

Development of Thermal-Insulated Bricks Using Eggshell Waste, Lime, and Sand as a Sustainable Clay Replacement

Tejas Kailas Khanapure, Rushikesh Sanjay Pardeshi, Ganesh Ravindra Patil, Krishna Shrikant Somani, Suraj Ashok Tayade

Department of Civil Engineering, All India Shri Shivaji Memorial Society's College of Engineering (AISSMS COE), Pune, affiliated to Savitribai Phule Pune University

Supervisor: Dr. P. B. Nangare, Civil Engineering Department, AISSMS COE, Pune

Abstract

The poor thermal insulation of a building's outer walls leads to a major increase in the energy used by air conditioners in homes. A key way to improve a building's energy efficiency is by using bricks that offer better thermal resistance. However, this issue is linked to another important challenge: managing waste in a way that is both cost-effective and eco-friendly, including using it to support industrial development, so as to minimize the negative impact of waste on the environment as waste production increases. To address this, the current study aimed to determine if adding a specific amount of eggshell waste, which acts as a calcium carbonate filler, can consistently result in fired clay bricks with good thermal insulation properties. By carefully examining the physical, chemical, and thermal properties of bricks with different levels of eggshell content, this research shows how waste materials can be reused to make sustainable construction materials with better performance. The results show major improvements in thermal conductivity, along with positive changes in porosity, bulk density, and mechanical strength. Heat Flow Meter analysis showed that the egg shell content namely, formation of siliceous melt leads to higher insulation properties. Compared to regular bricks, bricks made with 7% eggshell and a decrease in density as 8.75%, and an increase in compressive strength of 42.3%. The reduced shrinkage improves the bricks' stability, while the larger pores and higher porosity enhance their insulation properties, making the bricks more durable and energy-efficient. In particular, bricks with 10% eggshell fired at 1100°C showed the greatest reductions in thermal conductivity (73.3%) compared to pure bricks. Considering these results, adding eggshell waste can help lower the energy needed for heating and cooling buildings. Therefore, using eggshell waste to produce calcium silicate makes it a viable material for thermal insulation, offering a path toward more efficient and sustainable construction materials.

Keywords Clay-eggshell composite bricks, Eggshell waste recycling, Shrinkage behavior, Bulk density, Surface porosity, Thermal conductivity.

Reducing greenhouse gas emissions globally by using innovative eco-friendly building materials is an effective strategy. This is because the building industry is the largest consumer of energy, accounting for about 40% of the world's total energy use. Therefore, achieving significant energy savings in buildings is a key goal for sustainable construction. In Vidarbha Region, which has higher-than-average solar radiation, buildings often overheat due to solar penetration through windows and heat gain through the building structure. Homes that are fully exposed to sunlight need a lot of energy to keep the inside cool, and air conditioning systems are the main source of residential electricity consumption. For these reasons, using construction materials with low thermal conductivity is crucial for reducing heat transfer through the building envelope, especially in hot climates. This coincides with another issue: our societies are experiencing a serious sustainability crisis due to the massive growth in waste production, which produces two billion tones of solid trash a year. Considering landfill space is running short and natural ecosystems are being destroyed, there is presently concern regarding how to dispose of these wastes worldwide. To encourage sustainable development, waste should be recycled, reused, and used to create value-added goods.

To address these concerns, it was recently proposed that burnt clay bricks could possess a much-reduced thermal conductivity once correctly treated with waste additives, restricting the amount of heat that passes through building walls. Porous refractory insulation burnt bricks were frequently employed owing to their superior resistance to heat as well as efficiency for delivering insulating properties. The pore-forming elements that form within the burning process are employed to produce insulating clay bricks, since the air trapped in the pores within these porous materials significantly reduces heat transfer. The building insulation qualities of these bricks assist in minimizing undesired heat

gain and the amount of energy required by the building's cooling and heating systems. To attain the goal of thermal insulation bricks, recent research has included a variety of additives within the clay brick matrix.

