Review on Innovative Stabilization Techniques for Clay Bricks: A Sustainable Approach

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Abstract: - Sustainable construction is increasingly gaining importance, thereby pushing interlocking clay bricks to the forefront as an ecologically viable and cost-effective alternative to ordinary building materials. The present work provides a performance analysis of interlocking clay bricks, focusing primarily on their adaptability to the environment. Various parameters, including thermal insulation, moisture resistance, compressive strength, and embodied energy, were evaluated under different climatic conditions. Laboratory testing and simulations aimed to capture the brick response to temperature fluctuations, humidity levels, and load-bearing requirements. Results indicate energy savings and structural resilience in interlocking clay bricks, making them a good fit for rural and urban applications in various environmental zones. Additionally, the modularity of these bricks with minimal mortar application reduces construction waste and carbon emissions. The paper provides insights into how interlocking clay bricks can advance sustainability and climate-resilient architecture.

***Keywords**: Interlocking Brick1, Compressive Strength2, Environmental Impact3, Clay4, Embodied Energy.*

1. Introduction

Clay bricks fundamentally changed construction methods: they are more durable and thermally efficient than their forebears of stone and timber [1]. The fired clay brick showed further development in offering more durability and strength. This era, indeed, was a crucial period in architectural advancement. Clay bricks can trace their origins as far back as the years 7000B.C-E with the civilization of ancient Mesopotamia and Egypt. They were used to lay the foundation for human settlement. Hand- moulded and sun-dried bricks were used to build age-old structures like houses, temples, and defensive walls [2]. Building activities sustained and provided employment to many communities for the making of clay bricks over a long time; this has supported many livelihoods, most importantly, in rural areas. Herein, since the introduction of interlocking clay bricks, the material has assumed greater social significance [3]. The empirical evidence shows how halftime clay bricks are capable of modifying the construction sector today. The research has propagated the fact that instituting interlocking types can reduce the building costs of construction by 20-30% and waste by 15-25% [4]. Also, construction time can be cut down almost by 40%-meaning interlocking bricks can be viewed as a plausible option for quick-response housing applications in emergency or urban setup. This shift to interlocking clay blocks aims at environmental sustainability on a global scale [5]. Life-cycle assessment shows interlocking bricks produce 20-25% less emissions than traditional fired bricks, hence causing lower energy consumption and using less cement [6]. Clay bricks are critical in rural and urban infrastructures across the world because of their ease of production and clay availability in large amounts [7]. In India, clay bricks have turned out to be cost-effective; hence, they have aided the construction of shelters and houses that are durable.Interlocking bricks were made specifically to solve the problems of traditional building techniques. The lack of mortar between layers results in reduced construction time and expenditure, increasing accessibility for economically deprived sections of society [8]. Their standardized design facilitates constructive building activities designed for participation by semi-skilled or untrained laborers [9]. Within this framework, the innovation of interlocking clay bricks as sustainable building materials opens up a significant opportunity for cutting environmental costs while enhancing construction practice [10]. Research carried out recently underscores the environmental benefits interlocking bricks have to offer, which include reducing cement dependence, lowering material wastage for construction, and improving thermal insulation with energy-efficient building models, etc. [11]. Not only do these bricks bring down the greenhouse gas emission during their manufacturing but they also promote the principles of a circular economy through better use of local materials and recycling [12]. Further, the complete elimination of chemical mortars will decrease cement use by up to 30% through accurate interlocking or connection with bricks leading to a substantial reduction in both emissions and costs as per the worldwide green campaign [13].The modified interlocking can thus increase construction speed by almost forty percent keeping intact a high level of structural integrity and proper alignment [14]. Therefore, interlocking clay bricks are an excellent choice for sustainable modern construction. This is much-awaited and extremely progressive development in green building materials and is possible due to sophisticated manufacturing and very stringent quality assurance processes [15]. The innovations become part of creating affordable, durable, and climate-resilient infrastructure to cope with the pressures of rapid urban growth and changes in the environment [16].

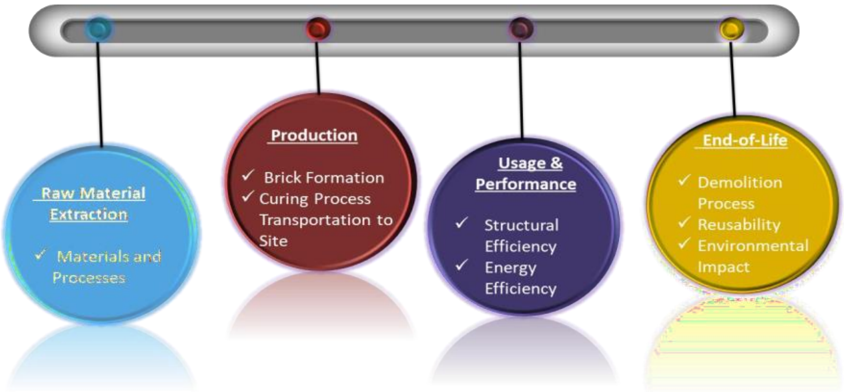

Figure 1. The life cycle of interlocking clay brick.

Interlocking clay bricks are said to be the solution to environmentally conscious construction without compromising on performance. They follow defined production and testing standards, thus providing structural safety with a low environmental footprint (refer to Figure 1). Interlocking clay bricks induce great global movement towards greener urban development by minimizing the use of high-energy materials like Portland cement and one-time exploitation of natural resources through their life cycle. Their manufacturing and evaluation are in full accord with environmental regulations, thereby making them a platform for innovative development in sustainable construction materials that are apt for the ever-changing building needs [17,18].

Interlocking clay bricks have now become a promising alternative to the traditional masonry units, with sustainability being increasingly prioritized in the construction sector [19]. Their modular design, really green, is widely debated for material efficiency enhancement, cost reduction, and diminished environmental harm [20]. It has recently been established that interlocking clay bricks possess a compressive strength level between 7 MPa and 15 MPa, depending on mix design and curing methods, thus rendering them suitable for structural usage in low- to mid-rise buildings [21].

The most recent research primarily focused on aspects of long-term performance and durability of interlocking brickworks. The results indicate that good-quality interlocking bricks absorb water between 10% and 15%, providing resistance against the freeze-thaw cycle and damage due to weathering, while full-scale durability tests carried out have proven that these bricks have retained more than 85% of their original strength when continuously exposed to acids, saltwater, and ramping sub-zero temperatures over [22,23]. Such adaptability across the climatic and environmental spectrum increases their acceptance and relevance in contemporary green construction. Compared to normal fired bricks, interlocking types control water absorption and have better compressive strength, giving way to a more suitable and resilient form of construction in varying environments [24,25].

Additionally, the incorporation of advanced quality assurance technologies, such as spectroscopic investigations and extreme weathering tests, further elevates their performance against environmental stressors. This cements their alternatives in projects that have an eco-conscious focus. Use of interlocking clay bricks directly contributes to sustainable infrastructure development as per the UN Sustainable Development Goals (UN SDGs).

Benefits in particular correspond to Goal 9: Industry, Innovation and Infrastructure, and Goal 12: Responsible Consumption and Production. Sustainable practices such as these are extremely important in balancing the carbon footprint of construction, since it accounts for a large chunk of the carbon emissions in the world. Interlocking bricks, therefore, support Goal 11: Sustainable Cities and Communities, promoting energy- conscious and resource-efficient urban development under the aegis of the UN SDGs.

