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Research Article

Integrated optimization of mix design and mold dimensions for clay brick manufacturing in Adrar region

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Abstract

This research optimizes raw clay brick composition and production through systematic evaluation of mechanical and thermal properties. Four clay compositions (C1; C2; C3 and C4) and three production moulds (M1; M2 and M3) with varying geometries were investigated under controlled conditions. Comprehensive testing assessed compressive strength, flexural strength, and thermal conductivity using standardized methods with statistical validation. Results revealed that composition C2 demonstrated superior performance with optimal compressive strength (1.30 MPa), highest flexural strength (0.71 MPa), and lowest thermal conductivity (0.60 W/m·K), making it ideal for thermal insulation in hot climates. Production mould M1 achieved maximum bending resistance (1.22 MPa) with excellent mechanical cohesion, ensuring consistent quality and structural integrity. The optimal C2-M1 combination provides a sustainable construction solution for the Adrar region, offering enhanced mechanical properties, superior thermal performance, production stability, and compliance with international clay brick standards. These findings contribute significantly to sustainable construction material development, presenting an environmentally friendly alternative that meets performance requirements while promoting energy-efficient building practices in arid regions.

1. Introduction

Clay-based construction techniques constitute a fundamental paradigm of sustainable human-environment interaction, with historical roots extending over nine millennia [1]. Archaeological evidence indicates independent evolution among various civilizations, ranging from the Indus Valley to South America [2], positioning these traditional technologies as viable solutions for climate change impacts and energy security concerns [3]. Recent investigations demonstrate earthen construction methods achieve energy efficiency improvements of up to 60% compared to conventional modern materials [4]. Worldwide manifestations exhibit remarkable diversity reflecting local climatic conditions. Middle Eastern regions showcase clay high-rise structures in Sana'a [5], while South Asian examples include Gislamir Castle in India with botanical additives enhancing mud durability by 40% [6]. Peruvian Chan Chan city represents functional sustainability models [8], and African applications reveal 70% of rural populations utilizing mud construction methods [9] .The Genier Grand Mosque in Mali is recognized as the largest clay structure globally, whereas complexes in Morocco and Nigeria exemplify strategies for environmental adaptation [10].

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Algeria's clay heritage demonstrates significant sustainable potential through superior thermal properties, with historical settlements documenting 60% reduced energy consumption compared to concrete alternatives [11]. The Mizab Valley mud palaces exhibit integrated urban planning [12], whereas the mud architecture of Timimoun showcases remarkable climate-responsive design, achieving interior temperatures 7-10°C lower than external peaks and maintaining humidity levels between 40-50%, resulting in energy savings of up to 65% [13].

The Adrar region is noted for its unique traditional earthen construction, utilizing plentiful high-quality clay resources [14].The clays of Adrar are distinguished by high silica content [15] and natural mineral salt compositions [16]. Optimal earthen brick performance requires specific mechanical and thermal characteristics. International standards (ISO 13784-1, ASTM E2392) specify minimum compressive strength of 2-5 MPa for load-bearing applications [17],[18] , thermal conductivity below 0.8 W/mK for effective insulation[19], and thermal mass capacity above 1500 J/kg·K for temperature regulation in hot climates[20]. Despite Adrar clay's documented advantages in traditional construction[21], systematic investigation of its mechanical-thermal synergy remains limited, particularly regarding how its high silica content influences the optimization of structural integrity and thermal performance compared to other regional clays.

This research addresses this knowledge gap by systematically characterizing four clay compositions and three moulds configurations from Adrar region, integrating mechanical strength testing with thermal performance analysis. The objective is to establish evidence-based optimal combinations that meet international construction standards while maximizing energy efficiency for sustainable building applications in hot arid climates.

2. Materials and Methods

2.1 Materials Using

2.1.1 Raw Material Sources and Collection

Within the framework of this pilot study, clay samples were collected from the main quarry in Adrar region, and sand samples were obtained from two distinct sources: dune sand from Buda quarries and Sand of category (2.5-2 mm) from the area adjacent to the clay quarries. (Fig. 1) presents the geographical distribution of sampling locations. These materials underwent a series of advanced physical and chemical analyses prior to raw clay brick manufacturing, following the material collection and characterization protocol illustrated in (Fig. 2).

