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An Investigative Preparation of Unfired Bricks from Clay and Fine Sand in the Presence of Sodium Hydroxide as an Activator through Geo-polymerization

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ABSTRACT

The present work was focused on an alternative method for the preparation of clay bricks by the mediation of sodium hydroxide solution as an efficient activator. The traditional brick preparation requires a firing process, but the present innovation avoids it by the use of commercially viable alkali as an activator. Various brick specimens were prepared by the addition of sodium hydroxide solution having different molarities to clay samples. This was done to optimize the process and contribute to process cost reduction. The blends obtained were molded as per the standard brick dimension (19X9X9 cm) and exposed to the ambient atmosphere in a well-ventilated room for curing (14-28 days). The clay samples and the brick specimens were subjected to some critical qualitative tests. Based on the results it was established that increasing the alkali addition to clay had gradually reduced the brick quality. Moreover, the inclusion of fine sand in the blend enhanced the brick quality. In this work, we emphasized optimizing the alkali input, the impact of reduced curing duration, avoiding brick firing, and the fine sand impact on the brick quality.

INTRODUCTION

The traditional method of producing clay bricks (Figure 1) has long been entrenched with the combination of clay and water, followed by a relatively high-temperature firing process (Dalkılıç & Nabikoǧlu, 2017; Lakho & Zardari, 2016a; Lakho et al., 2016b; Villeda-Muñoz et al., 2011). This conventional approach carries inherent challenges such as high energy consumption, significant carbon emissions, and a significant reliance on valuable natural resources (Furszyfer Del Rio et al., 2022; Dabaieh et al., 2020; Ukwatta et al., 2018; Murmu & Patel, 2018). The concept of geo-polymerization had emerged as an alternative process for the unfired clay brick preparation. It was influenced by the presence of activators like hydroxides (Na/K) and silicates (Na/Al/Ca) to catalyze the transformation of the brick blend into a durable brick in the absence of high-temperature impact. The chemical reactions induced by activators would facilitate binding the clay particles firmly (Subramani & Venkataraman, 2013; Akanyeti et al., 2020; Youssef et al., 2019). This approach not only eliminates the energy-intensive heating step but also confers superior strength and durability to bricks through simple polymerization (Phoo-ngernkham et al., 2015; Dahal, 2022). This methodology paved the way for sustainable construction practices with low energy consumption and reduced emissions (Ahmed et al., 2021; Maheshwari & Jain, 2017).


Figure 1. Clay brick

Present work endeavors to explore, analyze, and advocate for a transformative approach to unfired clay brick manufacturing that aligns with the imperatives of green technology. A systematic survey of prior arts will provide a comprehensive overview of numerous innovative approaches adopted toward sustainable construction practices. Meanwhile, the geo-polymerization-driven brick manufacturing trends to date are analyzed.

Statkauskas et al. (2024) reported the preparation of unfired alkali-activated bricks from wastes (ceramic brick and metakaolin) and phosphogypsum. NaOH solution was used as an activator to impose geo-polymerization. The use of metakaolin waste resulted in the formation of poor-quality bricks due to a very highly porous structure. The best quality bricks are obtained from the combination of ceramic brick waste (80%) and metakaolin waste (20%). Kurtay, (2024) demonstrated the preparation of mortars from hollow brick waste powder and NaOH solution (6-10 M). It was established that the mortar isolated by the use of 6M NaOH solution had given the best quality bricks having the highest compressive (63.67 MPa) and flexural strength (6.63 MPa).

Borchate et al. (2023) explored the incorporation of red mud (processed from the alumina manufacturing process) Na_2O-SiO_2 and NaOH in optimum proportions to prepare geo-polymerization-driven unfired clay bricks. Under this context, a few brick specimens were prepared by replacing clay with fly ash with the above constituents. It was concluded that the compressive strength of these unfired bricks is comparable to conventional fired clay bricks and the water absorption ability was observed to be least (1.76%). Kumble et al. (2023) illustrated the preparation and bond strength evaluation of alkali-activated fly ash bricks and mortars.

More importantly, alkali-activated fly ash bricks bonded with alkali-activated mortar displayed superior bond strength. Verma et al. (2023) reported the incorporation of fly ash and boiler ash to prepare alkali-activated bricks. The ash-based bricks had comparable features with routinely fired clay bricks. Capasso et al. (2023) demonstrated the utilization of waste from tuff sawing and brick grinding to obtain a geo-polymeric blend for the remediation of historical buildings. It was established that brick waste-based geo-polymeric blends were more compact than the tuff sawing-based ones. Krishnan et al. (2023) disclosed the method to incorporate recycled plastics and glass fine in varied proportions with clay to prepare alkali-activated bricks at low temperatures (50-155^{o}C). The disclosure employed a 20% activator solution (NaOH and Na_2O-SiO_2) to impose geo-polymerization in the innovative blend to get bricks of satisfactory quality. Prathiksha et al. (2023) evaluated the feasibility of incorporating waste glass powder (7-22%) with natural clay to prepare fired clay bricks having superior features than traditional ones. It was established that the addition of waste glass powder (17%) to clay resulted in good-quality bricks. Under this context, waste glass powder had acted as an activator under elevated curing temperature.

Thejas & Hossiney, (2022) investigated the use of iron ore tailings (IOT), fly ash, and GGBS for the production of alkali (8% of Na_2O-SiO_2 solution) activated unfired bricks. The isolated bricks had high compressive strength, and low water absorption, and displayed better resistance to aging. Zhang et al. (2022) explored the incorporation of wastes (glass and plastic) with brick clay mill residue to prepare alkali-activated unfired bricks. The process was empowered to accommodate waste glass (55% by Wt) and waste plastic (2% by Wt) if used distinctly. Interestingly, it can accommodate waste glass (25% bt Wt) and waste plastic (2% by Wt), if both are used together.

Based on the analysis, glass particles had better bonding with mill residues than plastic particles. The mixture of NaOH and Na_2O-SiO_2 was used as an activator to impose geo-polymerization in the blend. Akinyemi et al. (2022) explored the influence of alkali activators on the thermo-physical properties of eco-friendly unfired clay bricks sourced from anthill mounds, shedding light on the potential of utilizing natural resources for sustainable construction practices. Bumanis & Vaiciukyniene, (2022) demonstrated the utility of calcined illite clay and red brick waste (from brick plants) for brick preparation by the mediation of NaOH solution (6 & 7 M). Even silica gel addition was incorporated to obtain alkali-activated materials. As per the results, the red brick waste-based brick exhibited superior features than calcined illite clay-based alkali-activated brick. Vasavi et al. (2022) demonstrated the preparation of alkali-activated fly ash earth bricks with M-sand and without M-sand.

