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Developing sustainable burnt clay bricks incorporating agro-industrial waste

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K E Y W O R D S

Agro and industrial waste

Burned clay bricks

Compressive strength

Durability test of bricks

Eco-friendly construction

A B S T R A C T

The study addresses environmental pollution and waste disposal issues resulting from rapid industrialization by investigating the use of agro-industrial waste materials to improve the quality of burnt clay bricks. The research evaluated the effects of incorporating fly ash (FA), silica fume (SF), rice husk ash (RHA), and sugarcane bagasse ash (SBA) in proportions ranging from 2% to 8% into brick earth. Results showed that in the Hyderabad zone, the compressive strength increased by 28%, 31%, 16%, and 8% with the addition of 4% FA, 4% SF, 2% RHA, and 2% SBA, respectively. However, in the Kandhkot locality, compressive strength enhancements were noted at 24%, 36%, 23%, and 27%, respectively, with consistent raw material ratios. For long-term durability, water absorption and efflorescence tests were conducted, which showed a reduction because of the addition of these waste materials. In both locations, the brick dimensions remained within the allowed range. In conclusion, the results suggest that the construction sector has the potential to enhance the properties of bricks by employing these agro-industrial waste materials and promoting sustainable methods for controlling environmental factors.

1. Introduction

Nowadays, the waste management sector faces the challenges of industrial and agricultural waste, which are crucial methods for development in innovation and sustainability. However, brick masonry is an ancient building material that plays a critical responsibility as the primary material in the construction industry[1]. The rapid growth of populations is the main reason for the production of massive quantities of different waste materials, concluding points including the population around the world[2, 3]. Basically, the manufacture of brick masonry using the fired method in a kiln is a more energy-consuming method, which is the main cause of environmental air pollution and major carbon dioxide emissions, mostly in interior Sindh, Pakistan. But a significant amendment is occurring within construction manufacturing, intent on sustainable brick manufacture methods that include industrial and agricultural waste raw materials, for instance, rice husk ash (RHA), silica fume (SF), fly ash (FA), metakaolin (MK), and various other waste materials. This is another possibility to maintain the overall stability of buildings while offering durability, structural reliability, and flexibility for significant architectural purposes [4–6]. Due to the high increase in construction projects, the production of bricks has increased by 1.5 trillion/year[7]. Moreover, because of ongoing infrastructure expansion, there are limited land resources for open-space waste disposal. In countries like Pakistan, waste products are either dumped into rivers and lakes or burnt in open areas, resulting in water and air pollution [3,4]. These environmental issues can be solved by using industrial wastes in brick production processes. The possibility of adding different industrial and agro-waste materials to improve the sustainability and performance of burnt clay bricks has been the subject of several studies [8–13]. Kumar et al. [13] In this investigation, it was noticed that the structural performance of all fired clay bricks was enhanced when additives were added in comparison to traditional bricks that were devoid of additives. The bricks that exhibited the highest structural efficiency were those that contained 4% fly ash (FA) and 4% silica fume (SF), with values of 9.51 $\times 10^3$ N/m² and 10.43 $\times 10^3$ N/m², respectively. Thus, the most effective additive proportions for enhancing the strength and durability of bricks are 4% FA and 4% SF. In contrast, Kazmi et al.[10] it was reported that the compressive strength decreased as the percentage of FA incorporation increased. At 5% FA concentration, efflorescence was negligible, but at 20% FA level, it was considerable. Also, the incorporation of 25% FA provided for an 18% weight reduction, which resulted in the production of lightweight bricks. Kayali et al. [14], according to the findings, the utilization of only FA as a brick material resulted in a 28% decrease in brick weight, a 24% increase in compressive strength, and a 40% increase in bond strength when contrasted with clay bricks. Moreover, Shakir et al.[15] observed that adding 30% FA to brick earth resulted in a 22% reduction in water absorption. In another study by Lingling et al.[16], studies were conducted on the combustion parameters of FA bricks. They found that high FA volume ratios required a sintering temperature range of 50–1000°C, which is higher than that needed for clay bricks. In comparison to conventional clay bricks, these FA bricks demonstrated superior compressive strength, reduced water absorption, increased resistance to frost melting, and resistance to lime-induced cracking.