(a) (b) (c)

Fig. 1. Geographical location of samples (a)clay, (b) dune sand, (c) Sand of category (2.5-2 mm)

2.2 A Method of Preparing and Shaping Raw Clay Bricks

We prepared a set of experimental samples of raw clay bricks according to traditional methods recognized in rural areas, making some adjustments to the component proportions to study their influence on the characteristics of the final product Table 1. All manufacturing stages were carried out outdoors under the natural weather conditions prevailing in the region during the research period. We determined the percentages of raw materials accurately based on Table 1, where the experimental mixtures included varying percentages of clay, sand, straw (Fig. 3) and water. Initially, we kneaded the clay with a water content 20% above the optimum moisture content to facilitate fermentation. We then left this dough for four full days in partially covered containers to ensure a homogeneous fermentation, with daily stirring to ensure an even distribution of moisture and prevent the formation of hardened layers. After the fermentation period was complete, we gradually added the secondary ingredients (sand and straw) with controlled amounts of water to ensure the desired consistency of the mixture was achieved. We determined the percentage of sand based on the improvement of compressive strength, while we added straw in different proportions to improve thermal insulation and reduce cracking during the drying process. The mechanical kneading process was continued for at least two hours for each mixture to ensure a homogeneous distribution of the ingredients. We formed the samples by hand using iron and wooden molds specially prepared for this purpose, with different standard dimensions. We made sure to compress

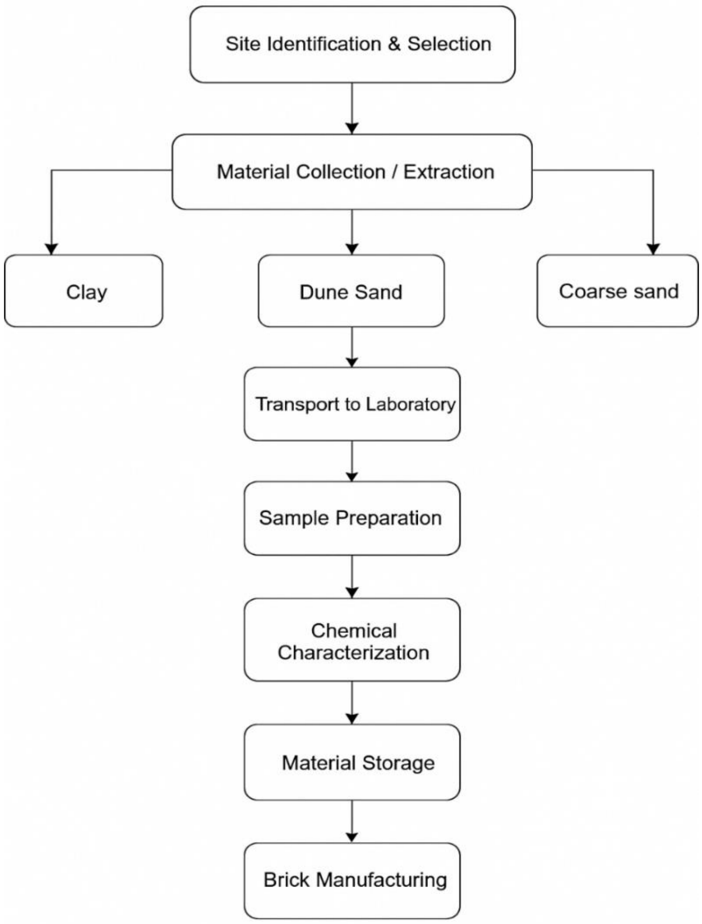


Fig. 2. Material collection and preparation workflow for clay brick production

the mixture evenly in the molds to eliminate air voids and avoid structural deformations. After shaping, we left the upper surfaces smooth using special tools to ensure the surfaces were regular. All samples underwent a natural drying period under direct sunlight for two to three weeks. During this period, we monitored the drying process through a system of decreasing daily weight of the samples until the weights stabilized, showing that the moisture loss process was completed. We also made sure to turn the molds periodically to ensure a homogeneous drying on all sides. To protect the samples from sudden weather changes such as rain or strong winds, we used transportable plastic covers.