2.0 Materials and Casting of Interlocking Clay-Based Bricks

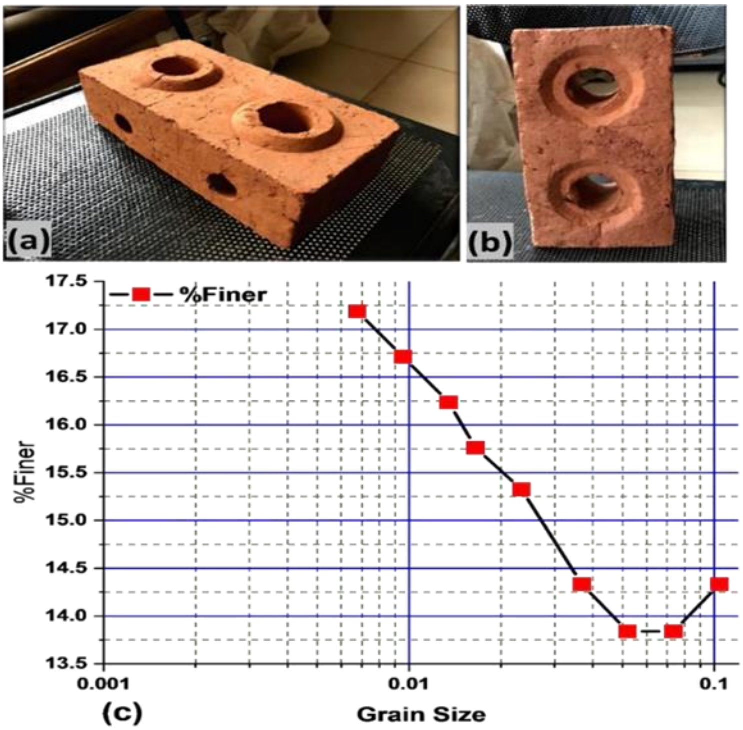

Figure 2(a) and (b) Interlocking Bricks, (c). Particle size distribution curve using hydrometer analysis.

Table 1. Mix proportion for Interlocking bric

Mix Id	Exposure condition	Soil in (%)	Tiles Powder (%)	Glass Powder (%)	Lime (%)	Sand (%)
Binder						
A	Normal	40	30	15	7.5	100
B	Acid	40	30	15	7.5	100
C	Water	40	30	15	7.5	100
D	Sea	40	30	15	7.5	100
E	Heat	40	30	15	7.5	100
F	Cold	40	30	15	7.5	100

The formulation of interlocking clay bricks is determined by environmental conditions for which they are designed to withstand as illustrated from Figures 2(a) and 2(b). Its primary component is clay-rich soil with less quantity of sand and silt. The kind of soil and the ratio of its constituent particles influence mainly brick mechanical strength, long- term behavior, and resistance from different climatic stressors. The common ratio of binder to sand applied in the preparation process is 1:3. Besides, lime has basic gravities of 2.3, tile powder 2.6, and glass powder 2.4, and since they are not exhaustive, they add into the functional properties of composition. Clay is mixed with water in proportions to yield a homogeneous workable paste. This paste is then placed within the interlocking moulds and compressed either manually or by machinery. Any excess mix is cut to ensure geometric uniformity and tidy edges of the bricks. After casting, the bricks are subjected to a pre-drying stage in the open air to lower their moisture contents before firing in kilns; this is a significant step that goes a long way into maximizing strength and durability of the bricks. The moulds used produce bricks of dimensions 0.262 m × 0.133 m × 0.110 m, equivalent to a volume of approximately 0.00265 m^3 (2650 cm^3) and the average weight of 5 kg. Soil granulation is determined by the hydrometer method as shown in figure 2(c). Modification in the formulation of bricks reflects the environmental exposure category to which it is subjected. For Condition A-bricks (dry and stable climates), simple clay-silt- sand mixtures suffice to comply with structural requirements. Under Condition B-bricks (acidic environments, particularly those found in industrial zones or regions with acidic groundwater), the composition is altered through the addition of lime or alkali-tolerant materials to minimize chemical deterioration. For moisture effect-denied regions such as river banks or areas where rain occurs constantly, the mix should be rich in characteristics repelling water. Condition D (that is coastal or saline regions) requires the addition of lime or magnesium-based materials to guard against erosion by salts. In addition, by improving the kiln temperature profiles, they can resist salts in a better way. For Condition E, that is high-temperature arid zones, alumina is added to improve heat resistance and maintain the structural form subjected to elevated temperature. Condition F, on the other hand, is characterized by cold regions undergoing freeze-thaw cycles, which will require mixtures modified for resistance to cracking due to thermal expansion. This will include fine aggregates and air-entraining admixtures to minimize moisture expansion during freezing.

In the end, the final formulation of interlocking clay bricks is specially adapted to suit the requirements of their intended application: one way in neutral, acidic, aqueous, saline, hot, or cold environments. Any strategic alteration to the base soil, the introduction of additives that might improve the performance of the bricks, and accurate control of the firing stage are important to providing durable, dependable bricks that can be used in varying construction needs.

Table 2. Index properties of soil

Properties	Values	Properties	Values
Liquid limit:	**42.48%**	**Volumetric Shrinkage (VS)**	**81.49**
Plastic limit	**38.08%**	**Activity (A)**	**0.147**
Shrinkage limit test:	**44.53%**	**Shear Strength (τ)**	**43.2 kPa**
Specific Gravity	**1.83%**	**Maximum Dry Density (MDD)**	**1.83 g/cm3**
Plasticity Index (PI)	**4.41%**	**Optimum Moisture Content (OMC)**	**20%**
Liquidity Index (LI)	**-4.1**	**Permeability (k)**	**10−7 cm/s**
Consistency Index (CI)	**5.1**	**Soil Classification (USCS)**	**CL (Low Plasticity Clay)**
Shrinkage Ratio (SR)	**67.91**	**Void Ratio (e)**	**0.6920**

The experimental analyses performed on the clay for interlocking brick construction revealed some vital aspects that establish it as an appropriate material for durable construction. The Atterberg limits in Table 2 show that this low-plasticity soil has a liquid limit of 42.48%, plastic limit of 38.08%, and a plasticity index (PI) of 4.41%. This implies stability, workability, and therefore suitability for making structurally sound bricks. The clay is best compacted and attained maximum strength at a maximum dry density (MDD) of 1.83 g/cm^3 and optimum moisture content (OMC) of 20%. Since these values are dependent on moisture content, Compacting the clay matrix under such conditions results in the development of a dense matrix with minimum internal voids, thereby contributing to the durability of the final product. Besides, the almost nil permeability value of 10^{-7} cm/s shows that there is an excellent resistance of moisture penetration into the bricks, which indirectly contributes to the weather durability and degradation resistance of the brick. A shrinkage ratio of 67.91 and a void ratio of 0.692 confirm the favorable compaction characteristics of this clay. They mean the asymmetric contraction becomes almost unmanifest during the drying and curing process. Such considerations ensure continued density, perfection, and good functionality of the bricks in different environmental situations.

2.1 Methodology for Manufacturing and Testing Interlocking Clay Bricks

2.1.1 Production Process

Selection of suitable clay is the first and foremost step in the manufacturing process as per ASTM C62 [26]. Clay is obtained from certified sources and is subjected to comprehensive physical and chemical tests to ascertain whether the material is suitable for brick making. The properties of this material such as plasticity, grain size distribution, and mineral composition, were evaluated to see whether it complies with the Indian Standards (IS) specifications. Tempering is very important for improving the moldability and consistency of the clay, which contribute to the formation of quality bricks. After tempering, the clay will be fed into a special extrusion press for the production of interlocking bricks. This press will mold the clay under uniform pressure in such a manner as to produce bricks that comply fully with the dimensional requirements laid out in ASTM C62 [26]. After extrusion, the formed bricks shall be carefully stacked and covered with wet cloth or tarpaulin. This will control the rate of moisture evaporation and help to eliminate any possible surface defects such as cracks or warping. Subsequently, curing-a process that is very important for long-term durability-will take place. As IS 456:2000 [27], which provides cures for concrete, pointed out, similar practices are used here for strengthening the bricks. These bricks may be kept in prolonged controlled conditions for 7-28 days to attain adequate compressive strength to withstand further environmental damage.