Additionally, the integration of natural fibers, rice husk ash, wood chips, soapstone powder, and Fe-Si-Mn slag into brick earth proved significant potential for improving the general properties of bricks [17, 18]. Hegazy et al.[19] added SF, RHA, and water sludge to the brick earth. They observed that the chemical composition of water sludges was remarkably like that of masonry clay. The mechanical and durability properties of the modified bricks were effectively enhanced using a suitable mix of 50% water sludge, 25% SF, and 25% rice husk ash. Baspinar et al. [9] observed that the method of sintering improved due to the reactive amorphous properties of SF, resulting in higher strength. In burnt bricks, the temperature during the procedure is the primary factor determining the impact of SF. When temperatures are lower, the bulk density is diminished, while when temperatures are higher, the bulk density is increased. Also, higher amounts of SF were observed to reduce efflorescence. These experiments, however, were limited using a single source of soil and were conducted primarily in the controlled laboratory. However, there was a particular case in which a study was conducted in an actual field [13], although it was restricted to a particular region and necessitated the utilization of two agro-wastes: red clay, plastic, bagasse ash, rice husk ash, and silica fume [8, 20–24]. This study was carried out in real-world brick manufacturing settings in two separate locales, Hyderabad and Kandhkot, using local production procedures. The study focused on using various quantities of FA, SF, rice husk ash (RHA), and sugarcane bagasse ash (SBA) as improvements in brick manufacture. The findings give significant recommendations for South Asia's brick manufacturing industry by demonstrating how agro-industrial waste may be used efficiently as brick earth modifiers to improve the performance and sustainability of burnt clay bricks. The rapid increase of industrial activity has resulted in garbage disposal in open areas, which causes environmental pollution and contributes to land scarcity challenges [25, 26]. In underdeveloped countries like Pakistan, garbage is thrown into rivers or is burnt, causing water and air pollution [27]. The research indicates that agricultural and industrial waste products that feature pozzolanic properties, including fly ash(FA) [24, 28, 29], silica fume(SF) [30], waste glass(WG), lime [31], red mud (RM), plastics, rice husk ash(RHA) [32, 33], and bagasse ash(BA) [34], can be reutilized [35, 36]. This research focuses on the use of agro-industrial waste as soil enhancers in local site kilns in the Hyderabad and Kandhkot regions to improve brick properties, promote environmentally friendly brick manufacturing, and reduce landfill-related pollution. Based on the conclusions of this research will be advantageous for the sustainable brick and construction industries in Pakistan as well as in both cities, Hyderabad and Kandhkot, Sindh, Pakistan.

2. Materials and Methodology

2.1 Materials and Properties

This research used agro-industrial waste, which is considered as pozzolanic materials such as low calcium FA, highly reactive SF, RHA, and SBA. These raw materials contain high silica content. These agro-waste samples were obtained locally to confirm their reliability and significance to the study. Fly ash and silica fume were obtained from a reliable provider in Karachi, while rice husk ash was obtained from a brick kiln in Kandhkot. Sugarcane bagasse ash, on the other hand, arrived from Matiari Sugar Mills Pvt Ltd.

In total, 1360 bricks were specifically constructed, with 680 at each location. Each sample consists of 40 bricks with varying proportions of materials, such as FA (2%, 4%, 6%, and 8%), SF (2%, 4%, 6%, and 8%), RHA (2%, 4%, 6%, and 8%), and SBA, as shown in Fig 1. Also, custom-made brick molds were produced to ensure that each brick sample was accurately identified. These molds included labels that indicated the place where the brick was developed as well as the exact agricultural waste used and its percentage.