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

Fig. 3. Raw materials for manufacturing raw clay bricks (a) Clay (<0,075mm), (b)Dune sand (0-2mm), (c) Coarse sand (2-2.5 mm), and (d) Straw fiber (25-30 mm)

Table 1. Material composition percentages of clay brick formulations including clay, sand, straw, and water content

Compositions	Clay %	Sand of dune %	Coarse Sand (2-2.5) mm %	Straw %	Water %
C1	73	18.73	8.27	1	12
C2	51	36	13	1	10
C3	30	70	0	1	10
C4	18.5	71.5	0	1	10

3. Mechanical Testing

Standardized tests following latest research protocols and international standards were conducted including uniaxial compression testing at ITPS Adrar laboratory on 15×15×15 cm^3 cubic samples to determine maximum compressive strength (UCS) per EN 12390-3 [22]chowing vertical/oblique fracture patterns (Fig. 5a), flexural strength testing at ITPS Ghardaïa per EN 1015-11 using concentrated loads on 4×4×16 cm^3 samples [23] recording maximum collapse loads (Fig. 5b), and The flexural load evaluation generating tensile stress in lower specimen fibers was conducted at the University of Bechar using three mold dimensions M1:10×12×25 cm^3 [24], M2:5×9×20 cm^3 [25] and M3:15×15×30 cm^3 (Fig. 4), reflecting material fracture resistance under bending moments as mechanical cohesion and internal structure quality indicators. The failure pattern observed in Fig. 5(c) demonstrates a shear-dominated failure mode rather than flexural failure. The specimen exhibits a diagonal crack propagating at an angle through the cross-section, which is characteristic of shear failure. Unlike flexural failures that show horizontal cracks perpendicular to the loading direction, this diagonal cracking pattern indicates that shear stresses exceeded the material's capacity before significant flexural deformation occurred. The distinct angular separation and sudden brittle failure, rather than gradual deformation, confirms the shear-dominated mechanism. This failure pattern suggests that the specimen's geometry and loading configuration resulted in critical shear stresses developing before flexural failure, which has important implications for design and load capacity calculations.

4. Thermal Testing

Thermal characterization tests using CT meter on 10×10×10 cm^3 cubic samples (Fig. 5d) at CNERIB laboratory Algeria following ISO 8894-1/ISO 8894-2 standards [26] employed Contact Transient Method technology with thermal probe contacting sample surface, applying thermal pulse, measuring temperature response over time to calculate thermal conductivity, thermal diffusion, and specific heat capacity through non-destructive method providing accurate results without sample damage, ideal for evaluating clay bricks' thermal insulation and energy storage capabilities in construction applications.