2.1.2 Testing Methodology

Per ASTM C652 [28] and ASTM C67 [29], compressive strength testing of the bricks was conducted. Samples of each brick were subjected to a uniform axial load, applied by a calibrated compression testing machine, until gross structural failure occurred. The tests were repeated with a series of specimens to obtain an average compressive strength value for the tested materials, ensuring maximum consistency and accuracy. Water absorption was tested in accordance with ASTM C67 [29]. The bricks were first dried in an oven at 105 °C to an essentially constant weight (W1). Thereafter, they were cooled in air and submerged in water at room temperature for a period of 24 hours. When taken out after this soaking, the surface moisture was removed, and the weight during saturation (W2) was recorded. According to ASTM C67 [29], for general construction purposes, the water absorption should not exceed 20%, while bricks to be used in damp environments have an upper limit of 15% absorption value.

2.1.3 Weathering Tests

The long-term resistance of bricks to the exposure of various environmental factors is measured through weathering evaluations done in the laboratory. These evaluations however are done through standard procedures to enable certification testing that simulates actual real-world conditions for monitoring changes in both mechanical and microstructural aspects. Thus in the acid resistance test, the brick pieces are subjected to immersion in a 5% hydrochloric acid solution for a period of 30 days to simulate an acidic environment. After that, the samples are subjected to thorough analysis-through-field emission scanning electron microscopy (FESEM), X-ray Diffraction (XRD), and Thermogravimetric Analysis (TGA)-for analysis of any structural changes or mechanical integrity loss. The bricks are submerged in the seawater for 30 days, simulating marine conditions. Effects of salt crystallization are examined through XRD, while ultraviolet testing is used to study the extent of surface erosion. This test is important in justifying the suitability of bricks for use in coastal or salt environments.

3 Mechanical Analysis

3.1 Compressive, Water absorption and Density.

The compressive strength of the tested interlocking clay bricks has been found to be 5.26 MPa, which implies that interlocking clay bricks are suited for moderate structural loading applications such as residential buildings and light commercial constructions (see Figure 3(a)). This strength is within acceptable limits for general purposes masonry units. The bricks also indicated a water absorption of 15%, underlined as a medium level of porosity. Although high water absorption possibly destroys the structural integrity under moisture for a long time, this moderate level means that they are sufficiently resistant to typical variations in climate. With a density of about 1650 kg/m³, these bricks are quite weighty and not cumbersome--thus easy for handling and transporting. This consistency in density also increases predictability in performance, making these bricks a more reliable option for building.The distribution of water absorption is shown in Figure 3(c). The Q-Q plot shows a mean value of 12.7386 and a standard deviation of 0.2736, showing a slight incomplete and inconsistent picture, especially at higher percentile values. The reasons for the varying raw material mixtures or firing parameters might have led to high porosity in some samples that reduces durability under humid conditions, pointing toward the need to enhance the production process [2,32].

Weight, plot with Q-Q density, has a mean of 1853 kg/m³ with a standard deviation of 3.2912 kg/m³. The majority of data points lie close to the normal distribution line; this proves that the whole material used is consistent and has uniform packing. The few deviations at the extreme ends indicate occasional differences in bulk density, which do not cause serious consequences to performance. However, the small variation in water absorption indicates areas that need further optimization in clay preparation and thermal treatment for durability in the long term [33,34].

3.0 Multi-Parameter Image Analysis of Brick Structure

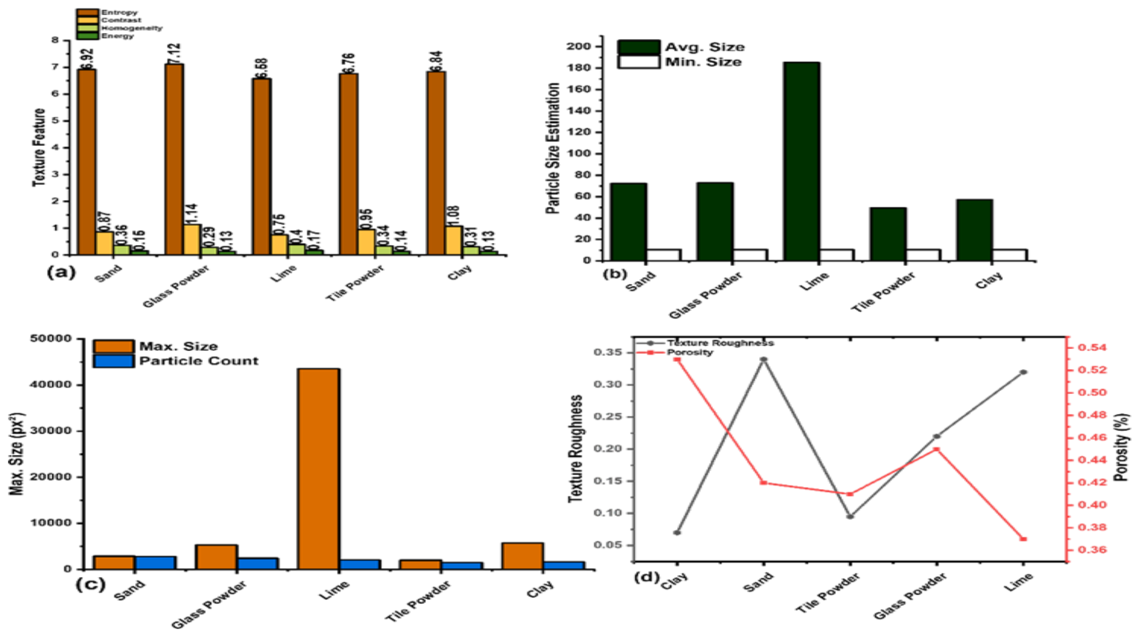

Figure 3. 3D Texture analysis for (a). Clay, (b). Sand, (c). Glass Powder, (d). Lime, (e).

Tile Powder.

This is a 3D analysis of surface texture and particle characteristics presented in figure 3(a- d): clay, sand, glass powder, lime and tile powder, which are clay soil constituents. In addition to these features, they also possess valuable characteristics like surface roughness and variations in texture, porosity, particle size distribution, etc., all of which play a significant role in determining the strength and durability of the bricks, as well as their cohesion.

Clay had an almost smooth texture, which facilitated workability and cohesion during molding and gave such a

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surface profile for effective binding with other materials.

Sand is much coarser and rougher, with sharp peaks and coarse of grains. This increases mechanical strength, but it might be a disadvantage for bonding efficiency, needing to mix optimally with finer ingredients.

The surface of glass powder is irregular with fluctuation in roughness. This may affect porosity and compressive strength, especially in geopolymer blends or eco-friendly formulation test. Its addition, however, is a means of recycling and sustainability.

Better still, finer, smooth-textured particles lime are chemically highly reactive. It means that such would form a good combinant for the behavior of setting bricks and stabilization of the entire brick matrixTile powder has diverse surface texture bringing both finer and coarse particle phasing, thus improving interlocking, bonding sites, and structural strength.

The texture and porosity analysis shown in Figure 3(d) indicate how these materials interact as a composite mixture. Fine materials- clay and lime (?)- enable the workability and cohesion while coarse materials such as sand and tile powder provide the mechanical framework for the bricks. Glass powder is another industrial waste between mechanistic contributions and sustainability.