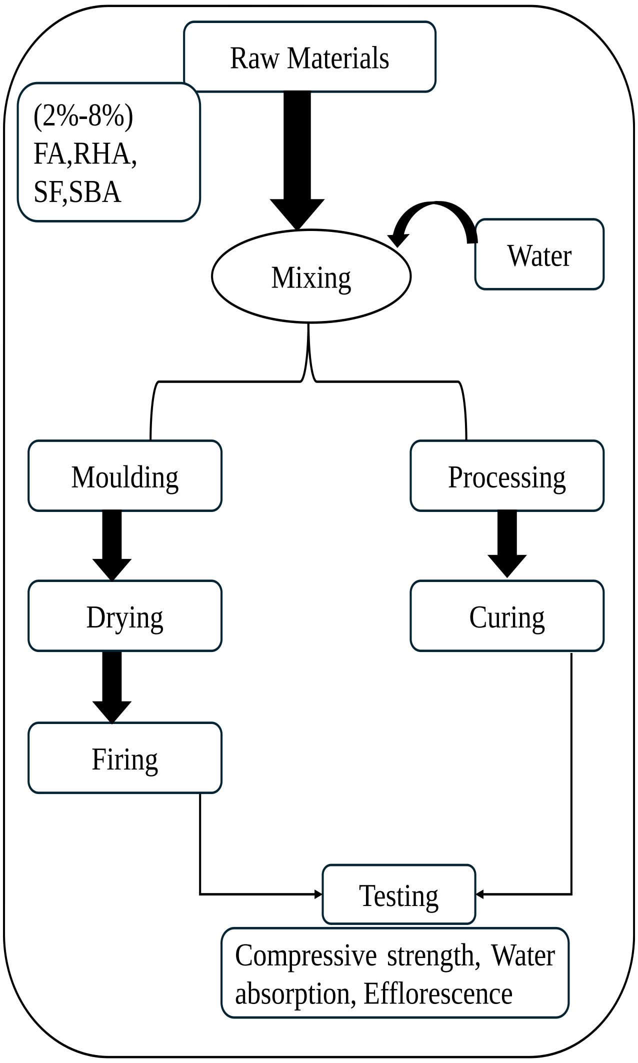

Fig. 1. Manufacturing Of Bricks By Using Waste Materials

2.2 Methodology

A five-stage procedure was implemented during the research, as illustrated in Fig. 2, which was conducted in two distinct locations within the Sindh province: Kandhkot and Hyderabad. Bricks were manufactured at nearby kiln sites in these regions, and the foundational soil used in the brick molding process was obtained directly from these locations.

The selection of this clayey soil was detailed to ensure that the samples accurately reflected the local context and conditions of each respective region under the research objectives.

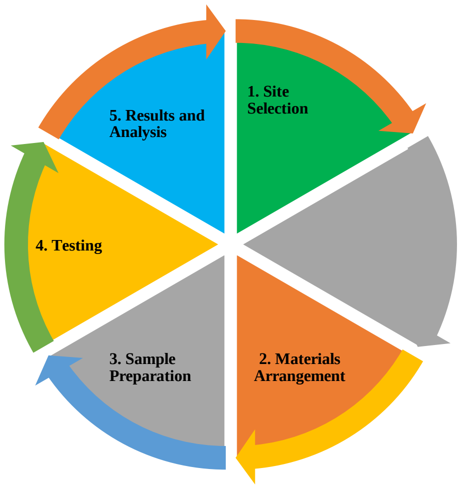

Fig. 2. Methodology

For this study, brick samples of 220mm x 110mm x 75mm were precisely constructed. The agro-industrial waste materials, including FA, SF, RHA, and SBA, were added to the soil at varying percentages (2%, 4%, 6%, and 8%, respectively, based on the dried weight of the soil). In this study, 40 samples were prepared for each percentage of agro-industrial waste, as listed first. In conclusion, 680 samples were prepared for both the Hyderabad and the Kandhkot regions. However, brick samples are prepared using traditional methods, such as brick masonry by soil. Then, these bricks are carried to the MUET laboratory for compressive strength and durability performance, which will be discussed later.

2.3 Procedure for Sample Bricks Preparation

1) To determine the weight of soil in one cubic foot, an on-site cubic foot box was employed, as illustrated in Fig.3.

Fig. 3. Determination of Soil Weight

2) A digital balance ensures accuracy by precisely quantifying the weight of soil in one cubic foot in kilograms.

3) Various proportions of agro-waste were added to the soil sample's net weight as part of the experimental process. The study focused on four ratios: 2%, 4%, 6%, and 8%.

4) The four agro-industrial waste components were combined with soil samples and saturated for 24 hours. Using the following categories, a total of 17

soil samples were prepared: 2%-FA, 4%-FA, 6%-FA, 8%-FA, 2%-SF, 4%-SF, 6%-SF, 8%-SF, 2%-RHA, 4%-RHA, 6%-RHA, 8%-RHA, 2%-SCBA, 4%-SCBA, 6%-SCBA, and 8%-SCBA. A control sample made up of the control brick soil was also prepared.Refer to Fig.4.

Fig. 4. Dry Mixing Agro-wastes

5) After the 24-hour saturation period, each sample was molded independently, producing 40 bricks. As seen in Fig. 5.

Fig. 5. Molding of Bricks

6) The molded bricks were subsequently set aside for the drying process, allowing for the natural evaporation of moisture as shown in Fig. 6.

Fig. 6. Setting up Bricks for Drying

7) After drying, the bricks were subjected to a controlled burning procedure within the brick kiln for 2 to 3 weeks.

8) After kiln burning, burnt bricks were transported to Mehran University of Engineering and Technology (MUET) laboratories for thorough testing and analysis as mentioned in Fig. 7.

Fig. 7. Collection of Bricks

2.4 Results and Discussion

In the context of material analysis, the basic materials were given a comprehensive evaluation that involved the application of a variety of techniques. Table 1 provides a comprehensive summary of the results of the chemical composition analyses that were conducted during these evaluations. Moreover, soil samples taken from nearby kiln locations in the Hyderabad and Kandhkot regions were classified using the AASHTO Soil classification method; Table 2 shows the results of this classification. Furthermore, particle size distribution curves for both soil samples were developed and demonstrated in Fig. 9.