The ratio of fly ash to soil and fly ash to activator was 0.4 and 0.6 respectively. NaOH and Na_2O-SiO_2 were used as the activator to impose geo-polymerization in the blend. Wet and dry samples were subjected to various qualitative tests. França et al. (2022) disclosed a comprehensive comparative review article about high-calcium and low-calcium-based alkali-activated materials. It was concluded that the low-calcium-based one exhibited better performance concerning durability and fresh properties. Furthermore, high-calcium-based ones displayed better performance concerning mechanical properties. Revathi & Vidhya, (2021) reported the preparation of alkali-activated bricks derived from municipal incinerated ash under the impact of an activator (NaOH and Na_2O-SiO_2). Evaluation of bricks had hinted that these innovative bricks can tolerate up to 40% of ash addition.

Fahmi et al. (2021) investigated the mechanical strength of NaOH solution (6-14 M) activated laterite-based geo-polymeric samples under different curing temperatures in the oven. The study highlighted the impact of curing temperature on the strength of prepared bricks. Robayo et al. (2021) presented the prototypic design and construction of an eco-friendly house constructed from concrete blocks obtained by the use of alkali-driven geopolymerization. These innovative blocks were prepared from various starting materials like natural volcanic pozzolan, ground granulated blast furnace slag, fly ash, construction and demolition waste, and red clay brick waste. The carbon footprint of these sustainable blocks is substantially lower than the routine cement blocks. Kejkar & Wanjari, (2021) illustrated the preparation of industrial waste-based geo-polymer bricks. Moreover, these bricks were proved to be cost viable and energy-efficient than the routine clay bricks and other related geo-polymer bricks. Alzeebaree et al. (2021) disclosed the preparation of alkali-activated mortars using recycled clay brick and fine soil. Furthermore, the impact of glass powder addition and NaOH solution (8-16 M) was also studied. As per the results, replacing the clay brick with fine soil improved the quality of mortar.

The complete replacement of clay brick with fine soil lowered the quality of mortar significantly. Hasan et al. (2021) reported the replacement of fine aggregates in the mortar with clay bricks and waste glass to get sustainable mortar mix at elevated temperature (200-600^{o}C) exposure. The results obtained for the variants at different temperatures were disclosed and numerous insights were presented in the work. Akinwande et al. (2021) illustrated the development of sustainable paper bricks using unique materials like unmodified banana fibers, alkali-modified banana fibers, fine sand, ordinary Portland cement, and waste paper pulp. The experimental outcome revealed that the water absorption features had increased with fiber loading. Whereas, alkali-treated banana fibers embedded samples showed lower water absorption features than unmodified banana fibers embedded ones. It was established that the curing length and alkali modification of banana fibers were important to get good-quality paper bricks. Modha et al. (2021) illustrated the preparation of alkali-activated material, which can be used as concrete, bricks, paver blocks, mortar, etc. This was achieved by using abundantly available key raw materials like fly ash, slag, metakaolin, red mud, etc., and alkaline activator solution (NaOH and Na_2O-SiO_2). Khalifa et al. (2020) demonstrated the potential of clay minerals as an alternative precursor for alkali-activated cement, thereby addressing the challenges and giving insights into their future applications in cement and concrete research. These studies collectively contribute to the development of sustainable construction materials, offering promising alternatives to traditional construction practices and highlighting the potential of natural resources and alternative precursors in sustainable construction.

Gavali et al. (2020) demonstrated the use of alkali activators to prepare bricks from industrial wastes. The disclosed process involves the addition of NaOH (8 M) and Na_2O-SiO_2 solution to ash and stone dust in varied proportions. The bricks prepared had low density, water absorption, and thermal conductivity. This process produced good quality bricks compared to burnt clay and fly ash bricks. Moreover, the bricks obtained can be used for load-bearing as well as framed structure construction. Gado et al. (2020) reported the reuse of waste-fired clay bricks to get superior quality bricks through modulative geo-polymerization consequences. Based on the process optimization initiatives, the optimum silica modulus (1.25) and H_2O/Na_2O molar ratio (12.5) were established to isolate bricks with high compressive strength (37.5 MPa). Rivera et al. (2020) demonstrated the preparation of sustainable blocks from clay soil and alkali-activated binders.

Different clay soil variants were used and the binder was generated from fly ash. The addition of lime and blast furnace slag was done to increase the calcium content in the blend. The sand content-rich clay soil used block variant exhibited superior features with the least permeable pores, less water absorption, and an average compressive strength (17 MPa). Sasikumar et al. (2020) illustrated the preparation of geo-polymer bricks from different fly ash types (Class C and F). The silica-rich fly ash would react with added activator solution (NaOH and Na_2O-SiO_2) to induce geo-polymerization in the blend to provide good quality bricks. The work explored the impact of the concentration of activator solution (4-12 M) and the curing temperature (25-90^oC). It was established that fly ash (class F) based brick obtained by the addition of activator solution (10M) and cured at 60 ^oC exhibited superior features than other variants. Mejía-Arcila et al. (2020) demonstrated the mixing of fly ash with ground granulated blast furnace slag or ordinary Portland cement in the presence of an activator to prepare blocks. The work involves the use of a mixture of NaOH and Na_2O-SiO_2 as a traditional activator (SN), and a mixture of rice husk ash and NaOH as an alternative activator (RN). Based on the results, fly ash/slag/RN-based blocks exhibited superior features. Xia et al. (2020) illustrated the solidification of electroplating sludge with alkali-activated fly ash and ordinary Portland cement to isolate unfired bricks formed through geo-polymerization. The qualitative tests performed on the bricks gave satisfactory results hence making it an excellent pathway to deal with hazardous electroplating sludge. Interestingly, the hazard quotient (HQ) of heavy metals (including Zn, Ni, and Cu) was much less than the limit value. Whereas, both the HQ and cancer risk of Cr were over the corresponding limit values.

Khalifa et al. (2019) reported the use of four different calcined natural clay samples to get geo-polymer blends. Alone NaOH solution or the combination of NaOH and Na_2O-SiO_2 were introduced as the activators. The work explored the best natural clay (kaolinite-based) variant to exhibit more reactivity towards alkali activation than smectite or illite-based natural clay.