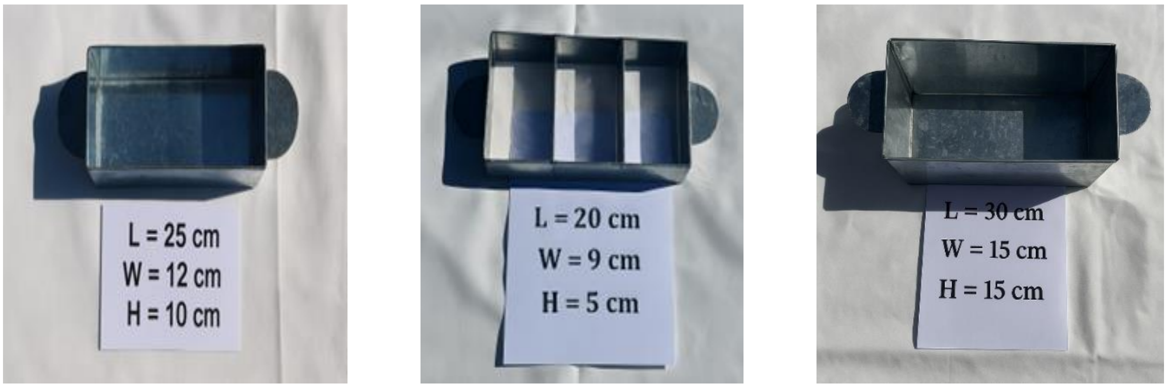
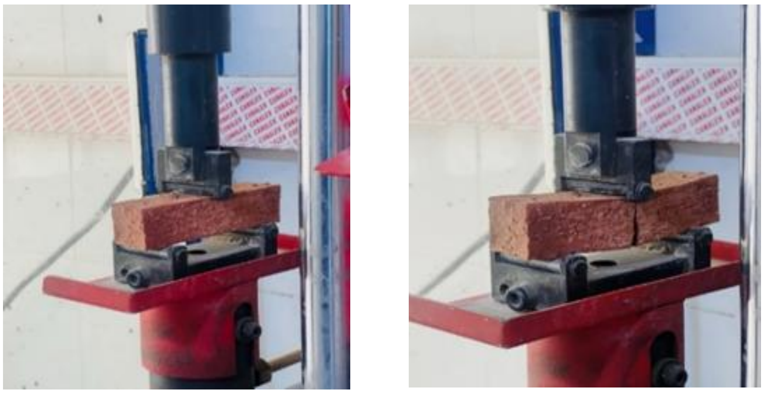


Fig. 4. Raw clay Brick Production Molds (M1, M2 and M3)

(a)



(b)

(c)

(d)

Fig. 5. Tests: (a) Compression test; (b) and (c) 3-point flexural test and (d) measurement of thermo-physical characteristic

5. Results and Discussions

5.1 Physico-Chemical Characterization

Table 2 of the laboratory data shows that the clay has outstanding plasticity characteristics (liquid limit 77%, plastic limit 36.5%, plasticity index 40.5%), a high methylene blue value (9.5%), and 47% fine particles (<2 microns), which are perfect for building clay bricks. The complementary sand materials (dune sand and 2-2.5mm classified sand) provide structural integrity with acceptable sand equivalent (83-90.95%), while low soluble salts (≤0.18%), minimal organic matter (≤2.5%), and appropriate calcium carbonate levels (0.015-10.3%) ensure chemical stability for high-quality, durable clay brick manufacturing.

Table 2. Physico-chemical characteristics of local materials for brick manufacturing: Clay, dune sand, and graded sand from Adrar area

Physical and Chemical Characteristics	Clay	Sand of dune	Sand of class (2-2.5) mm	Standard
Particle size on % elements < 2µm (%)	47	1.76	0	XP P94-041
Liquidity limit W l (%)	77	/	/	NF P 94–051
Plasticity limit W p (%)	36.5	/	/	NF P 94–051
Plasticity index Ip (%)	40.5	/	/	NF P 94–051
Specific density (γs) (g/cm^3)	2.66	2.64	2.60	NF P 18–555
Value of blue VB	9.5	0.06	0.013	NF P94-068
Sand equivalent (%)	0.25	90.95	83	NF P 18–597
Moisture content (%)	0.42	0.1	0.2	NF P 94-050
Calcium carbonate content $CaCO_3$ (%)	0.015	5,6	10,3	NF P94 048
pH	8.12	8.22	9.06	ASTM D6276-99a
Organic matter (%)	1.99	2.50	Nul	NF P 94–055
Soluble salt Cl^- (%)	0.11	0,18	0,11	NF EN 196-2

Table 3 shows mixing water sourced from Adrar city's drinking network and analysed at National Water Resources Agency laboratory confirms WHO compliance with pH (6.5-9), sulphate <250 mg/L, chloride <200 mg/L, potassium <12 mg/L, magnesium <150 mg/L, ensuring absence of harmful substances or excess salts that could negatively impact hydration and cohesion processes in clay brick mixtures. Toxin-free composition contributes to safe, high-quality final products, making.