Table 1

Chemical Composition of soil samples and agro-industrial waste materials.

Oxides (%)	SiO2	Al2O3	CaO	Fe2O3	K2O	TiO2	SO3	MnO
FA	59.30	17.87	9.43	8.28	3.60	0.96	0.25	0.13
SF	96.89	-	0.467	0.084	0.59	-	1.92	0.02
RHA	78.47	5.98	6.91	3.04	3.97	0.34	1.04	0.11
SCBA	78.01	-	8.22	2.47	8.67	0.21	1.30	0.14
Clay (H)	50.88	30.54	7.34	6.88	1.32	1.48	1.01	0.1
Clay (K)	52.89	17.80	13.10	10.93	3.68	1.18	-	0.16

Table 2

AASHTO Classification of soil samples taken from kiln sites.

S.no	Region	Soil Types		
1	Hyderabad (H)	A-7-5	Silt-Clay Materials	Clayey Soils
2	Kandhkot (k)	A-6		Clayey Soils

Fig. 8 shows the relative proportions of various particle sizes within a soil sample, which is also referred to as a grain size distribution curve or a gradation curve. This curve serves as a critical tool for conveying essential insights into the dispersion of particle sizes within a given soil sample. This information is significant in comprehending the soil's engineering and geological characteristics. The grain size distribution curves adhere to the specifications outlined in accordance with the ASTM Standard D422-63, 2007.

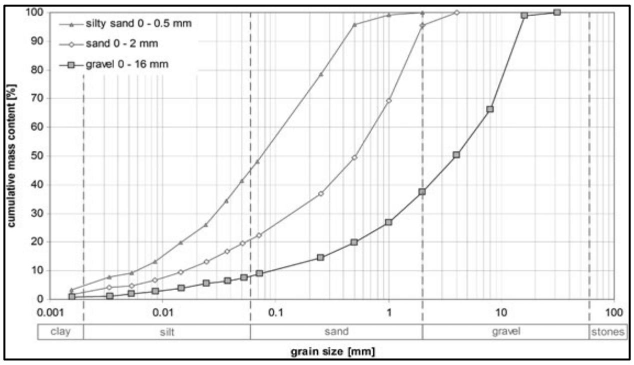

Fig. 8. ASTM D422-63, 2007 Distribution Curve

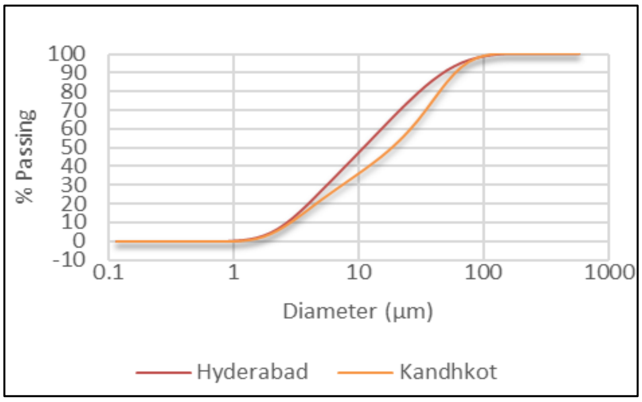

Fig. 9. Particle Size Distribution Curve of Soil Samples

The mining department of Mehran University of Engineering and Technology (MUET) in Jamshoro carried out a detailed analysis and study of the particle size distribution of soil samples from Hyderabad and Kandhkot. The primary purpose of this study is to conduct and analyze the influence of particle size, chemical composition, and physical properties of agro-industrial materials on compressive strength and durability performances.

The conclusions of this research were regularly incorporated into an illustration in Fig. 9. The soil properties of the Hyderabad and Kandhkot locations were expressed in red and orange, respectively. This graph clearly shows and discusses how the particle size distribution in both regions is separated.

The Hyderabad and Kandhkot soils were methodically classified as clay, silt, and sand in accordance with the American Society for Testing and Materials standards (ASTM D422-63, 2007). This classification highlighted the differences in their chemical and physical properties, concentrating on the occurrence of a broad range of particle sizes that contribute to their unique performance under different conditions. The study elaborates on an assortment of procedures, including a compressive strength test, efflorescence test, water absorption, and tolerance test. These multifaceted evaluations were essential in ensuring that the raw materials not only met the required standards for their intended applications but also provided invaluable data to advance the research objectives and control the environmental challenges.