In this context, certain waste materials and natural substances used in brick production share similar chemical characteristics. Because of this, there is a strong focus on recycling waste to enhance the quality of construction materials by offering an alternative source of raw materials. Waste from agriculture and manufacturing are both considered categories of trash. Even though industrial processes often provide better mechanical performance, recycling agricultural waste offers several advantages: it is cost-effective, easily accessible, lightweight, biodegradable, energy-efficient, and environmentally friendly. One specific agricultural byproduct is eggshells, which form the tough outer layer of eggs, making up about 10% of an egg's weight. Eggshell waste is being explored as a potential substitute for clay in brick production. Globally, over 110 billion eggshells end up in landfills each year. In 2016, the world produced an estimated 1,360 billion eggs. This type of waste has a negative impact on the environment as it raises the cost of waste management and emits unpleasant odors. The Environmental Protection Agency ranks eggshell waste as the fifteenth most significant source of contamination in the food industry. Considering their various benefits, like durability, affordability, low density, and resistance to high temperatures, eggshells have attracted the attention of researchers. In more detail, eggshells are mostly made up of calcium carbonate (94% calcite), magnesium carbonate, calcium phosphate, and organic matter. Eggshell waste consists of two main parts: a protein-filled shell layer and a calcified eggshell. A fresh eggshell has three distinct layers: a spongy middle layer with a texture similar to porcelain; a layer made up of thin, layered structures; and an outer layer with a frothy cuticle, similar to porcelain. Figure 1 shows a schematic representation of eggshell waste composition, with clear labels for each layer and its unique properties. It is commonly believed that eggshells have little commercial value, even though they are rich in minerals, amino acids, and calcium oxide, which account for 94–98% of the eggshell's composition.

1. Introduction

Reducing greenhouse gas emissions globally by using innovative eco-friendly building materials is an effective strategy. This is because the building industry is the largest consumer of energy, accounting for about 40% of the world's total energy use. Therefore, achieving significant energy savings in buildings is a key goal for sustainable construction. In Vidarbha Region, which has higher-than-average solar radiation, buildings often overheat due to solar penetration through windows and heat gain through the building structure. Homes that are fully exposed to sunlight need a lot of energy to keep the inside cool, and air conditioning systems are the main source of residential electricity consumption. For these reasons, using construction materials with low thermal conductivity is crucial for reducing heat transfer through the building envelope, especially in hot climates. This coincides with another issue: our societies are experiencing a serious sustainability crisis due to the massive growth in waste production, which produces two billion tones of solid trash a year. Considering landfill space is running short and natural ecosystems are being destroyed, there is presently concern regarding how to dispose of these wastes worldwide. To encourage sustainable development, waste should be recycled, reused, and used to create value-added goods.

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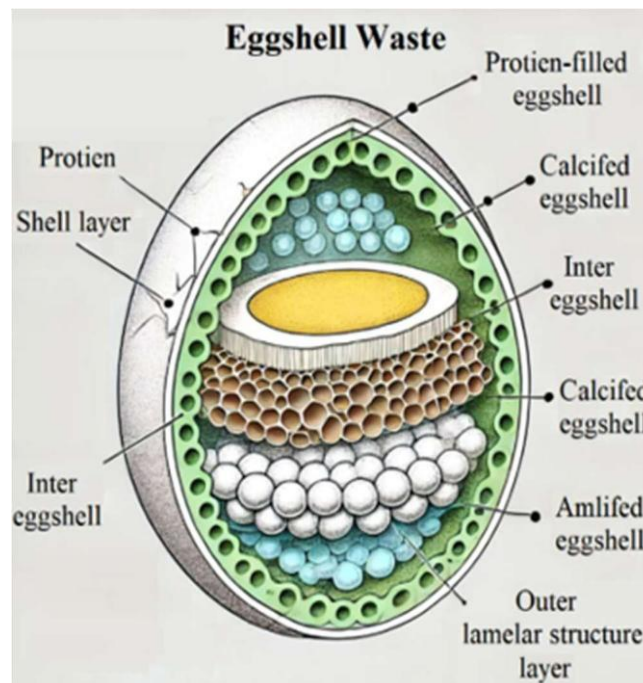