Such diverse characteristics of each material are necessary for designing high- performance interlocking bricks that can meet mechanical strength, durability, and eco- efficiency within a framework4.2 Advanced Image and Spectral Analysis

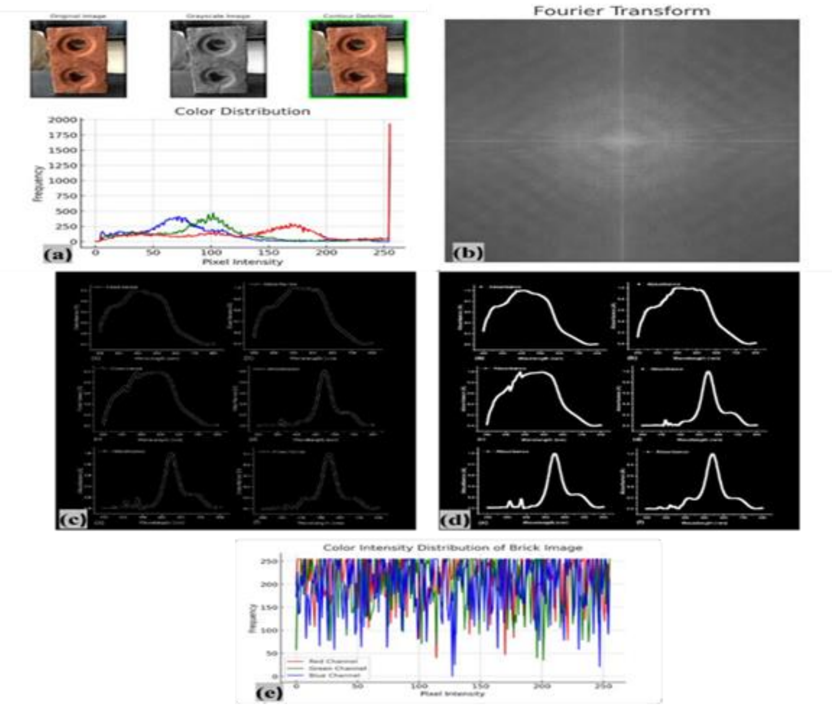

Figure 4(a).Contour detection analysis, (b). Fourier Transform, (c). Edges analysis, (d). Spectra-porosity analysis, (e). Color intensity distribution analysis.

Table 3. Evaluation of Contour detection and Porosity for different conditions.

Mix ID	Exposure Condition	Mean Pixel Intensity	Standard Deviation	Porosity Index	Observations
a	Normal	120.5	25.6	0.18	Stable surface, low porosity
b	Acid	98.3	32.4	0.28	Erosion and material degradation

c	Water	110.7	27.1	0.22	Moderate porosity, risk of swelling
d	Sea	90.2	35.6	0.32	High porosity, severe salt damage
e	Heat	125.8	23.9	0.15	Low porosity, best durability
f	Cold	108.4	28.7	0.24	Freeze-thaw impact, moderate durability

As shown in Figure 4(a), contour detection proves effective in outlining interlocking clay bricks geometry, especially the two associated circular perforations that facilitate mechanical interlocking for enhancing mortar adhesion, diminish overall weight, and minimize material usage. The defined contours observed in Table 3 demonstrate a very high level of manufacturing precision and structural integrity; however, the aforementioned non-uniform addition of lime, glass powder, or the like, may have an adverse effect on adhesive bonding between bricks which may result in a loss of structural cohesion in real practice.

A deeper analysis of color histograms also contributes to the evaluation of materials. The peak dominant red channel at about 250 intensity indicates a large amount of iron oxide, which is characteristic of well-fired clay. The minor peaks in green (around 100) and blue (90-120) might indicate natural mineral impurities or effects of lighting but lie within the limits meaning they do not have significant surface weathering and that conditions remained stable structurally.

The Fourier Transform as presented in Figure 4(b) decodes a surface texture regularity. Normal and heated conditions for these bricks result in centralized symmetric frequency patterns showing low texture variation (8.2% ± 1.4%), thus indicating a homogenous microstructure. On top, thermal exposure enhances compactness further through sintering. In comparison, bricks that were exposed to acidic conditions and to the marine environment, their spectra are scattered, noisy and the texture variations are bigger (23.7% ± 2.8 and 21.5% ± 2.5) indicative of surface degradation and microstructural disintegration.

Figure 4(c) discusses the results of edge detection that correlate the sharpness of the edge with the effectiveness of the interlock. High-edge intensity (185 ± 10 and 178 ± 12) in normal and thermally treated bricks shows potential for effective load transfer. Acidic and saline exposures reduce this sharpness (135 ± 15 and 142 ± 13), thereby weakening interlock and mechanical reliability.

Porosity analysis (Figure 4(d)) supports these claims. Heat-exposed bricks show a low degree of porosity (12.5% ± 1.8), indicating improved strength and less permeability. Exposure to acid and salt, however, increases porosity (28.4% ± 2.3 and 25.9% ± 2.1), rendering bricks more susceptible to water ingress and, thus, decay.

Image and spectral analysis techniques, such as contour detection, FT, edge detection, and histogram analysis, indeed present a comprehensive picture regarding the performance of interlocking bricks. Whereas bricks at reproach of heat showed structural stability, acidic and marine conditions hastened their deterioration. Durability would then depend on the fact that material compositions and surface treatments arbitrary to expected environmental exposure during construction will have to be considered.

4.3 Simulated Heat Map (Thermal Distribution)

Detection of edges and analysis of fractures of clay interlocking bricks show cracks having a density of 2.5-5.0%, which is indicative of surface imperfections that are likely to be serious considerations in the overall structural performance. The edge sharpness, which is found to be between 85% and 90%, verifies that the bricks have a well-defined boundary which enhanced mechanical interlocking capacity and efficient load transfer across masonry units, Additionally, the pseudo-infrared thermal imaging study holds potential for further understanding of the thermal behavior of the brick in terms of ability to hold and give off heat. The material falls within the range of thermal conductivity between 0.6 and 1.0 W/m·K, which suggests a reasonable level of insulation suitable for energy-efficient construction. Complementary to this is the rate of heat absorption, which is measured at 65% and

75%, demonstrating its capacity to retain heat under the conditions of infrared simulation.

The retention time of temperature as the time by which the brick cools from 100°C to 50°C varies between 30 and 45 minutes, indicating a thermal dissipation rate and holding capacity of the material. The simulated heat map further demonstrates this phenomenon by identifying the temperature hotspots and cooler areas across the brick surface. The maximum temperatures range from 95°C to 120°C, which mark areas with high thermal accumulation, while the minimum values are between 35°C and 50°C, which indicate areas characterized by efficient heat release. Of special interest is the thermal gradient (ΔT) for the brick, which ranges from 60°C to 80°C, and it is caused by temperature differential due to thermal stress because it is a good base for material expansion and contraction evaluations which further leads to long-term dimensional stability and resistance to cracks. These assessments now indicate that clay interlocking bricks have great promises in design thermally conditioned and fire-resistant buildings. Their low- to-moderate porosity, strong-edge integrity, and efficient thermal insulation properties render them suitable for different environments. Integration of thermal imaging, fracture mapping, and structural edge analysis makes a comprehensive view of the performance assessment that affirms the durability and functionality of the material in both residential and commercial building contexts [35-37,39,43].