Sedira et al. (2018) illustrated the preparation of alkali-activated binders from tungsten mining waste mud and red clay brick waste. In this context, NaOH and Na_2O-SiO_2 solutions were employed as activators to impose geo-polymerization. It was established from test results that, the binder matrix becomes denser and more compact upon a gradual increase in red clay brick waste content (up to 50%) in the blend mixture. Brîndus-Simut et al. (2018) reported the impact of particle size of input raw material to prepare alkali-activated materials. The input raw material was waste brick powder (5 different variants) and glass powder as an activator. The microstructure, flexural, and compressive strengths of prepared bricks were checked and it was correlated with input particle size, curing duration, and time. Vyšvařil et al. (2018) illustrated the preparation of alkali-activated pastes by the use of brick powder. The activator solution (NaOH or KOH and Na_2O-SiO_2) was used to impose the geo-polymerization in the blend. The flow properties, elastic modulus, and viscous modulus data of the blend were estimated. Parhi et al. (2018) reported the use of alkali-activated fly ash as an alternate cementitious material for the stabilization of expansive soil in India. The activators like NaOH and Na_2O-SiO_2 were used in varied proportions. The work demonstrated a considerable improvement in the geotechnical properties of the stabilized soil with the addition of alkali-activated fly ash.

Robayo et al. (2017) demonstrated the feasibility of using waste red clay bricks, concrete waste, and glass waste to prepare alkali-activated cement. The activators used for the preparation of hybrid cement are in the form of a solution of either NaOH or a mixture of NaOH and waste glass. That can be used to fabricate blocks, pavers, roof tiles, and tiles. The alkaline activators used were solutions of either NaOH or NaOH and water glass. Based on the compressive strength estimation, hybrid cement obtained from waste red clay bricks in combination with ordinary Portland cement was superior to other combinations. Poinot et al. (2017) illustrated the preparation of alkali-activated unfired bricks by the incorporation of boiler ash. The disclosed method uses clay, ash, lime, and NaOH solution in varied proportions to isolate good quality unfired bricks. In the absence of thermal impact, a curing duration of 28-29 days was established in the disclosure.

Robayo et al. (2016) disclosed the manufacturing method of hybrid cement by the addition of an alkali solution (NaOH and Na_2O-SiO_2) to waste red clay bricks. The impact of Na_2O-SiO_2 solution as an activator was established to be extremely higher than NaOH solution concerning the compression strength of the hybrid cement. Ding et al. (2016) reported a comprehensive overview of the mechanical properties of Alkali-Activated Concrete (AAC), with valuable insight for researchers and engineers interested in the properties and potential applications of AAC. Khater et al. (2016) reported the preparation of alkali-activated binders from construction and demolition wastes (ceramic and clay brick) in the presence of sand and NaOH solution as activators. By this process, good quality heavy-duty bricks can be prepared by the partial replacement of ceramic waste by clay brick waste (up to 20%). Ezzat et al. (2016) demonstrated the preparation of alkali (NaOH) activated bricks by the use of partial binder addition, water-cooled slag, with clay brick waste. The bricks prepared by the substitution (up to 40%) of water-cooled slag with clay brick waste exhibited superior features. Further attempts at substitution did not give the expected results due to enhanced crystallinity. Ahmed & Abass, (2016) reported the preparation of alkali-activated bricks from clay (Iraqi Attapulgite) under the mediation of NaOH solution (4-8 M) as an activator. The best results were gathered for the bricks prepared by the use of NaOH solution (4 M). But for the ones prepared using 6M and 8M, they failed in water absorption test. All the alkali-mediated brick variants were dried at 80-120^{o}C.

Aponte et al. (2015) disclosed the impact of formation pressure and particle size distribution in alkali-activated bricks to decrease water absorption ability. It was established that formation pressure had an important role in the brick quality concerning compressive strength and water absorption features. Puertas et al. (2015) illustrated the incorporation of recycled clay-based construction and demolition waste to prepare alkali-driven geo-polymerized cement mortars. The mechanical strength in ordinary Portland cement, alkali-activated slag, and alkali-activated fly ash mortars and the impact of partial replacement of the slag and ash by clay-based waste materials were estimated.

Reig et al. (2013) demonstrated the utilization of red clay brick waste to prepare alkali-activated cement pastes and mortars by the impact of activators like NaOH and Na_2O-SiO_2 solution. It was established that a higher input of alkali had decreased the formed zeolitic structures. Faheem et al. (2013) highlighted the importance of source material nature-based geo-polymerization in brick preparation. Under the context, calcined (calcined kaolin, fly ash, ground granulated blast furnace slag, etc) and non-calcined (raw kaolin) materials were explored to get the geo-polymer. The work provided the process optimization studies and employed NaOH and Na_2O-SiO_2 as activators. Bektas et al. (2007) reported the intrusion of clay brick, fly ash, and natural pozzolan into the mortar as a replacement for cement (20-35% by Wt). The waste clay brick-based mortar exhibited high potential to reduce the alkali-silica reaction expansion and also the alkali-silica reaction associated strength loss.

The survey of prior arts gave us enough insights regarding the applicability of activators, wastes, natural resources, and alternative precursors in the development of sustainable building materials. These studies explored the mineralogical, physical, and environmental characteristics of sustainable construction materials: (1) To determine the optimum proportion of alkali to the selected type of locally available natural clay, (2) To estimate the strength and durability of alkali-activated geopolymer-driven bricks in the presence and absence of fine sand, (3) To eliminate the conventional, prolonged and expensive brick firing process, (4) To check the performance of bricks under reduced curing duration at ambient temperature with a check on carbon emission.

METHODS

Materials Used

The key raw materials used in this study are clay samples (two variants), commercial-grade NaOH, and fine sand. The soil samples were collected from different areas to understand various associated soil properties like texture, composition, moisture content, etc and more particularly sandy soil was preferred. The solution of NaOH in varied molarities would serve as an activator to impose the intended geo-polymerization in the blend. The fabrication of the brick involves the use of two distinct soil samples soil sample-1 (SS-1, clay soil) and soil sample-2 (SS-2, red soil) Figure. 2. We wanted to study the alkali impact on the locally sourced soil variants. The fine sand was collected from the seashore near Mangalore.

Instruments Used

The instruments used by us to execute the preparation of alkali-mediated unfired bricks are tabulated in Table 1. Meanwhile, basic safety measures were followed during the work execution.

Table 1. List of instruments used for the clay brick preparation

Sl. No.	Instrument/equipments
1.	Sieves
2.	Glass beaker (2 L)
3.	Electric heater
4.	Brick mould
5.	Mixing tray
6.	Scoop
7.	Weighing balance
8.	Compression test machine
9.	Water absorption test pot
10.	Hot air oven
11.	Hand gloves
12.	Safety goggles
13.	Dust mask

Incorporated Method

The preparation of alkali-mediated unfired clay bricks involves some sequential steps as practiced in normal brick making (Shakir & Mohammed, 2013). In this venture, it was executed with minor modulations to introduce the activator to impose geo-polymerization.