Table 3. Mineral composition of Adrar region water used in clay brick manufacturing

Composition	Concentration mg/L
pH	7,53
Rs	640
Ca+	50
Mg+	36.5
Na+	99.91
K+	7
Cl-	140
SO_4^-	210
NO_3^-	19.144
HCO_3^-	118
NH_4^+	0.007
NO_2^-	0.01
PO_4^-	0
MO	1,30
SI	685

5.2 Mechanical Testing

Figure 6 illustrates three distinct phases of compressive strength development with error bars representing standard deviation to enhance result reliability: the first phase (0-10 days) exhibited rapid growth achieving 60-65% of final strength through initial drying and clay bonding with limited variation between samples, the second phase (10-28 days) showed moderate growth during continued hardening with slightly wider error bars reflecting natural variation in drying rates, and the third phase (post-28 days) demonstrated relative stability indicating drying completion. The experimental results with high statistical reliability show that C2 achieved superior performance (1.32 ± 0.08 MPa), C1 reached 1.10 ± 0.07 MPa, while C3 and C4 showed similar performance (0.85 ± 0.05 MPa and 0.82 ± 0.06 MPa respectively), with relatively small error bars (coefficient of variation less than 7%) indicating good reproducibility and high reliability in manufacturing and testing processes. Table 4 presents a comparative analysis of the obtained compressive strength values with existing literature and international standards. Although ASTM standards suggest 3-3.5 MPa as desirable compressive strength for sustainable construction materials, the experimental results fall within acceptable ranges for raw clay bricks (0.7-2.0 MPa) as reported in various studies. The lower strength values compared to ASTM recommendations can be attributed to the use of unfired clay bricks without stabilizers, which is typical for traditional earth construction. Despite these lower values, the statistically validated results confirm the importance of drying control, the reliability of post-28-day design values, and the adoption of C2 as production reference due to its optimal performance within the raw clay brick category, with potential for strength improvement through natural stabilizers in future studies.

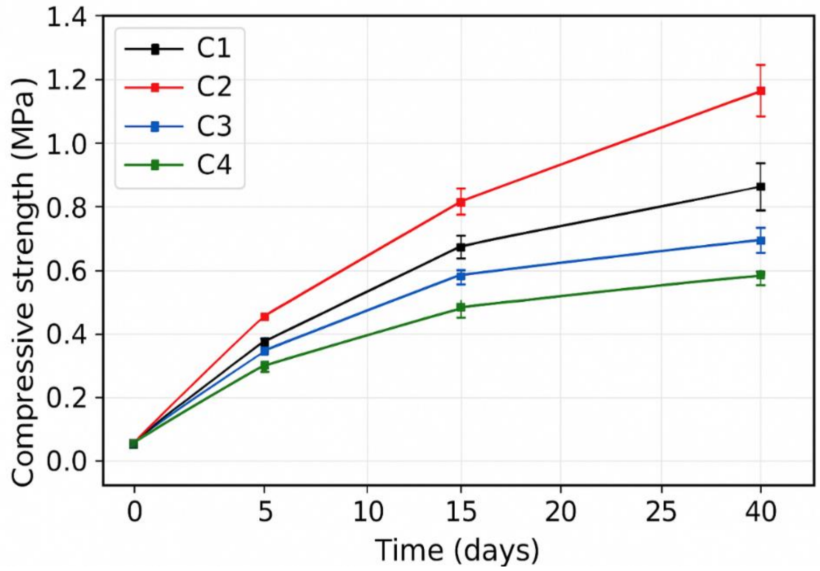


Fig. 6. Compressive strength of raw clay bricks samples

Table 4. Comparison of compressive strength with literature and standards

Standard	Material Type	Compressive Strength (MPa)	Notes
[27]	Adobe stabilized	1.40 – 2.05	Improved performance due to fiber reinforcement
[28]	Adobes stabilized	2.3 - 2.8	Natural fiber reinforcement – sustainable approach
[29]	Adobe reinforced	2 - 1.2	Bio-reinforced adobe with natural fibers
[30]	Building brick	3.0 – 3.5	for sustainable construction
[31]	Compressed earth block	0.3	Very low mechanical strength
[32]	Adobe	3.41	best mechanical behavior
Present Study - C2	Raw clay brick	1.32	Optimal composition
Present Study - C1	Raw clay brick	1.10	Second best performance
Present Study - C3	Raw clay brick	0.85	Acceptable range
Present Study - C4	Raw clay brick	0.82	Acceptable range