Fig. 1. Schematic of eggshell waste composition

These enable eggshell recyclables to be utilized as a substitute for natural lime. To reduce the use of cement while maintaining the natural properties of raw lime, eggshell is considered a biomaterial with chemical properties similar to limestone. The calcium in eggshells is more easily absorbed by the body compared to calcium in limestone or coral. Given these properties, incorporating eggshell as a calcium carbonate filler in major construction materials can

significantly reduce the amount of flux required, which in turn helps lower energy consumption and manage eggshell waste. Despite the potential benefits of using eggshell as an eco-friendly resource to reduce environmental waste, there has been limited research on how it affects the structural and thermal performance of fired clay bricks. This study investigated the thermophysical properties of eggshell-modified clay bricks, including their density, shrinkage, thermal characteristics, and porosity. The unique clay composites developed in this study contain three uncommon mineral phases—Sanidine, Leucite, and Wollastonite. These minerals contribute to the insulation and mechanical strength of the bricks. Sanidine and Leucite offer excellent mechanical properties, while Wollastonite, known for its low thermal conductivity, is commonly used in thermal insulation materials such as ceramics and foundry linings. The study aimed to minimize environmental waste by repurposing eggshells into construction bricks and to improve their thermal, physical, and structural properties. In the future, these bricks are expected to be suitable for various thermal insulation applications.

Materials and Methods

1.1 Materials

Lavale situated between 18.523481° N and 73.718361° E in the Pune District, supplied the clay used in this study. This clay consists of fine crystalline mineral particles and displays a range of colors, such as grey, red, purple, and green. This clay is provided by locally available brick manufacturer construction company. On the other hand, waste materials containing broken eggshells were collected from online platforms like Flipkart. The eggshells were collected, cleaned, and then dried in the sun for two days before being ground into a fine powder and added to boiling water for five to ten minutes.



Fig. 2 Materials and Manufacturing

1.2 Mix design

Three mix proportions were designed to evaluate the effect of increasing eggshell content while maintaining a constant sand fraction (15%) and compensating clay reduction with additional lime, as summarised in Table 1

Table 1. Mix proportions (by weight) used for brick casting.

Material	Mix 1 (CEs3%)	Mix 2 (CEs5%)	Mix 3 (CEs7%)
Clay (%)	72	68	63
Sand (%)	15	15	15
Hydrated lime (%)	10	12	15
Eggshell powder (%)	3	5	7

1.3 Brick manufacturing process

Dry constituents were first blended to ensure even distribution before water was added incrementally to achieve a workable, lump-free consistency. The paste was hand-compacted into standard rectangular moulds, levelled, and demoulded after initial set. Bricks were rested in shade for several hours and then cured under ambient sunlight for multiple days to allow the lime binder to react and the specimens to gain strength, with periodic inspection for shrinkage cracking. No kiln firing was applied; curing relied entirely on lime carbonation and natural drying.

1.4 Testing

Compressive strength was determined per IS 3495 (Part 1): 1992. Specimens were soaked in water for 24 hours, their frogs filled flush with 1:1 cement–sand mortar, cured under damp gunny bags and then immersed in water for three days, and finally loaded axially in a Compression Testing Machine at a uniform rate until failure; reported values are the average of five specimens per mix. Thermal conductivity was measured using a heat-flow-meter apparatus operating on the steady-state principle described in IS 15377 / EN 12667, with specimens of fixed thickness (76.2 mm) placed between hot and cold plates and conductivity computed from the measured heat flux, plate temperatures, and specimen geometry. Bulk density was recorded directly from the mass and volume of each cured specimen at the time of thermal testing.

2. Results

Table 2 summarises the measured compressive strength, thermal conductivity, and density of the three eggshell-modified mixes alongside a conventional fired red clay brick tested for comparison.

Table 2. Measured properties of eggshell-modified bricks versus conventional clay brick.

Sample	Compressive strength (MPa)	Thermal conductivity (W/m·K)	Density (kg/m ³)
Eggshell 3% (Mix 1)	5.50	0.4551	1850
Eggshell 5% (Mix 2)	4.95	0.4000	1825
Eggshell 7% (Mix 3)	4.50	0.3662	1800
Conventional red clay brick	3.50	0.50	1800–2100*

*Typical literature range for conventional fired clay brick density; the project's own conventional-brick specimen was recorded at 1800 kg/m³.