Collection: Natural clay was collected from two different venues in Ujire (25 Kg each). To minimize the organic debris, clay was collected from 2 feet below the surface.

Crushing: Natural clay variants were crushed well in separate trays to enhance the clay particle uniformity. This process would facilitate to increase in the rate and effectiveness of chemical reactions associated with geo-polymerization.

Figure 2. Soil sample

Sieving: Two soil samples (Figure 2) were separately subjected to a sieving process to eliminate larger particles. This process will make the clay sample ready for further steps with fine and uniform texture (Figure 3).

Figure 3. Sieving of weathered soil

Preparation NaOH solution: The commercial grade NaOH flakes were weighed sequentially and added to water slowly under stirring to prepare differently concentrated solutions (0.5 to 15 M). During the process of alkali dissolution, the exothermic nature of the reaction will make the solution slightly warm (33-35^oC). To enhance the reactivity of clay particles with an activator, the alkali solution in the glass beaker was heated over an electric heater to 60-70^oC (Figure 4).

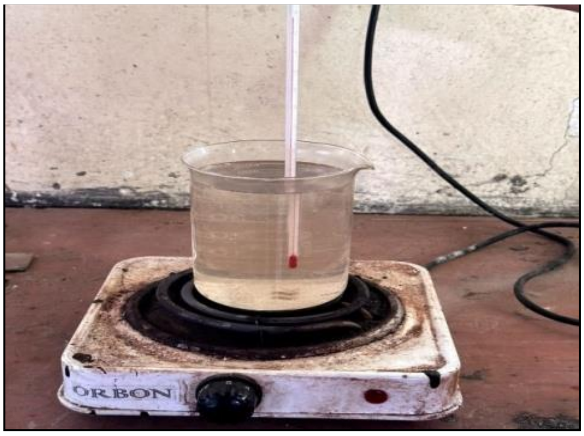

Figure 4. Heating of NaOH solution

Addition of NaOH solution to clay and mixing: To the clay sample (each 3.0 Kg) in the tray, add pre-heated NaOH solution (0.5-15 M) and mix well to form a cohesive paste (Figure 5). The overall water input was fixed to 33% by weight of clay. It was estimated by the analysis of the optimum moisture content of clay. Meanwhile, a blend without alkali input was prepared as per the normal clay brick procedure. Another blend was prepared by the addition of alkali (0.5 M) and fine sand (10% by Wt) to clay. While preparing the different blends, cross-contamination, and cross-labelling parts were taken care of. An efficient mixing will ensure the even distribution of alkali in the blend and hence promote reactions facilitating geo-polymerization.

Figure 5. Addition of activator solution to soil

*Molding***:** The blends prepared were carefully added into different molds of standard dimension (19X9X9, cm). Complete compaction was ensured by achieving the required density to gain structural integrity during curing (Figure 6).

Figure 6. Addition of the paste to brick mold

*Curing***:** The wet brick samples were carefully removed from the molds and kept in a well-ventilated room for curing. This stage ensures the gradual removal of water and the progress of geo-polymerization reactions. In this stage, only ambient temperature curing for 7 to 14 days was done and the subsequent firing process was eliminated. Each day during curing, the brick position was changed to expose all the brick surfaces to ambient temperature equally. Meanwhile, wet cloth was covered in regular intervals on the exposed surfaces of the brick. Intentionally, we have not done the extended curing of these brick specimens (Figure 7). We are more curious regarding the extent of geo-polymerization contributing to the strength of bricks.

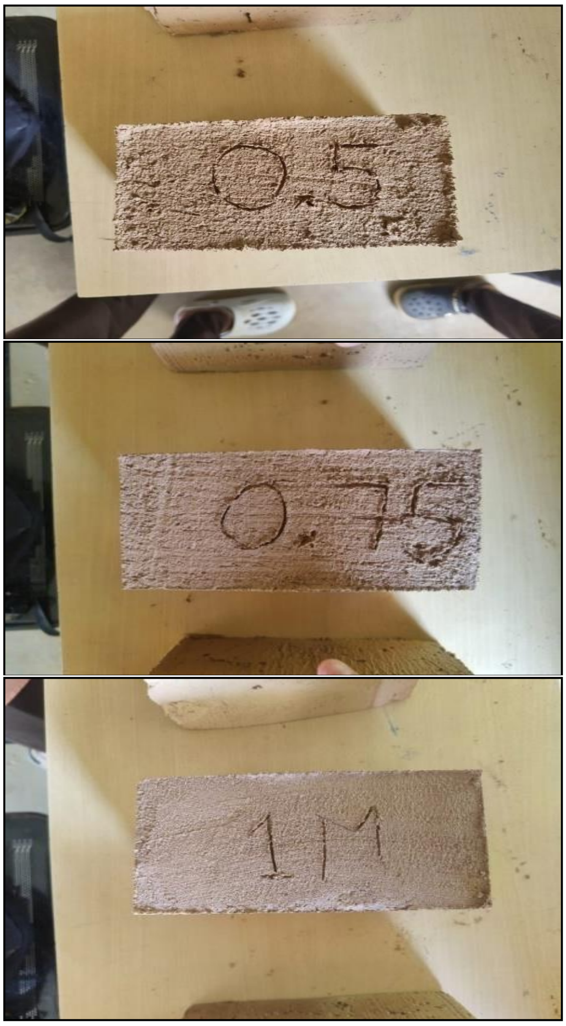

Figure 7. Bricks prepared by the addition of varied quantities of NaOH solution

RESULTS AND DISCUSSION

The clay variants and the prepared brick specimens were subjected to various qualitative tests to estimate important parameters like clay nature, plasticity index, compression strength, and water absorption.

Analysis of Input Clay Variants

It was done by two popular estimation methods like modified proctor test and the plasticity index.

Modified proctor test: This test provides higher maximum dry density (MDD) and lower optimum moisture content (OMC). These features are essential to understanding the compaction characteristics of clay (BIS, Part 8., 1983). It was done separately for the input clay variants.

For soil sample-1 (SS-1): The test outcome provided the MDD value of 1.88 g/cc and the corresponding OMC to be 22%, (Figure 8).