Flexural strength analysis (Fig. 7) shows rapid 5-day growth achieving 85-90% final strength through surface drying and clay bonding, then stability from day 5-20 indicating hardening completion. The error bars in (Fig. 7) represent the standard deviation of three replicate specimens, demonstrating good repeatability and reliability of the experimental results. C2 achieved superior performance (0.71 ± 0.03 MPa) with post-day-7 stability, C1 reached 0.64 ± 0.04 MPa, while C3 and C4 showed similar performance (0.60 ± 0.05 MPa and 0.59 ± 0.04 MPa respectively) with slight fluctuations. The small error bars confirm the consistency of the testing procedure and the homogeneity of the clay brick specimens. These results confirm surface drying sensitivity, one-week design value estimation capability, and typical 1:2 flexural-to-compressive strength ratio for clay-based materials.

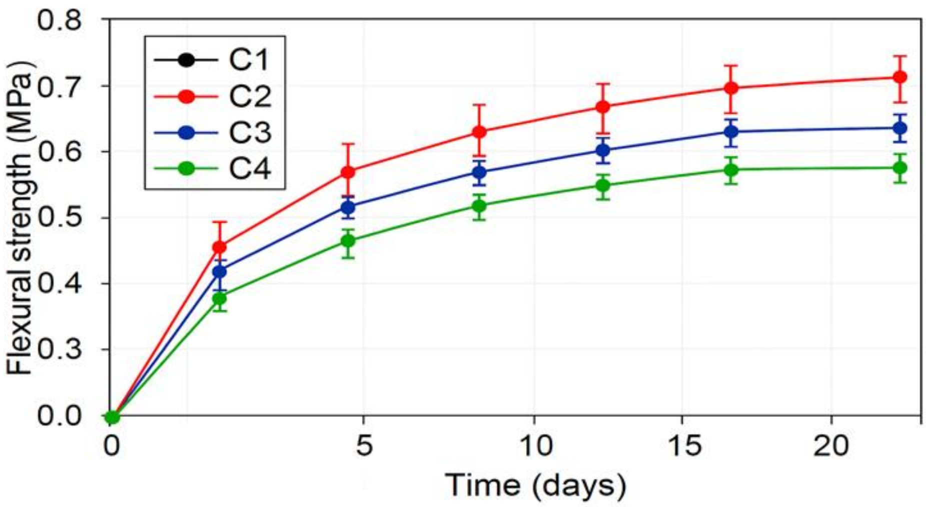


Fig. 7. Flexural strength of raw clay bricks samples

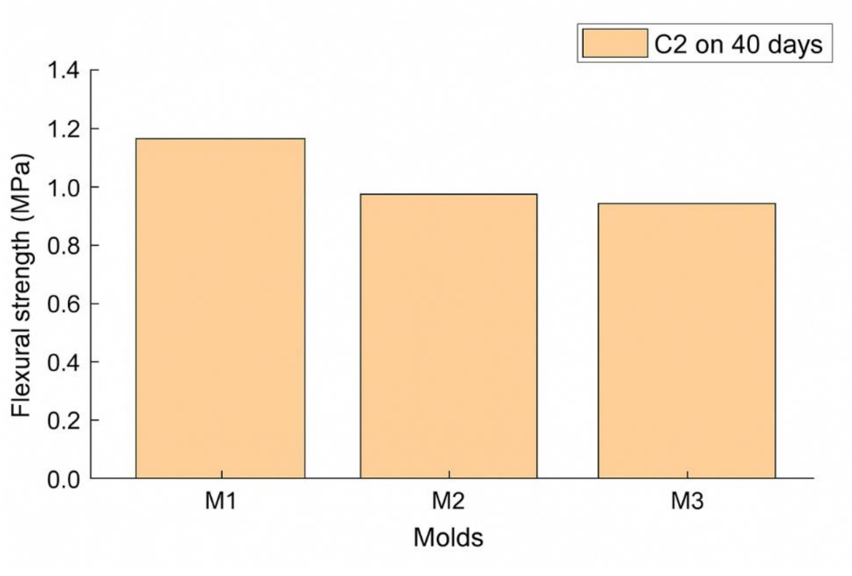


Fig. 8. Flexural strength of sample 2 as a function of molds