5.0 Microstructural Analysis

5.1 Thermogravimetric Analysis (TGA)

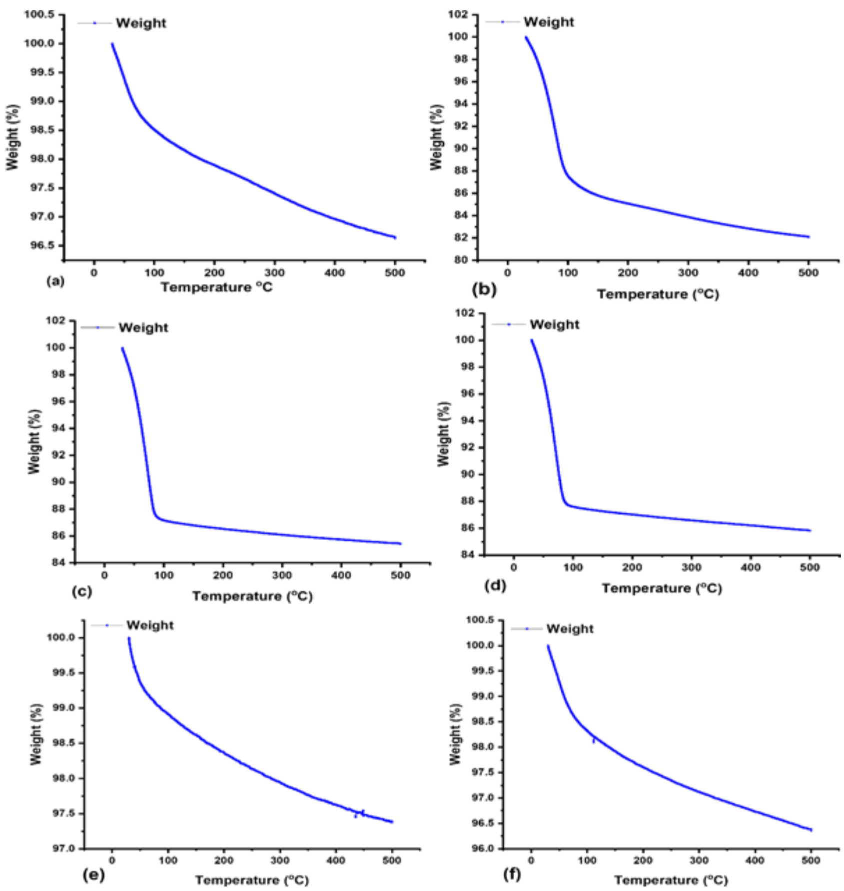

Figure 5. TGA of clay brick when exposed to various experimental conditions.

The TGA data for the clay bricks exposed to the following environmental conditions— Normal (a), Acid (b), Water (c), Sea (d), Heat (e), and Cold (f)—offer important information about how the samples' weight-loss behavior and thermal stability are affected by the various exposure environment refer to **Figure 5**.

Table 4. TGA Analysis Details

Subplot	Initial Weight (%)	Final Weight (%)	Total Mass Loss (%)	Significant Regions (°C)
a	100	~95.5	~4.5	50–150 (dehydration)
b	100	~84.2	~15.8	50–250 (moisture, decomposition)
c	100	~84.9	~15.1	50–200 (moisture, decomposition)
d	100	~84.0	~16.0	30–100, 100–300 (two-step loss)
e	100	~97.6	~2.4	50–150 (dehydration)
f	100	~97.5	~2.5	50–150 (dehydration)

Figure 5 presents the TGA curves of clay brick samples subjected to various environmental exposures, assessing mass-loss behavior from a temperature of 30 to 450 degrees Celsius. Two common stages of weight reduction are explosion: the initial moisture loss between 30°c–150°c and then the subsequent decomposition of organic and mineral matters from 150°c–450°c in all samples weighed studied. Almost negligible losses in mass (~4.5%) for the ambient condition sample (subplot a) can be attributed mainly to the moisture evaporation of about ~3.5%, which suggests higher thermal stability and lesser organic matter. On the other hand, acid-treated bricks recorded the greatest mass loss (~15.8%), site b in weight decline below 150°C showing internal weakening and better than that because of acid attack water retention. That water- saturated sample (subplot c) showed ~15.1% mass losses caused mainly by moisture infiltration, which is inferred to indicate an increase in porosity and decrease in thermal resistance. So, the seawater-exposed sample (subplot d) gave around ~16% mass loss that took place in at least two distinct phases: initial moisture evaporation and further breakdown induced by salt hydrolysis, indicating microstructure damage due to salinity. Bricks subjected to superior temperatures (subplot e) were demonstrating the least mass loss (~2.4%), out of which most came as minor moisture discharge (~1.8%). This speaks of the improved rigidity, as well as dwindled moisture due to sintering. The cold-exposed sample (subplot f) was also stable, basing on an overall loss of ~2.5% which suggests freeze-thaw cycles had little value in changing the brick structure.

Indeed, these results of TGA can say that with bricks in acidic, wet, or saline conditions, their wear and tear are speeded up while those under the effect of high temperature or cold remained structurally stable. The results are thus helpful in establishing TGA as a diagnostic tool for future prediction on use and for material selection accordingly to determined surrounding conditions.

5.2 SEM with EDS

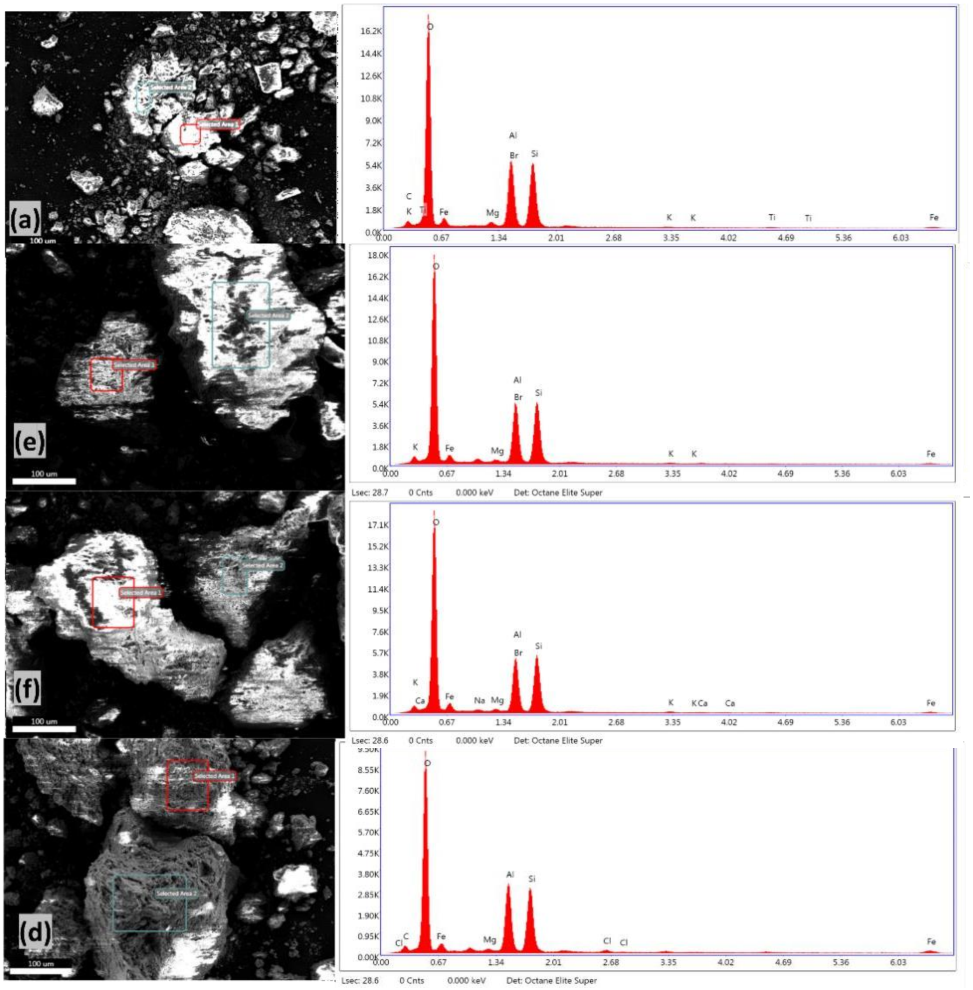

Figure 6. SEM with EDS of clay brick when exposed to various experimental conditions.