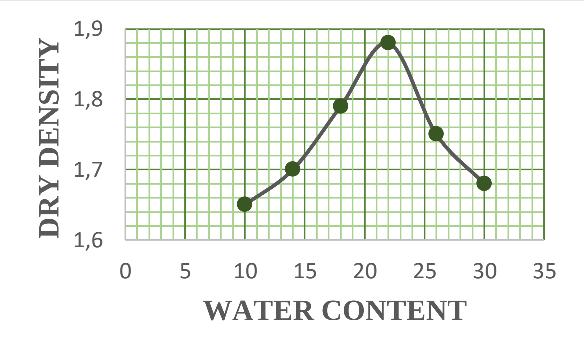

Figure 8. Optimum moisture content data of SS-1

For soil sample-2 (SS-2): The test outcome provided the MDD value of 1.74 g/cc and the corresponding OMC to be 22%, (Figure. 9).

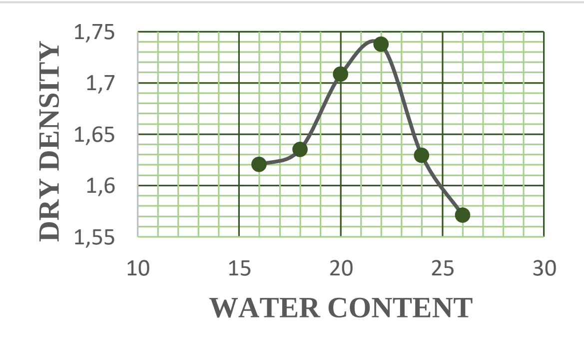

Figure 9. Optimum moisture content data of SS-2

Plasticity index (PI): The clay variants with high PI are more plastic in nature and exhibit greater changes in volume in response to moisture content. This estimation can provide essential insights into particle settlement, shrinkage, and slope stability of the blend (BIS, Part 2 & 5., 1973 & 1983). With this data, proper engineering solutions can be provided by reducing the risks associated with soil instability and deformation.

For SS-1: The liquid limit of the soil was found to be 30.96%, while the plastic limit was determined to be 29.0% and hence the PI was 1.96%, (Figures 10 & 11).

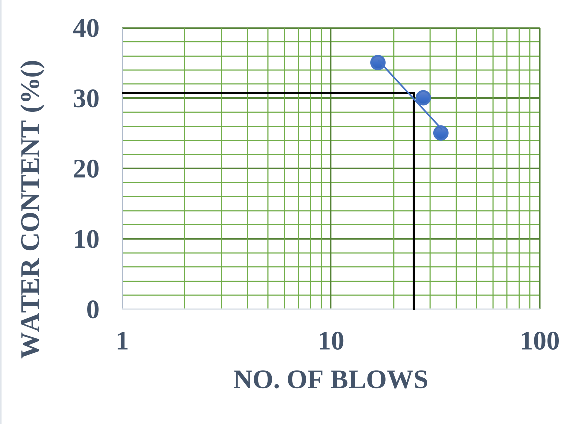

Figure 10. Flow curve of SS-1

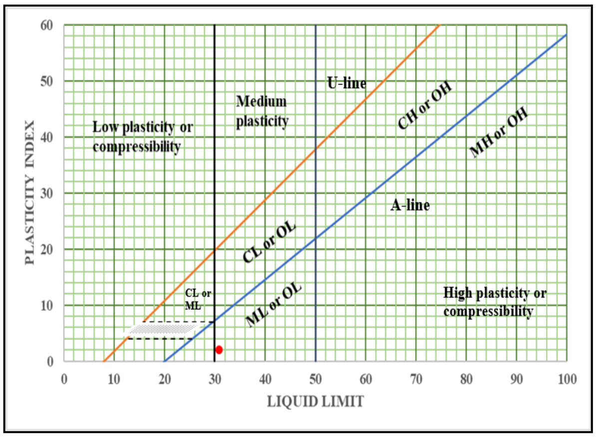

Figure 11. Plasticity chart of SS-1

For SS-2: The liquid limit of the soil was found to be 37.3%, the plastic limit was determined to be 36.0% and hence the PI was 1.3%, (Figures 12 & 13).

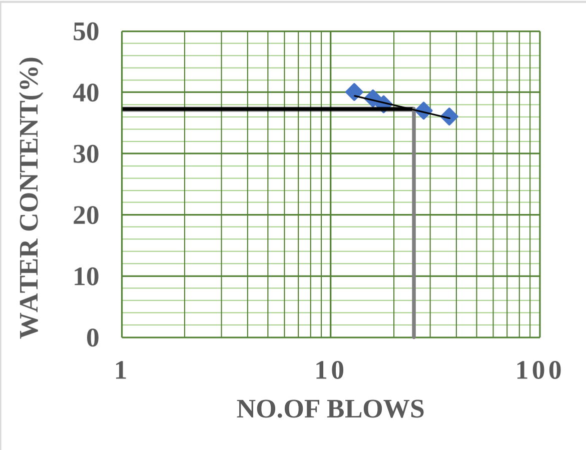

Figure 12. Flow curve of SS-2

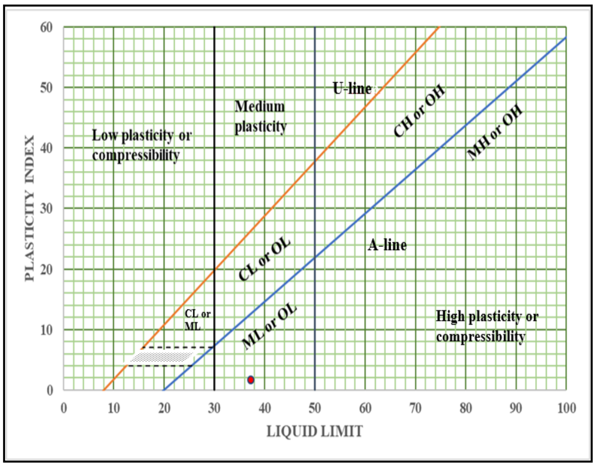

Figure 13. Plasticity chart of SS-2

Analysis of Brick Specimens

The prepared brick specimens were subjected to two critical tests by exposing them to applied compression and forced water absorption.

