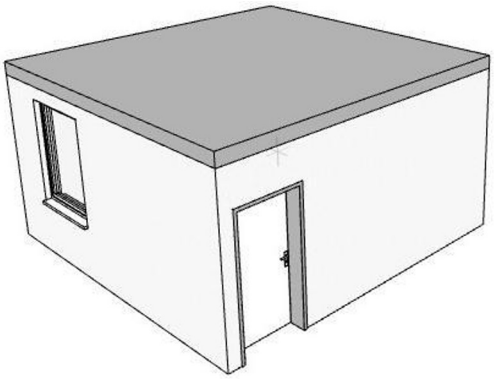

Fig. 8. Three-dimensional model of the standard room used for the TRNSYS simulation.

The simulated room, a standalone unit with four walls exposed to the exterior, was modeled to represent a worst-case scenario for thermal loads. The energy simulation was performed under the following standard comfort conditions: heating was activated when the indoor temperature dropped below 20°C, and cooling was activated when it exceeded 26°C. This model allows for a clear assessment of the wall materials' impact on the building's energy demand without the mitigating effects of adjacent conditioned spaces.

As illustrated in Fig. 9, incorporating 30% (SSA) into clay walls leads to a notable reduction in the building's annual energy demand. The cooling energy demand for a room constructed with conventional clay bricks is approximately 59.1 kWh/m³, which decreases to 51.05 kWh/m³ when SSA-modified clay is used representing a reduction of 13.62%. This decrease is primarily attributed to the improved insulating properties of the modified material, resulting from the lower thermal conductivity and higher specific heat capacity of SSA-enhanced clay, which reduces heat transfer into the indoor space during hot seasons. Similarly, the heating energy demand decreases from 6.03 kWh/m³ to 5.53 kWh/m³, corresponding to a reduction of 8.29%. This improvement can be explained by the increased thermal mass of the SSA-based walls, which allows more heat to be stored during the day and released at night, enhancing thermal comfort during colder periods. As a result, the total annual energy consumption drops from 64.92 kWh/m³ to approximately 56.61 kWh/m³, reflecting an overall improvement in energy efficiency of around 12.80%. These results are particularly relevant for semi-arid climates such as that of Oujda, where prolonged periods of high temperatures significantly increase cooling loads. Therefore, integrating SSA into unfired clay bricks presents a promising and effective solution for reducing annual energy consumption and promoting environmentally sustainable construction practices that are well adapted to local climatic conditions.

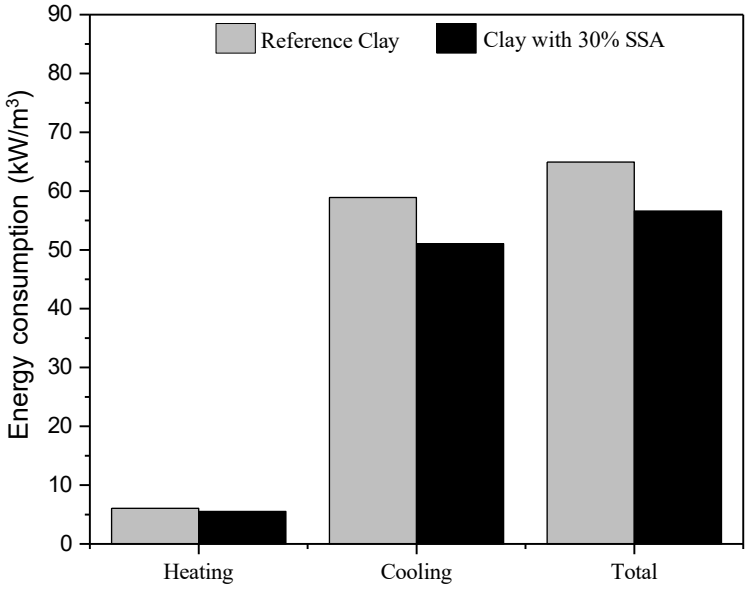

Fig. 9. Annual energy demand for clay versus clay walls modified with 30% SSA.

5 Conclusion

This research investigated the potential of using steel slag aggregate (SSA), a by-product of the Moroccan steel industry, as a partial substitute for clay in the manufacture of unfired bricks. The aim was to develop sustainable, energy-efficient construction materials through the valorisation of industrial waste within a circular economic framework. Various clay–SSA composite specimens were prepared using substitution rates ranging from 0% to 30% and were subjected to thorough thermophysical and density characterizations. The following key conclusions can be drawn from the experimental and simulation results:

- The incorporation of SSA into clay significantly affected the thermophysical properties of the resulting composites.
- Thermal conductivity and diffusivity decreased progressively with increasing SSA content, reaching reductions of 21.9% and 34.4% respectively at 30% SSA.
- A moderate increase of 7.47% in specific heat capacity was observed, improving the thermal inertia of the material.
- Density increased by 10.13%, indicating enhanced compaction. While this suggests a potential for improved mechanical performance, a comprehensive evaluation of mechanical properties, such as compressive and flexural strength, remains an essential objective for future work to fully validate the structural suitability of these composites.
- TRNSYS-based dynamic thermal simulations showed that walls made with 30% SSA reduced annual cooling and heating energy requirements by 13.62% and 8.29% respectively, resulting in a global energy saving of 12.80%.

Based on these findings, recommend the use of SSA as a promising additive in unfired clay bricks for sustainable construction, especially in semi-arid regions where thermal performance and energy efficiency are critical.

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