2.4.1 Compressive strength analysis of bricks manufactured by waste materials

Brick compressive strength test, which determines the maximum load a brick can resist before crushing/cracks, showing its structural integrity in construction projects. ASTM C67-20 outlines standards for testing accordance. Compressive strength is measured by using a UTM(Universal testing machine), and bricks are subjected to an increasing load until fracture appears. , expressed in megapascals (MPa) or pounds per square inch (psi), is calculated by dividing the maximum failure load by the brick's face area[37].

Compressive Strength = Maximum Failure Load / Face Area

A numerical value obtained from this mathematical calculation shows the brick's compressive strength. By conducting such tests and obtaining compressive data, builders, engineers, and architects acquire valuable insights to make informed decisions about the suitableness of these bricks for a variety of construction applications.

In this research, 85 burnt clay bricks were manufactured for compressive strength testing, with varying percentages of four different Agro-industrial waste sources. Five control bricks were incorporated for comparative purposes. As illustrated in Fig. 10, the brick samples were appropriately prepared by applying sand mortar capping to both sides of each brick to facilitate the testing procedure within the compression machine.

Fig. 10. Compressive Strength Test

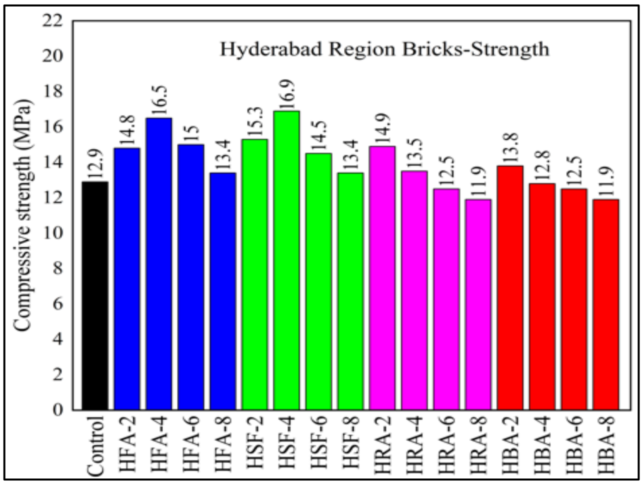

Fig. 11. Compressive strength of Bricks Hyderabad region

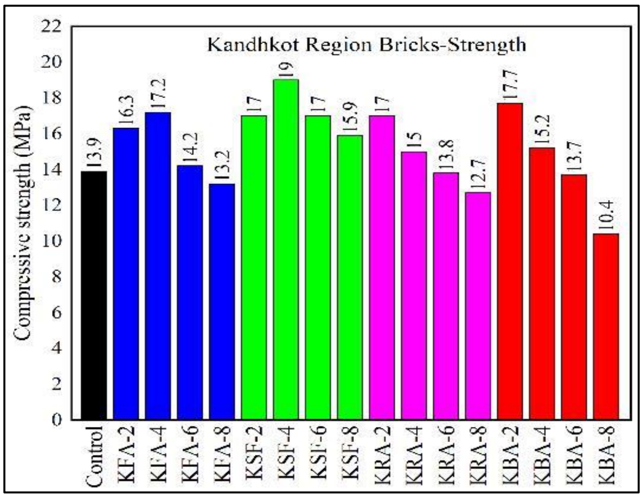

Fig. 12. Compressive Strength Of Bricks Kandhkot Region

1) Fly Ash (FA):

Various proportions of fly ash (FA) were incorporated into the brick earth, ranging from 2% to 8%, serving as an additive to enhance its properties mechanical and durability properties. The most significant increase in compressive strength was observed when 4% of fly ash was introduced into the brick earth. Analyzing the data presented in Fig. 11 and 12, it becomes evident that the maximum enhancement in compressive strength, as compared to the control bricks of the respective regions, was 28% for the Hyderabad region and 24% for the Kandhkot region. In Fig. 11 and Fig.12, bricks produced with fly ash are visually highlighted in blue. Specifically, the labels HFA-2 to HFA-8 and KFA-2 to KFA-8 denote bricks manufactured in the Hyderabad and Kandhkot region, utilizing varying percentages (2%, 4%, 6%, and 8%) of fly ash.

2) Silica Fume (SF):

The most significant increase in compressive strength was achieved when 4% of SF was introduced into the brick earth for both regions. In the Hyderabad region, this resulted in an impressive 31% improvement in compressive strength, while in the Kandhkot region, an even more remarkable 37% increase was observed. These improvements were in direct comparison to the control bricks from both regions. Fig. 11 distinctly portrays bricks that were prepared with varying percentages of silica fume, ranging from 2% to 8%, and these are visually highlighted in green. Specifically, the designations HSF-2 to HSF-8 and KSF-2 to KSF-8 signify bricks prepared in the Hyderabad and Kandhkot region respectively, employing different proportions (2%, 4%, 6%, and 8%) of SF. A parallel representation is presented in Fig.5 and Fig.12, reflecting the situation in the Kandhkot region.