Compressive strength test: A crucial test to determine the structural integrity, stability, and suitability of brick specimens for construction purposes (BIS, Part 1., 1992). The brick will be subjected to a gradual rise in compression pressure and the process will continue until they disintegrate. The maximum force applied before the failure will be recorded as the compressive strength of individual brick specimens. This test will give an idea regarding the ability of brick specimens to bear the real-time construction workload. If the recorded values are high then the brick specimens will have better structural stability and durability. The test results of SS-1-based bricks (Table 2) indicated that lower input of alkali and higher curing duration had contributed to the increase in brick strength (Sl. No 4, 8 & 9). For SS-2-based bricks, a similar trend was observed with a bit higher compressive strength for all the brick variants. Based on the insights gathered from SS-1-based brick variants, SS-2-based ones are prepared by the input of less alkali (0.5-4 M). To get higher strength with the least alkali input, we introduced fine sand to the blend. Interestingly, the addition of fine sand (10% bt Wt) to the blend having NaOH solution (0.5 M) had a noticeable impact on the brick strength (Sl. No. 8 & 9).

Table 2. Results of compressive strength test conducted on SS-1-based brick variants

Sl. No.	Strength of NaOH solution	Curing duration (days)	Compressive strength (MPa)
1.	15 M	14	0.18
2.	10 M	14	0.47
3.	2 M	14	0.95
4.	1 M	14	1.7
5.	0.75 M	14	1.58
6.	0.5 M	14	1.52
7.	0 M	14	1.49
8.	1 M	28	3.75
9.	0 M	28	3.15

Table 3. Results of compressive strength test conducted on SS-2-based brick variants

Sl. No.	Strength of NaOH solution	Curing duration (days)	Compressive strength (MPa)
1.	4 M	14	0.99
2.	3 M	14	1.05
3.	2 M	14	1.29
4.	1 M	14	2.99
5.	0.75 M	14	2.92
6.	0.5 M	14	2.84
7.	0 M	14	1.58
8.	0.5 M (10% fine sand)	14	3.05
9.	0.5 M (10% fine sand)	28	5.57
10.	0 M	28	3.35

Table 4. Results of the water absorption test conducted for the selected brick variants

Sl. No.	Brick variants	Additives	Curing (days)	Inference
1.	SS-1	1 M NaOH	14	Crumbled
2.	SS-1	1 M NaOH	28	26%
3.	SS-2	1 M NaOH	14	Crumbled
4.	SS-2	1 M NaOH	28	19.8%
5.	SS-2	0.5 M NaOH,10% fine sand	14	17.6%
6.	SS-2	0.5 M NaOH,10% fine sand	28	12.4%

Water absorption test: A crucial test to estimate the quality and performance of prepared bricks (BIS, Part 2., 1992). A few brick variants having good strength were subjected to this test. The extent of water absorption was estimated by checking the before and after weight of brick specimens. As per the obtained results (Table 4), a few brick variants had crumbled by absorbing water to a higher extent (Sl. No. 1 & 3), one variant (Sl. No. 2) had displayed high water absorption (26%) and the remaining variants (Sl. No. 4-6) had exhibited moderate to less water absorption (19.8%, 17.6% & 12.4% respectively). The SS-1-based brick variants had slightly higher slit content which contributed to more water absorption. However, curing duration and the presence of fine sand also contributed to low water absorption due to reduced brick porosity.

CONCLUSION

In this work, we investigated the feasibility of preparing alkali-mediated unfired clay bricks through geo-polymerization. The addition of NaOH solution to the locally sourced soil variants in varied proportions (0.5-15 N) was done and the obtained brick specimens were analyzed. A few unfired bricks were prepared by the addition of alkali and 10% of fine sand to clay. Additionally, some reference bricks were also prepared in the absence of alkali input. The prepared brick specimens were kept exposed to an ambient atmosphere in a well-ventilated room for curing (14-28 days). A satisfactory compressive strength was recorded for the brick specimens with low alkali content (0.5-1 M) and a curing duration of 28 days. Interestingly, one brick variant (0.5 M, 10% fine sand, 28 days) exhibited less water absorption.

REFERENCES

1. Ahmed, N., Abdel-Hamid, M., Abd El-Razik, M. M., & El-Dash, K. M. (2021). Impact of sustainable design in the construction sector on climate change. *Ain Shams Engineering Journal*, 12(2), 1375–1383.
2. Ahmed, T. S., & Abbas, W. A. (2016). Alkali activated brick at low temperatures based on Iraqi Attapulgite. *Global Journal of Engineering Science and Research Management*, 3(7), 52–58.
3. Akanyeti, I., Damdelen, Ö., & Anvarov, A. (2020). Geo-polymerization technique for brick production from coal ash and cigarette butts. *Journal of Materials Research and Technology*, 9(6), 12855–12868.
4. Akinwande, A. A., Adediran, A. A., Balogun, O. A., Olusoju, O. S., & Adesina, O. S. (2021). Influence of alkaline modification on selected properties of banana fiber paperbricks. *Scientific Reports*, 11(1), 5793.
5. Akinyemi, B. A., Orogbade, B. O., Ogheneyome, A., Abeer, M. A., Khan, A., Mahmoud, A. H., & Asiri, A. (2022). Influence of alkali activators on thermo-physical properties of ecofriendly unfired clay bricks from anthill mounds. *European Journal of Environmental and Civil Engineering*, 26(11), 5167–5179.
6. Alzeebaree, R., Mawlod, A. O., Mohammedameen, A., & NiŞ, A. (2021). Using of recycled clay brick/fine soil to produce sodium hydroxide alkali activated mortars. *Advances in Structural Engineering*, *24*(13), 2996–3009.
7. Aponte, C. (2015). Decreasing water absorption in and environmental analysis of alkali activated bricks. *Thesis*: Massachusetts Institute of Technology, Department of Materials Science and Engineering.