Increasing the eggshell content from 3% to 7% produced a consistent downward trend in both density and thermal conductivity. Thermal conductivity fell from 0.4551 W/m·K (3% eggshell) to 0.4000 W/m·K (5%) and 0.3662 W/m·K (7%)

— a reduction of about 19.5% across the tested range, and roughly 26.8% lower than the conventional clay brick value of 0.50 W/m·K. Density decreased modestly and monotonically from 1850 kg/m³ to 1800 kg/m³ over the same range, consistent with the lower particle density of CaCO₃-rich eggshell relative to clay and the additional microporosity it introduces. Compressive strength showed the expected inverse trend, declining from 5.50 MPa at 3% eggshell to 4.95 MPa at 5% and 4.50 MPa at 7%, a drop of about 18% across the range. Despite this reduction, every Eggshell mix exceeded both the IS 3495 minimum requirement of 3.5 MPa for load-bearing brick and the conventional clay brick baseline measured in this study (3.5 MPa), indicating that the trade-off between insulation and strength remained favourable across the entire tested composition range.

Table 3 places the best-performing mix (7% eggshell) directly against the conventional brick baseline.

Table 3. Eggshell brick (7%) versus conventional clay brick: net change.

Property	Conventional clay brick	Best eggshell mix (7%)	Change
Thermal conductivity (W/m·K)	0.50	0.366	−26.8%
Compressive strength (MPa)	3.50	4.50	+28.6%
Density (kg/m ³)	~1950 (avg.)	1800	−7.7%
Waste utilisation	None	7% eggshell waste	—

3. Discussion

The observed reduction in thermal conductivity with increasing eggshell content is consistent with the mechanism reported for fired clay–eggshell composites in the literature: calcium carbonate is hydrophobic and lower in specific gravity than clay, and its presence increases internal microporosity, either through entrapped air at the filler–matrix interface or, in fired systems, through CO₂ evolution during calcite decomposition. Although the present bricks were lime-cured rather than kiln-fired, the same compositional principle appears to govern behaviour: eggshell addition dilutes the denser clay fraction and introduces a more porous, lower-conductivity matrix, lowering both bulk density and heat flow through the brick.

The accompanying loss of compressive strength is the conventional trade-off observed across nearly all porosity-enhancing brick additives, including fly ash, rice husk ash, marble dust, and eggshell ash reported elsewhere. In the present study this trade-off remained controlled: even the highest eggshell loading (7%) retained a compressive strength (4.50 MPa) comfortably above the IS 3495 minimum and above the conventional brick baseline, suggesting the lime binder compensated adequately for the reduced clay fraction within the tested range. This is a meaningfully different strength outcome from high-temperature fired eggshell-clay bricks reported in the literature, where compressive strength at comparable eggshell fractions can fall well below 1 MPa; the difference is plausibly attributable to the lime-carbonation binding mechanism used here, which does not depend on vitrification or calcite-driven pore formation during firing, and therefore avoids the steep strength penalty associated with kiln-fired high-eggshell mixes.

From a sustainability standpoint, the 7% eggshell mix simultaneously reduced density (lighter, easier-to-handle units), reduced thermal conductivity (lower operational heating/cooling energy), and diverted eggshell waste from landfill disposal, while requiring no kiln firing — a potentially significant energy and cost advantage over conventional brick production for small-scale or rural applications. The principal limitation of the present mixes is the comparatively higher unit cost (estimated at roughly Rs. 11 per brick versus Rs. 7 for a conventional brick in this study), driven mainly by the cost of procuring eggshell powder and hydrated lime; at larger production scale, on-site eggshell collection from food-service or poultry-processing sources would likely narrow this gap substantially.

4. Conclusion

This study demonstrates that eggshell powder, blended with clay, sand and hydrated lime, can be used to produce lime-cured (non-fired) bricks with improved thermal insulation relative to conventional fired clay bricks, while retaining adequate compressive strength for masonry use. Across eggshell contents of 3–7%, thermal conductivity decreased progressively (down to 0.366 W/m·K at 7% eggshell, a 26.8% reduction versus the conventional brick), density decreased modestly (to 1800 kg/m³), and compressive strength, although declining with higher eggshell content, remained above both the IS 3495 minimum and the conventional brick benchmark throughout. These results support eggshell waste as a viable, low-cost filler for sustainable, energy-efficient masonry, and point toward a practical, kiln-free manufacturing route suitable for small-scale and resource-limited construction settings.

5. Future Scope

Future work should extend the eggshell content beyond 7% to identify the upper limit before strength becomes unacceptable, evaluate long-term durability under wetting–drying and freeze–thaw cycles, and assess water absorption and efflorescence behaviour of the lime-bound matrix. Life-cycle costing at production scale, and a comparison of embodied energy against fired clay and fly-ash bricks, would further clarify the net environmental benefit of adopting this material in green building practice.

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