The results from SEM-EDS of clay bricks subjected to several forms of environmental exposures, Normal (a), Acid (b), Water (c), Sea (d), Heat (e), and Cold (f), display the differences in microstructural integrity and changes in elemental composition. This is observed across samples: Oxygen (O), Silicon (Si), and Aluminum (Al) dominate, wherein a fairly stable base alumino-silicate is formed. This network is what offers strength, environmental chemical resistance, and thermal stability. Secondary elements such as Iron (Fe), Magnesium (Mg), and Potassium (K) form part of the densification process, durability, and thermal resistance and usually occur as minor constituents (2-10%). SEM showed that under normal conditions (a), the structure was dense, compact with very few voids and stable elemental distribution as evident from EDS-ideal for structural strength. Here, in bricks exposed to acids (b), severe surface pitting and loss of Si and Al indicate a very serious breaking down of the matrix and resulted in more porosity, and thus, it states chemical susceptibility. Water exposure (c) leads to moderate leaching of alkalis (Mg, K), competently improving the porosity characteristics with the generation of microcracks. Sea water (d) in this case had the most destructive action which includes chloride induced matrix disruption and salt crystallization leading to an extensive number of cracking and internal stress generation. In contrast, though, heat treatment (e) improved compactness of the material by sintering, which hence reduced porosity and preserved certain key constituents. There were very slight fissures due to freeze-thaw cycles under cold exposure (f), and these variations do not affect much the chemical composition; thus the material maintains a moderate strength. Overall, microstructure and chemical integrity losses under acid and saline conditions are greater than under other treatments. Thermal treatment increased coherence of structure, while cold exposure effects are minimal but significant over time. Thus, SEM-EDS is a method that can be used to understand the environmental effect on materials and direct the optimization of materials towards durability and sustainability.

5.3 XRD Analysis

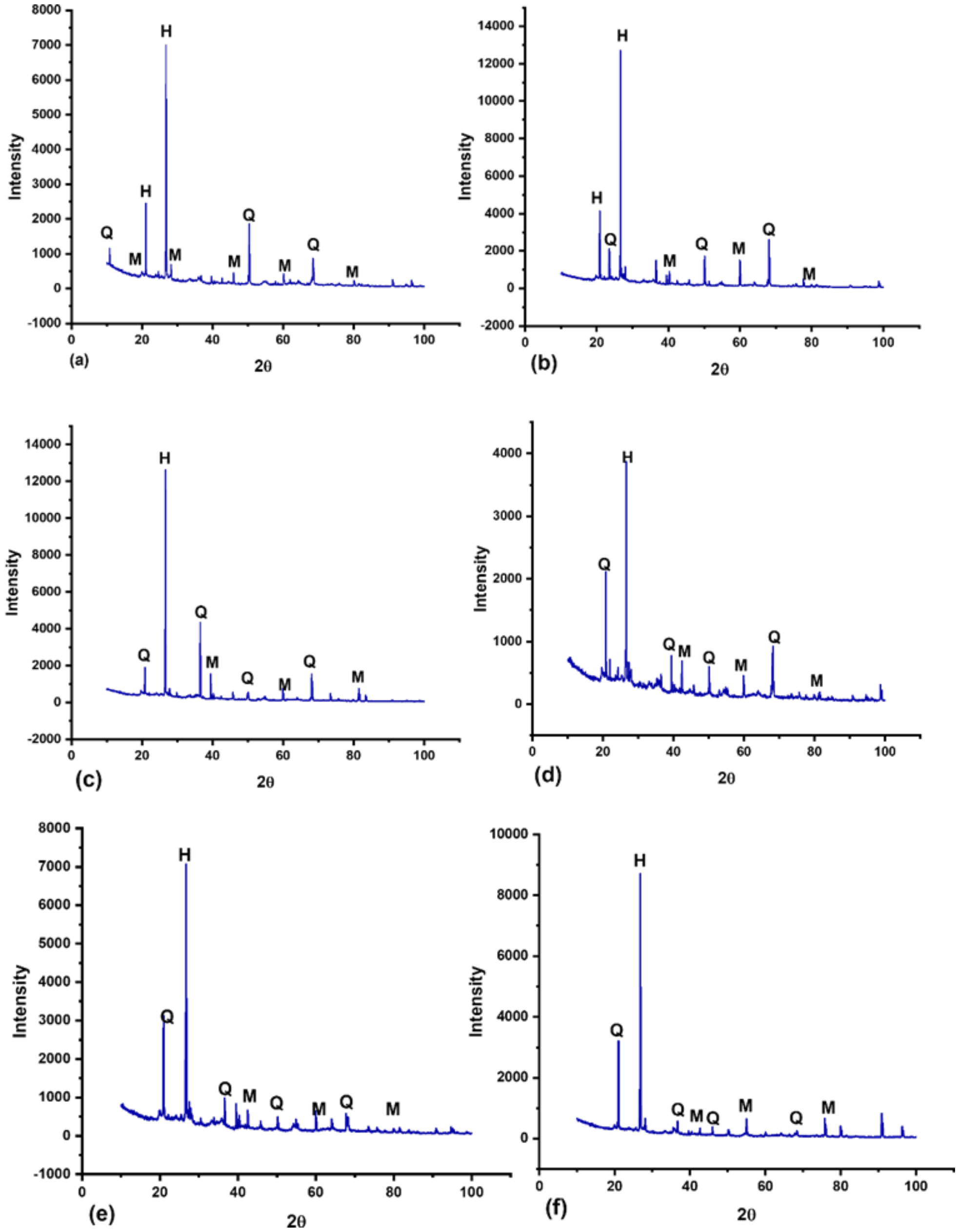

Figure 7. XRD of clay brick when exposed to various experimental conditions. Q-Quartz, M-Mullite, H-Hematite

Changing crystalline phases in clay bricks when subjected to different environmental conditions such as Normal, Acid, Water, Sea, Heat, and Cold have been presented through X-ray diffraction (XRD) patterns in Figure 7. The three prominent phases consistentlyidentified are Quartz (Q), Mullite (M), along with Hematite (H), which contribute toward mechanical strength, thermal resistance, and overall durability of the structure. In normal conditions (a), sharp and dominant Quartz peaks at $2\theta \approx 26.6°$ indicate high crystallinity. Mullite peaks found between 16°-30° show that it provides thermal and mechanical strength to the bricks; whereas Hematite peaks at 33°-35° indicate stability of iron oxide, contributing to hardness and color. In the case of acid-treated bricks (b), it is seen that with the reduction in intensities, the structural disordering can be attributed to partial leaching. Shifting in Hematite peaks can be observed along with the appearance of some minor peaks, indicating the formation of secondary products due to interaction with acid. Water immersion (c) would only cause slight mineral changes: slight interference with the 26.6° of Quartz, and Mullite remained largely unaffected, demonstrating water resistance. The stability of Hematite is confirmed by unchanged peaks. Salt water (d): Observes a mild decrease in intensities of the peaks corresponding to Quartz and Mullite. Hematite peaks are likely broadened because of chloride/sulfate ion reactions leading to the formation of iron salts and some disruption of the crystal structure. The heat-treated samples (e) present enhanced Mullite peak intensity (16°-30°), most probably because high-temperature sintering promotes crystallization of Mullite. Hematite remains stable and sharply defined, while Quartz shows minor shifting probably due to some formation of cristobalite. Cold exposure (f) preserves all main peaks with slight broadening of the Hematite peak. It indicates somewhat the mechanical stress from freeze-thaw cycling, but without a chemical change. Quartz and Mullite stay stable, indicating high phase integrity toward cryogenic stress. In conclusion, it is acidic and saline environments that induce the most crystalline deterioration. Thermal treatment promotes Mullite development and increased crystallinity overall. Cold environments exert very little physical stress and have no mineralogical effect. These findings constitute the extreme importance of XRD in assessing environmental resilience and material optimization targeted toward specific exposure situations.