3) Rice Husk Ash (RHA):

A significant increase in compressive strength was observed in both regions when 2% of RHA was incorporated into the brick earth, resulting in a 16% rise for the Hyderabad region and a 23% increase for the Kandhkot region. However, as the percentage of RHA increased, there was a decline in compressive strength observed in both areas. In Fig. 12, the bars indicated in purple the compressive strength of bricks prepared with varying percentages of rice husk ash HRA-2 to HRA-8 and KRA-2 to KRA-8 in the Kandhkot region. Similar parameters and designations are applied to Fig. 11, which pertains to the Hyderabad region.

4) Sugarcane Bagasse Ash (SBA):

The incorporation of 2% of sugarcane bagasse ash (SBA) yielded the most significant enhancement in compressive strength for both regions. However, as the SBA percentage further increased, there was a noticeable decline in compressive strength. The optimal improvements observed were 8% for the Hyderabad region and a remarkable 27% for the Kandhkot region. Fig. 11 is dedicated to illustrating the compressive strength of bricks prepared with varying percentages of sugarcane bagasse ash in the Hyderabad region, with these bars highlighted in red color. The designations HBA-2 through HBA-8 are assigned to bricks manufactured in the Hyderabad region, each corresponding to a specific percentage of sugarcane bagasse ash. A parallel representation is provided in Fig. 12, illustrating the location in the Kandhkot region.

2.4.2 Comparison of compressive strength of bricks in both Hyderabad and kandhkot regions

1) Fly Ash:

Upon scrutinising Fig. 13, a detailed comparative analysis shows significant insights into the outcomes originating from the Hyderabad and Kandhkot regions. This thorough examination encompasses various percentages of Fly Ash utilized in the composition of brick samples. What stands out conspicuously is the remarkable consistency observed in the trends identified across both regions.

Within this realm of uniformity, a noteworthy revelation surfaces: the Kandhkot region consistently outperforms its counterpart in Hyderabad. The data points, depicted in blue to represent the Kandhkot region, distinctly contrast with the purple data points, symbolizing the Hyderabad region on the graph. Delving deeper into the information conveyed by Graph 06 and conducting a rigorous comparative analysis of the results obtained from the Hyderabad and Kandhkot regions yields a wealth of valuable insights into the behavior of brick samples crafted with varying proportions of FA. The examination underscores the persistent patterns in results across both regions, even as different levels of waste incorporation are explored. Remarkably, the Kandhkot region consistently demonstrates more favorable outcomes when compared to the Hyderabad region. Within this realm of uniformity, a noteworthy revelation surfaces: the Kandhkot region consistently outperforms its counterpart in Hyderabad. The data points, depicted in green (KFA-2 to KFA-8), represent the Kandhkot region, and distinctly contrast with the red data (HFA-2 to HFA-8) points symbolizing the Hyderabad region on the graph. Delving deeper into the information conveyed by Graph 06 and conducting a rigorous comparative analysis of the results obtained from the Hyderabad and Kandhkot regions yields a wealth of valuable insights into the behaviour of brick samples crafted with varying proportions of Fly Ash. The assessment underscores the persistent patterns in results across both regions, even as different levels of waste incorporation are explored. Remarkably, the Kandhkot region consistently demonstrates more favorable outcomes when compared to the Hyderabad region.

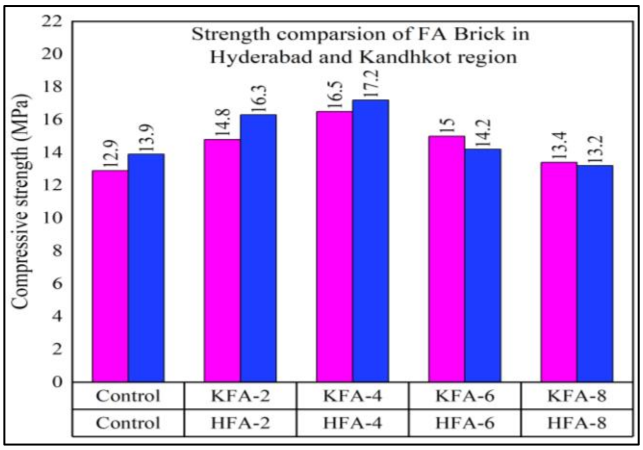

Fig. 13. Compressive Strength Comparison Of Fly Ash-Based Bricks

2) Silica Fume:

Upon a comprehensive examination of Fig. 14, a clear and consistent pattern comes to light, illustrating the behavior of detailed prepared brick samples with varying proportions of SF in both the Hyderabad and Kandhkot regions. Remarkably, these patterns maintain their consistency across the entire range of Silica Fume percentages. An evident visual distinction in the graph is the presence of color-coded bars in purple and blue. These bars serve as visual indicators, representing the Hyderabad (HSF-2 to HSF-8) and Kandhkot regions (KSF-2 to KSF-8), respectively. The red bars signify the Hyderabad region, specifically showcasing results obtained from brick samples with SF additions of 2%, 4%, 6%, and 8%. Conversely, the green bars symbolize the Kandhkot region, displaying outcomes achieved from brick samples infused with the exact SF percentages.

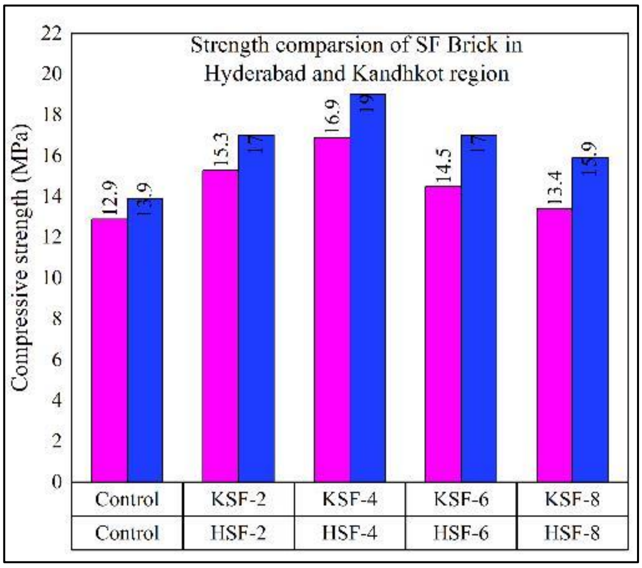

Fig. 14. Compressive Strength Comparison Of Silica Fume-Based Bricks

Significantly, it is the consistent trend observed in both regions. The highest performance is consistently achieved with a 4% addition of SF. This intriguing convergence highlights the optimal influence of this specific percentage on the mechanical properties of the brick samples.

However, there is a significant difference between the two regions. The Kandhkot region consistently exhibits superior results compared to the Hyderabad region, despite the fact that both regions show the same optimal performance at 4% SF.

3) Rice Husk Ash:

After studying Fig. 15, a unique and identifiable trend develops, identifying the behaviour of bricks made with varying percentages of RHA in both the Hyderabad and Kandhkot locations; significantly, these patterns are very reliable across the SF% range, providing important information about the material's performance in various situations.

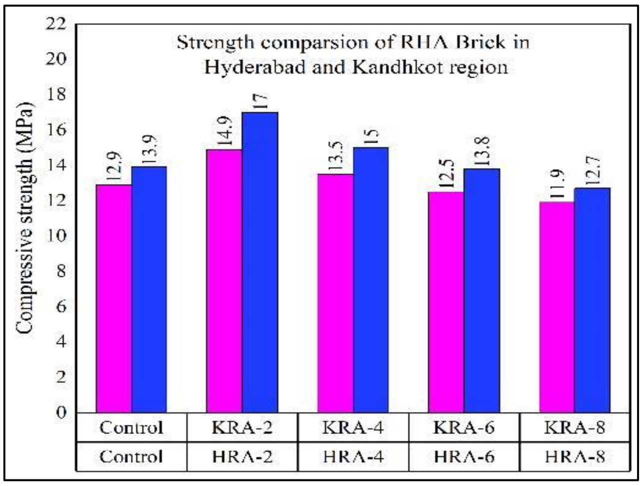

Fig. 15. Compressive Strength Comparison Of Rice Husk Ash-Based Bricks

In the graph, the selection of contrasting red and green bars is a noticeable visual element. The Hyderabad and Kandhkot regions are effectively distinguished by these marked with color bars. The results obtained from brick masonry samples incorporating RHA additions of 2%, 4%, 6%, and 8% are clearly shown by the purple bars (HRA-2 to HRA-8), which represent the Hyderabad region. On the other hand, the Kandhkot region is indicated by the blue bars (KRA-2 to KRA-8), which clearly show the results obtained from brick samples with matching amounts of RHA. The utilization of a 2% proportion of RHA results in a significant peak in performance in both regions, which is a consistent and notable trend. The significance of this particular percentage in affecting the brick samples is that this pattern can reveal the mechanical properties of convergence.