8. Bektas, F., Turanli, L., Wang, K., & Ceylan, H. (2007). Comparative performance of ground clay brick in mitigation of alkali–silica reaction. *Journal of Materials in Civil Engineering*, 19(12), 1070–1078.
9. BIS, I. (1973). 2720-Methods of Test for Soils: Part 2 Determination of Water content. *Bureau of Indian Standards,* New Delhi, India, 1-17.
10. BIS, I. (1983). 2720-Methods of Test for Soils: Part 5 Determination of Liquid and Plastic limit. *Bureau of Indian Standards,* New Delhi, India, 1-16.
11. BIS, I. (1983). 2720-Methods of test for soils: Part 8 Determination of water content-dry density relation using heavy compaction Factors. *Bureau of Indian Standards*, New Delhi, India, 1-9.
12. BIS, I. (1992). 3495-Methods of Tests of burnt Clay Building Bricks: Part 1 Determination of Compressive strength. *Bureau of Indian Standards,* New Delhi, India, 1-7.
13. BIS, I. (1992). 3495-Methods of Tests of burnt Clay Building Bricks: Part 2 Determination of Water absorption. *Bureau of Indian Standards,* New Delhi, India, 1-7.
14. Borchate, S. S., Hoolikantimath, N. P., Katageri, B., & Ghorpade, P. A. (2023). Red Mud-based geopolymeric clay brick. In *Lecture Notes in Civil Engineering* (pp. 553–564). Springer Nature Singapore.
15. Brîndus-Simut, J., Vyšvaril, M., Bayer, P., Keppert, M., & Rovnaníková, P. (2018). Effect of particle size of waste brick powder on the properties of alkaline activated materials. *IOP Conference Series. Materials Science and Engineering*, *379*, 012019.
16. Bumanis, G., & Vaiciukyniene, D. (2022). Alkali activation of milled red brick waste and calcined illite clay with silica gel addition. *Materials*, 15(9), 3195.
17. Capasso, I., D'Angelo, G., Fumo, M., del Rio Merino, M., Caputo, D., & Liguori, B. (2023). Valorisation of Tuff and brick wastes by alkali activation for historical building remediation. *Materials*, 16(20), 6619.
18. Dabaieh, M., Heinonen, J., El-Mahdy, D., & Hassan, D. M. (2020). A comparative study of life cycle carbon emissions and embodied energy between sun-dried bricks and fired clay bricks. *Journal of Cleaner Production*, 275 (122998), 122998.
19. Dahal, S. (2022). Synthesis of Alkali Activated Geopolymer Cement from Clay. *Journal of Civil and Environmental Engineering*, 12(6), 1–13.
20. Dalkılıç, N., & Nabikoglu, A. (2017). Traditional manufacturing of clay brick used in the historical buildings of Diyarbakir (Turkey). *Frontiers of Architectural Research*, 6(3), 346–359.
21. Ding, Y., Dai, J.-G., & Shi, C.-J. (2016). Mechanical properties of alkali-activated concrete: A state-of-the-art review. *Construction and Building Materials*, *127*, 68–79.
22. Ezzat, M., Khater, H. M., & El-nagar. (2016). Enhanced characteristics of alkali activated slag/ grog geopolymer bricks. *International Journal of Scientific & Engineering Research*, *7*(2), 230–243.
23. Faheem, M. T. M., Al-Bakri, A. M. M., Kamarudin, H., Ruzaidi, C. M., Binhussain. M., Izzat, A. M. (2013). The relationship of Na_2SiO_3/NaOH ratio, Kaolin/alkaline activator ratio and Sand/Kaolin ratio to the strength of Kaolin-based non load bearing geopolymer brick. *International Journal on Advanced Materials and Technologies 1*(4).
24. Fahmi, A., Amini, A. B., Marabi, Y., Zavaragh, S. R., & Majnouni-Toutakhane, A. (2021). Effect of curing temperature on the mechanical strength of alkali activated laterite geopolymeric samples. *Journal of Engineering Research*, 11 (1B), 38-51.
25. França, S., de Moura Solar Silva, M. V., Ribeiro Borges, P. H., & da Silva Bezerra, A. C. (2022). A review on some properties of alkali-activated materials. *Innovative Infrastructure Solutions*, 7(2).
26. Furszyfer Del Rio, D. D., Sovacool, B. K., Foley, A. M., Griffiths, S., Bazilian, M., Kim, J., & Rooney, D. (2022). Decarbonizing the ceramics industry: A systematic and critical review of policy options, developments and sociotechnical systems. *Renewable and Sustainable Energy Reviews*, *157*(112081), 112081.
27. Gado, R. A., Hebda, M., Łach, M., & Mikuła, J. (2020). Alkali activation of waste clay bricks:

Influence of the silica modulus, SiO_2/Na_2O, H_2O/Na_2O molar ratio, and liquid/solid ratio. *Materials*, *13*(2), 383.

28. Gavali, H. R., & Ralegaonkar, R. V. (2020). Design development of sustainable alkali-activated bricks. *Journal of Building Engineering*, *30*(101302), 101302.
29. Hasan, Z. A., Abdulridha, S. Q., & Abeer, S. Z. (2021). Sustainable mortar made with local clay bricks and glass waste exposed to elevated temperatures. *Civil Engineering Journal*, *7*(8), 1341–1354.
30. Kejkar, R. B., & Wanjari, S. P. (2021). Sustainable production of commercially viable alkali-activated bricks. *Proceedings of the Institution of Civil Engineers - Engineering Sustainability*, *174*(3), 109–119.
31. Khalifa, A. Z., Cizer, Ö., Pontikes, Y., Heath, A., Patureau, P., Bernal, S. A., & Marsh, A. T. M. (2020). Advances in alkali-activation of clay minerals. *Cement and Concrete Research*, 132 (106050), 106050.
32. Khalifa, A. Z., Pontikes, Y., Elsen, J., & Cizer, Ö. (2019). Comparing the reactivity of different natural clays under thermal and alkali activation. *RILEM Technical Letters*, *4*, 74–80.
33. Khater, H. M., El-Nagar, A. M., & Ezzat, M. (2016). Optimization of alkali activated grog/ceramic wastes geopolymer bricks. *International Journal of Innovative Research in Science, Engineering and Technology*, 5(1), 37–46.
34. Krishnan, A. K., Wong, Y. C., Zhang, Z., & Arulrajah, A. (2023). Recycling of glass fines and plastics in clay bricks at low temperatures. *Proceedings of the Institution of Civil Engineers. Waste and Resource Management*, *176*(4), 153–161.
35. Kumble, P., Prashant, S., & Achar, N. (2023). Bond strength of alkali-activated flyash based masonry system for sustainable construction. *SN Applied Sciences*, *5*(12).
36. Kurtay, Y, M. (2024). Designing hollow brick waste based alkali activated composites by Taguchi method. *Sakarya University Journal of Science*, *28*(1), 73–84.
37. Lakho, N. A., & Zardari, M. A. (2016a). Structural properties of baked clay bricks fired with alternate fuels. *Engineering*, *08*(10), 676–683.
38. Lakho, N. A., Zardari, M. A., & Memon, F. A. (2016b). Effect of intensity of compaction on crushing strength of indigenous baked clay. *Journal of Engineering Research*, *4*(2).
39. Maheshwari, H., & Jain, K. (2017). Carbon footprint of bricks production in fixed chimney bull's trench kilns in India. *Indian Journal of Science and Technology*, *10*(16), 1–11.
40. Mejía-Arcila, J., Valencia-Saavedra, W., & Mejía de Gutiérrez, R. (2020). Eco-efficient alkaline activated binders for manufacturing blocks and pedestrian pavers with low carbon footprint: Mechanical properties and LCA assessment. *Materiales de Construccion*, *70*(340), 232.
41. Modha, H., Sharma, N., & Singh, S. (2021). Alkali Activated Material Brick. In *Lecture Notes in Civil Engineering* (pp. 131–139). Springer Singapore.
42. Murmu, A. L., & Patel, A. (2018). Towards sustainable bricks production: An overview. *Construction and Building Materials*, *165*, 112–125.
43. Parhi, P. S., Garanayak, L., Mahamaya, M., & Das, S. K. (2018). Stabilization of an expansive soil using alkali activated fly ash based geopolymer. *Sustainable Civil Infrastructures* (36–50). Springer International Publishing.
44. Phoo-ngernkham, T., Maegawa, A., Mishima, N., Hatanaka, S., & Chindaprasirt, P. (2015). Effects of sodium hydroxide and sodium silicate solutions on compressive and shear bond strengths of FA–GBFS geopolymer. *Construction and Building Materials*, *91*, 1–8.
45. Poinot, T., Laracy, M. E., Aponte, C., Jennings, H. M., Ochsendorf, J. A., & Olivetti, E. A. (2017). Beneficial use of boiler ash in alkali-activated bricks. *Resources, Conservation, and Recycling*, *128*, 1–10.
46. Prathiksha, B., Hithesh, P. S., Subrahmanya, R. S., & Sanjay, S. S. (2023). An investigative study to incorporate waste glass powder with natural clay to manufacture baked glass infused-clay bricks. *Journal of Research Technology & Engineering*, *4*(4), 65–75.
47. Puertas, F., Santos, R., Alonso, M. M., & del Río, M. (2015). Alkali-activated cement mortars containing recycled clay-based construction and demolition waste. *Ceramics-Silikaty*, *59*(3), 202–210.