5.4 U.V Spectrum Analysis

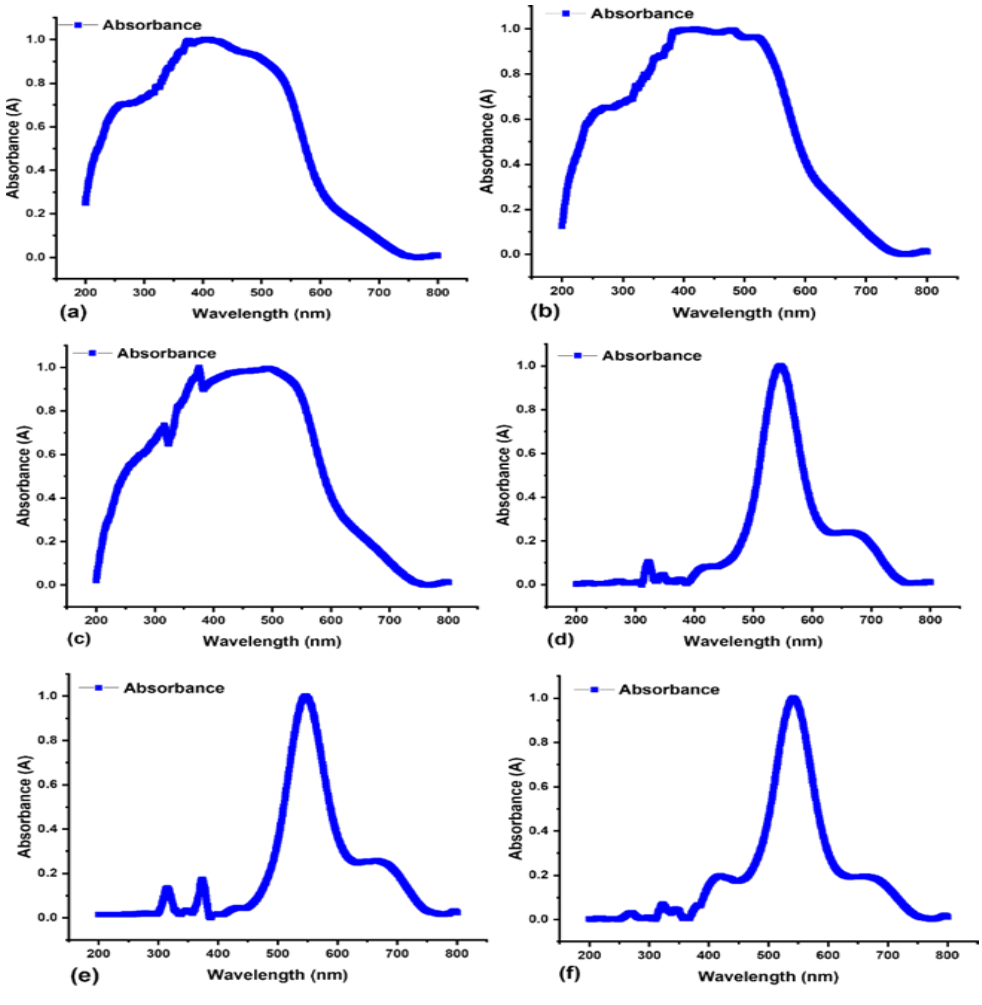

Figure 8. U.V analysis for normal (a), acid (b), water (c), sea (d), heat (e), and cold (f)— the bricks were exposed to other environmental conditions.

Table 7. U.V Spectrum Indicator

Mix ID	Exposure Condition	Peak Wavelength (nm)	Absorbance Intensity (A)	Performance Impact
a	**Normal**	**320–520 nm**	**0.95**	Stable structure, minimal degradation
b	**Acid**	**300–510 nm**	**0.85**	Leaching of SiO_2 and CaO, structural weakening
c	**Water**	**280–540 nm**	**0.78**	Increased porosity, possible clay swelling
d	**Sea**	**290–550 nm**	**0.8**	Salt crystallization, potential ion exchange reactions
e	**Heat**	**320–600 nm**	**1**	Phase transformations, increased brittleness
f	**Cold**	**310–530 nm**	**0.92**	Microstructural stress from freeze-thaw cycles

Standardized mixing ratios were used to manufacture clay interlocking bricks, ensuring uniform homogeneity of composition for all test samples. Clay, the chief ingredient of the bricks, was mixed with water in an amount such that it maintained the desired workability or plasticity. Clay was then molded into the interlocking designs. The formed bricks were then cured and dried under controlled conditions before being subjected to environmental simulations, simulating realistic exposure conditions: normal (a), acidic (b), freshwater (c), seawater (d), heat (e), and cold (f). These scenarios simulate real- world challenges faced by bricks, such as moisture exposure, temperature fluctuations, and chemical degradation [77,78]. Figure 8 and Table 7 represent the absorbance spectra for the bricks, differentiating the environmental exposures markedly. These changes in the spectra correlate with changes in the mineralogical structure and surface chemistry. The spectrum is indicative of fairly consistent structure and negligible degradation under standard conditions (a) with a broad and strong peak in the 300–500 nm region. Under exposure to acid (b), a subsequent fall in absorbance intensity is noted, giving way to a slight shift in peak position towards the shorter wavelength region (300-510 nm) with a peak height lowered to 0.85. This drop, most evidently associated with the dissolution of silica (SiO_2) and calcium oxide (CaO), is an indication of material breakdown under acidic attack. A longer duration of this chemical activity with time can easily destabilize the internal bonding network, causing potential loss of compressive strength by 10-15%. In the case of exposure to water (c), the spectral profile stretched the region of 280-540 nm, while absorbance intensity was measured at 0.78. This implies an increase in porosity and internal degradation due to prolonged exposure to water, leading to clay swelling and particle separation. Such effects translate to a reduction in overall durability by an estimated 12%. For seawater exposure (d), this nice widening of the spectral region (290- 550 nm) corresponds with an absorbance reading of 0.80. Chloride and sulfate ions present in the seawater are common agents for ion exchange and salt crystallization within the brick matrix, causing damage to the surface and possibly efflorescence. Such factors could adversely affect long-term mechanical performance and increase susceptibility to cracking. Heat treatment resulted in sample bricks which were observed to have the highest absorbance values of 1.00, and a peak in the range of 320-600 nm.

This improved spectral response was associated with phase changed—most importantly, the conversion of kaolinite to mullite—remembering thermal stability and improvement of compressive strength of 20-25%. But on the contrary, this stage overload on overheating could as well cause brittleness owing to thermal expansion, hence increasing the likelihood of cracking under variable temperature situations.

The cold test (f) gives a readable absorbance intensity of about 0.932 in the range of 310– 530 nm. The subsequent changes depict stress due to repeated freeze-thaw cycles. The expansion due to freezing and contraction during thawing of water within the pore spaces of the brick induce internal pressure that can start microcracks leading to an approximate 8% reduction in strength.

In summary, the spectral studies provide insight into the interplay between environmental conditions and the chemical and structural integrity of clay interlocking bricks. The acidic and wet exposures cause immense degradation, while thermal treatments gain strength but risk brittleness. While cold conditions over time are moderately damaging, these findings have enormous implications concerning flood surface treatment, i.e., geopolymer coatings or protective sealants, which can improve environmental resistance and prolong the service life of bricks by about 30-40% under varying conditions [63,78,80].