The Sample 2 flexural resistance evaluation (Fig. 8) across three moulds shows good convergence with limited variation reflecting production stability and minimal mould effects.with M1 achieving highest resistance (1.22 MPa) indicating excellent cohesion and optimal structure, M2 and M3 recording similar values (1.03-1.00 MPa) with 15-18% deviation, overall 0.22 MPa range and ~10% standard deviation indicating acceptable uniformity within normal clay material ranges affected by forming/drying factors, all values meeting acceptable flexural resistance rates confirming practical usability and consistent quantitative production performance.

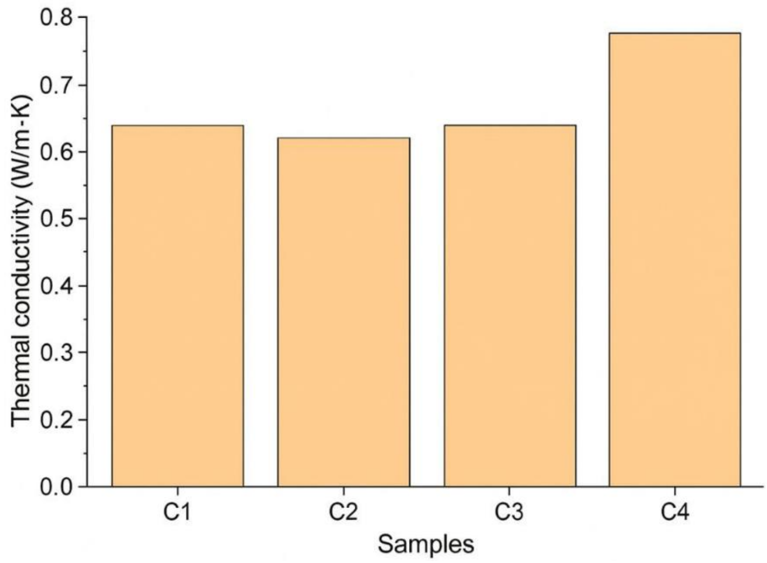


Fig. 9. Thermal conductivity of raw clay bricks samples

5.3 Thermo Physical Testing

Thermal conductivity measurements in (Fig. 9) show performance variation reflecting mixture composition effects, with C4 showing the highest value (0.78 W/m.K) indicating denser structure enabling greater heat transfer, while C1, C2, C3 achieved close values (0.60-0.63 W/m.K), with C2 lowest (0.60 W/m.K) due to differences in water content, additive proportions (straw/sand), and forming pressure as increased porosity and organic materials reduce conductivity through air insulation.