48. Reig, L., Tashima, M. M., Borrachero, M. V., Monzó, J., Cheeseman, C. R., & Payá, J. (2013). Properties and microstructure of alkali-activated red clay brick waste. *Construction and Building Materials*, *43*, 98-106.
49. Revathi, & Vidhya. (2021). Eco-sustainable alkali activated brick using municipal incinerated ash. *International Journal of Coal Preparation and Utilization*, *42*(3), 331–348.
50. Rivera, J. F., Mejía de Gutiérrez, R., Ramirez-Benavides, S., & Orobio, A. (2020). Compressed and stabilized soil blocks with fly ash-based alkali-activated cements. *Construction and Building Materials*, 264 (120285), 120285.
51. Robayo, R. A., Mulford, A., Munera, J., & Mejía de Gutiérrez, R. (2016). Alternative cements based on alkali-activated red clay brick waste. *Construction and Building Materials*, 128, 163–169.
52. Robayo, R. A., Rivera, J. F., & Mejía de Gutiérrez, R. (2017). Alkali-activated building materials made with recycled construction and demolition wastes. *Construction and Building Materials*, 149, 130–138.
53. Robayo, R. A., Valencia-Saavedra, W., Ramírez-Benavides, S., Mejía de Gutiérrez, R., & Orobio, A. (2021). Eco-house prototype constructed with alkali-activated blocks: Material production, characterization, design, construction, and environmental impact. *Materials*, 14(5), 1275.
54. Sasikumar, S., Natarajan, M., Balasundaram, N., & Karthik, V. (2020). Study on the behavior of geopolymer bricks under different curing temperatures and alkaline solution concentrations. *International Journal of Applied Engineering Research, 15*(7), 690–694.
55. Sedira, N., Castro-Gomes, J., & Magrinho, M. (2018). Red clay brick and tungsten mining waste-based alkali-activated binder: Microstructural and mechanical properties. *Construction and Building Materials*, 190, 1034–1048.
56. Shakir, A. A., & Mohammed, A. A. (2013). Manufacturing of Bricks in the Past, in the Present and in the Future: A state of the Art Review. *International Journal of Advances in Applied Sciences (IJAAS)*, *2*(3), 145–156
57. Statkauskas, M., Vaičiukynienė, D., & Grinys, A. (2024). Mechanical properties of low calcium alkali activated binder system under ambient curing conditions. *Scientific Reports*, *14*(1).
58. Subramani, S., & Venkataraman, G. (2023). Synthesis and evaluation of Eco-friendly, ambient-cured, geopolymer-based bricks using industrial by-products. *Buildings*, *13*(2), 510.
59. Thejas, & Hossiney, N. (2022). Alkali-activated bricks made with mining waste iron ore tailings. *Case Studies in Construction Materials*, *16*(e00973), e00973.
60. Ukwatta, A., Mohajerani, A., Setunge, S., & Eshtiaghi, N. (2018). A study of gas emissions during the firing process from bricks incorporating biosolids. *Waste Management*, 74, 413–426.
61. Vasavi, G. S., Mourougane, R., & Pavan, G. S. (2022). Strength and durability properties of alkali-activated fly ash earth bricks. *Lecture Notes in Civil Engineering* (141–152). Springer Singapore.
62. Verma, M. D., Agarwal, M., Junaid, M., & Fareed. (2023). A case study on eco fly ash bricks using alkali activation technology. *International Journal of Novel Research and Development,8*(5), 392–397.
63. Villeda-Muñoz, G., Castañeda-Miranda, A., Pless, R. C., Vega-Durán, J. T., & Pineda-Piñón, J. (2011). Clay-brick firing in a high-temperature solar furnace. *Ingeniería Investigación y Tecnología*, 12(4), 395–408.
64. Vyšvaril, M., Rovnaníková, P., & Keppert, M. (2018). Rheological properties of alkali-activated brick powder based pastes: Effect of alkali activator and silicate modulus. *Solid State Phenomena*, 276, 185–191.
65. Xia, M., Muhammad, F., Li, S., Lin, H., Huang, X., Jiao, B., & Li, D. (2020). Solidification of electroplating sludge with alkali-activated fly ash to prepare a non-burnt brick and its risk assessment. *RSC Advances*, *10*(8), 4640–4649.
66. Youssef, N., Rabenantoandro, A. Z., Dakhli, Z., Hage Chehade, F., & Lafhaj, Z. (2019). Environmental evaluation of geopolymer bricks. *MATEC Web of Conferences*, *281*, 03005.

67. Zhang, Z., Wong, Y. C., Sofi, M., & Mendis, P. (2022). Incorporation of glass and plastic waste into alkali-activated mill residue bricks. *Sustainability*, *14*(24), 16533.