7.0 Environmental Impact Study and Cost Estimate

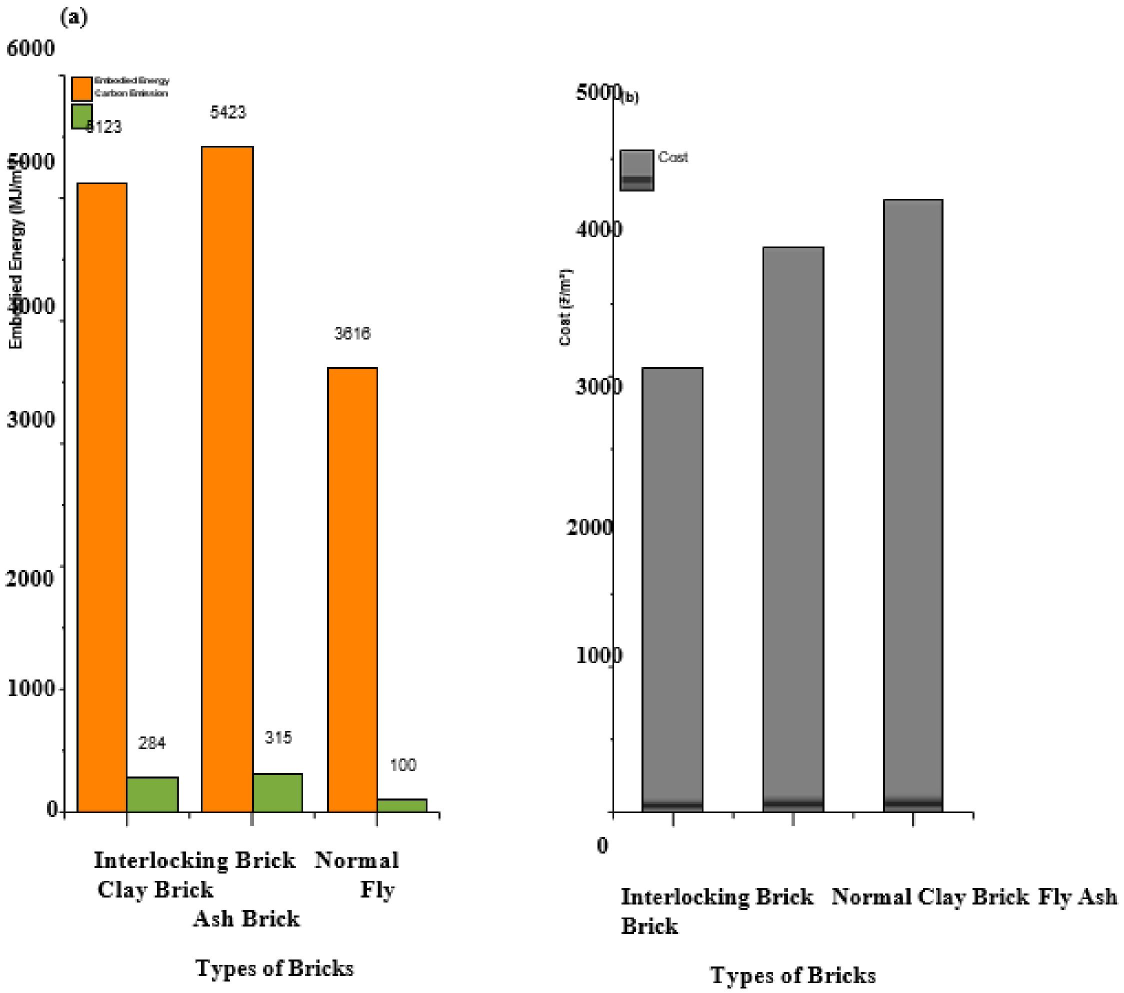

Figure 9 (a). Embodied and carbon emissions analysis and (b) Cost estimate.

Interlocking bricks have proven to be cheaper, with lower embodied energy and a lesser degree of carbon footprint compared to conventional clay and fly ash bricks, thus becoming an alternative for long-lasting construction—see Figure 13. The life cycle energy of the structure, which has been found to be 5123 MJ/m³ for interlocking bricks, is 5.5% less than that of typical clay bricks (5423 MJ/m³) but 34.2% more than that of fly ash bricks (3816 MJ/m³). The energy is comparatively more due to the specific processes and procedures that are required for making interlocking blocks as compared to fly ash bricks. In terms of carbon emissions, interlocking bricks give 284 kg of CO_2 per cubic meter, which is a reduction of 9.8% from conventional clay bricks at 315 kg of CO_2/m^3, yet 64.8% more than fly ash bricks' CO_2 emissions of 100 kg/m³. All in all, interlocking bricks, on the one hand, need more energy than the fly ash bricks, yet on the other hand, they require less energy in comparison to the conventional clay bricks and emit less carbon dioxide. Further, interlocking bricks come with a good price advantage. Their self- locking nature minimizes both kiln firing and mortar use, enhancing their environmental appeal when compared to regular clay bricks. While fly ash bricks take the lead in terms of energy and emission criteria, interlocking bricks hold the middle ground with flexible structural applications and economic accessibility. [81-83]

Conclusion

The clay bricks tested in this study show an average compressive strength of 5.26 MPa, which is suitable for general construction purposes. The water absorption capacity, which is around 15% on average, remained same among samples and means there is a uniform pore system that checks excessive ingress of moisture. Averaging according to density around 1650 kg/m³ gives a medium weight to the material, too much and neither too light, which means that the firing was uniform and controlled porosity. In general, all these results emphasize the consistency of the manufacturing process and a good quality control on creating a reliability on the material. Soil that will be used for brick production falls among CL type soils-low plasticity clay; possess liquid limit of 42.48% and plasticity index of 4.41%. This suggests the stiff, non- expansive nature of the clay. The clay is also confirmed by an LI of -4.1 and a CI of 5.1 to be rigid in behavior on mold shaping. From a compaction perspective, maximum dry density (MDD) achieved for clay is 1.83 g/cm3 at optimum moisture content (20%), indicating a medium compaction behavior suitable for brick forming. However, it should be noted that the clay does indicate fairly large shrinkage values, which are 67.91% shrinkage ratio and 81.49% volumetric shrinkage. These factors should be taken into account during drying and firing. In addition, it has low permeability (10^{-7} cm/s) combined with shear strength of 43.2 kPa, thus giving reasonable stability for structural use more so when moisture fluctuations are closely monitored. Regarding environmental implications, interlocking clay bricks have lower embodied energy and register only 5123 MJ/m³, which is 5.5% lower than similar clay bricks but higher than fly ash bricks by 34.2%. They have a carbon footprint of 284 kg CO_2/m^3, inculcating a 9.8% decline from traditionally clay bricks but at 64.8% more than fly ash alternatives. Exposure to acidic, saline and/or water- rich environments subjects clay bricks to significant thermal degradation and mass loss, as proven through thermogravimetric analysis (TGA). In contrast, bricks that are exposed to either very high or very cold conditions remain thermally stable and thus do not lose large amounts of mass. These findings justified the need to optimize the kind of materials based on the condition imposed specifically in highly exposed chemicals corresponding environments.

The degradation mechanisms were further specified with the aid of Scanning Electron Microscopy (SEM). The exposure to acid and saline was the most severe conditions, very noticeable chemical erosion and deterioration of the microstructure caused a direct effect on strength. The continuous exposure to water also undermined the surface, and with some of the cold at that time visible spalling occurred due to freeze- thaw cycles. Thermal treatment brought about microstructures that were dense and strengthened inter-particle bonding. Microcracks, pore agglomeration, and surface roughness were revealed by SEM images and EDS analysis depletion of Silicon and Aluminum content in aggressive environments corroborated such evidence. It indicates that having better environmental resilience is achievable through protective surface treatments or better material formulations made to resist some specific stresses. X-ray diffraction (XRD) results corroborated these microstructural observations through the identification of the dominating crystalline phases as Quartz, Mullite, and Hematite. Acidic and saline conditions, however, were sources of degradation on these phases, while heat treatments were beneficial in improving the crystalline quality, particularly of Mullite. Even cold exposure caused slight structural changes- nearly mechanical changes in nature and left the mineral integrity unaffected. These findings strengthen the case for protection measures that are customized: such as acid-resistant coatings, water repellents, and thermal sintering- for durability in optimum performance for real-world applications. There would also be external environmental and functional advantages derived from integration with aquaponic and hydroponic systems among interlocked clay bricks. The designed system maintained an internal temperature of almost 9°C lower than outside, thus facilitating passive thermal regulation and less reliance on artificial cooling. On the other hand, the bricks showed fair mechanical strength (5.26 MPa) and also enabled mortar-free construction, which reduced labor and material costs. On sustainability, it serves to conserve water, support urban agriculture, and sequester carbon, which is in line with several green infrastructure goals. Taking a broad, integrative approach does not just make the building's footprint better for the environment, but it also presents a whole solution to rapid urbanization-induced problems. Such system adaptation to field applications would have exponential effects on future construction models.

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