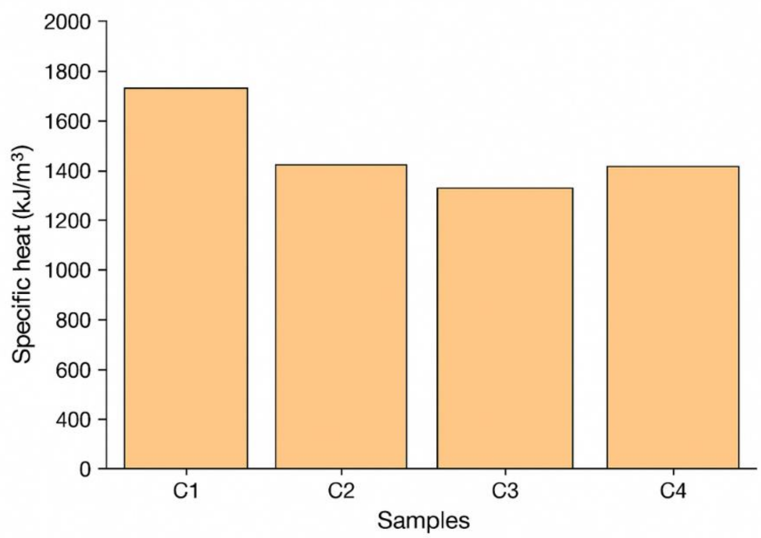


Fig. 10. Specific heat of raw clay bricks samples

Figure 10 shows a large range in specific heat capacity, which reflects the effects of mixture composition on thermal energy storage. C4 has an average performance of 1540 kJ/m^3.K, while C1 has the highest value of 1790 kJ/m^3.K. This indicates great heat storage and delayed transfer for better thermal comfort. C2 and C3 have the lowest values (1490-1420 kJ/m^3.K) due to changes in water content, clay quality, or quantities of organic additives, affecting building thermal performance. Higher levels allow for increased heat absorption during the day and gradual release at night, which contributes to internal stability. All values are within the predicted clay material limitations (1200-2000 kJ/m^3.K), with C1 being the optimal choice for hot climate building.

6. Conclusion

This study systematically investigated the optimal composition and manufacturing parameters for sustainable raw clay bricks through comprehensive laboratory testing and performance evaluation. Four distinct clay-sand compositions (C1, C2, C3, and C4) were carefully formulated with varying proportions and tested using three mould configurations (M1: 10×12×25 cm^3, M2: 5×9×20 cm^3 and M3: 15×15×30 cm^3) with distinct geometric dimensions. All samples underwent controlled curing under laboratory conditions for 28 days, with mechanical and thermal properties monitored at regular intervals to establish strength development patterns and ensure consistent quality control throughout the experimental process.

The full experimental program included tests for compressive strength, flexural strength, thermal conductivity, water absorption, and density. The results showed that Sample C2 had the best overall performance, with a compressive strength of 1.30 MPa, a flexural strength of 0.71 MPa, and a thermal conductivity of 0.60 W/mK. These numbers show that they are very good for use as thermal insulation in hot climates. Statistical analysis with error bars showed that the results were reliable and could be repeated. M1 was the best of the three moulds tested, with a maximum bending resistance of 1.22 MPa and excellent mechanical cohesion properties. The synergistic C2-M1 combination is the best choice for long-lasting construction projects because it strikes a good balance between mechanical performance, thermal efficiency, and production feasibility.

The novelty of this research lies in its integrated optimization approach that simultaneously addresses multiple critical parameters affecting brick performance. Unlike previous studies that examined single variables in isolation, this work establishes a comprehensive framework linking clay-sand ratios, water content optimization, and mould design to achieve predictable mechanical and thermal performance outcomes. The study introduces a systematic three-phase strength development model: rapid initial growth (0-10 days achieving 60-65% final strength), moderate progression (10-28 days), and post-28-day stability, providing reliable design values for practical applications in construction industry. Statistical validation through error bar analysis enhances the credibility of findings and ensures reproducibility in future research endeavors. Additionally, the identification of shear-dominated failure mechanisms in flexural testing provides important insights for structural design considerations, enabling engineers to develop more robust and durable building solutions using sustainable materials.

6.1 Applications of Adrar Clay Bricks

Future applications include low-cost housing in arid regions, non-load bearing walls, rural construction, eco-tourism facilities, and emergency shelters. Recommended research directions encompass: investigating natural fiber reinforcement using locally available materials (date palm, alfa grass, straw) to enhance compressive strength toward ASTM recommended values; conducting long-term durability studies under various environmental conditions including moisture cycling and temperature fluctuations; performing comprehensive life cycle assessment and carbon footprint analysis; optimizing industrial-scale production processes; integrating with modern construction techniques; exploring surface treatments for weather resistance; developing standardized testing protocols; and conducting economic feasibility studies across different regions. This research contributes significantly to reduced carbon emissions, preservation of traditional building techniques, and promotion of circular economy principles in sustainable construction.

Acknowledgments

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