However, comparing the two regions' results indicates a notable difference. While both areas obtain their maximal performance at 2% RHA, Kandhkot consistently performs better than the Hyderabad region’s bricks.

5) Sugarcane Bagasse Ash:

Fig. 16 shows a well-defined and continuous trend in the compressive strength qualities of bricks made with increasing amounts of Sugarcane Bagasse Ash (SBA) in the Hyderabad and Kandhkot regions. Observing the systematic variation at incremental SBA levels of 2%, 4%, 6%, and 8% provides critical insights into the mechanical behaviour and structural integrity of the material under region-specific conditions. The results show that bricks from the Hyderabad region show a gradual increase in compression strength, peaking at 6% SBA inclusion and then decreasing slightly to 8%. In contrast, bricks from the Kandhkot region show a more gradual increase, with the peak compressive strength measured at 8% SBA. The graphical representation uses an individual colour differently, with purple bars (HBA-2 to HBA-8) representing data from the Hyderabad region and blue bars (KBA-2 to KBA-8) representing results from the Kandhkot region. This precise visual division stresses the regional differences and enables a comprehensive assessment of the physical and mechanical properties of the manufactured bricks as the outcome of SBA.

However, a significant disparity becomes apparent when comparing the performance of the two regions. While both areas reach their respective performance peaks at 2% SBA, the Kandhkot region consistently outperforms the Hyderabad region.

The strength results of bricks made from waste agro-industrial materials are frequently compared to typical clay bricks and previous studies on similar alternative materials. Traditional clay bricks are commonly used as a standard for evaluating mechanical properties such as compressive strength, durability, and density, with established standards such as ASTM or ISO specifying minimum strength criteria for construction use. Waste materials such as rice husk ash, sugarcane bagasse ash, fly ash, and sawdust have been used in brick manufacture, with performance varying based on composition, particle size, and processing conditions. Compared with previously published studies, the strength results in this study may show gains or correlate with previous findings, depending on parameters such as the proportion of waste materials used, burning temperatures, and curing conditions. The addition of unavoidable agro-industrial waste frequently improves compressive strength due to pozzolanic activity while also providing benefits such as weight reduction and improved thermal characteristics.

Additionally, these outcomes show the environmental benefits and economy of recycling these waste materials, reducing reliance on virgin clay, and advancing sustainable construction methods. However, as mentioned in previous studies, in these conditions, using these waste materials lowers compressive strength compared to traditional bricks.

These measures are intended to focus on performance gaps and increase the serviceability of such materials. In general, the results make an essential contribution to the expanding database of research on sustainable building materials, showing their feasibility and emphasising the related trade-offs and opportunities for further innovation [6, 8, 20–24].

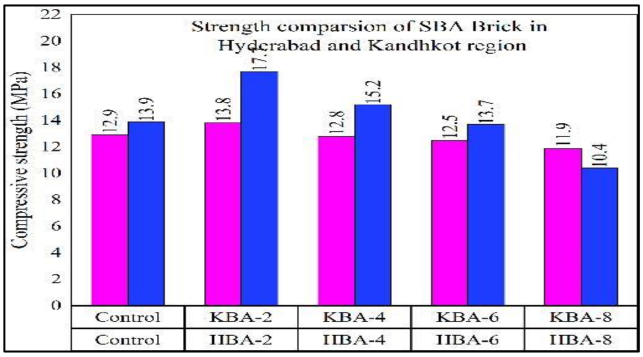

Fig. 16. Compressive Strength Comparison Of Sugarcane Bagasse Ash-Based Bricks

Based on experimental results, the brick's compressive strength is lower in RHA, SBA, and SF than in FA. This can be due to differences in their chemical composition, particle size, and reactivity, which affect the overall bonding and structure of the material. Further studies are needed to optimize the use of these materials to improve their performance and strengthen the bricks [2, 3].

3. Durability Properties of Bricks

Brick durability performance covers the capability to sustain different environmental impacts and mechanical effects except for significant degradation or breakdown over a prolonged period, significantly affecting their long life and efficiency in the construction sectors. Significantly, durability tests cover water absorption, efflorescence resistance, and tolerance tests. So, the choice of durable bricks depends on the projects that are vital for long-term construction applications, and the climate.

3.1 Water Absorption

Based on the guidelines outlined in ASTM C67-20 [28], a total of 5 bricks were selected from each of the prepared samples to undergo water absorption testing. The collective average results of these 5 bricks, obtained from both regions, have been detailed compiled and are graphically depicted in Fig. 17 and 18.

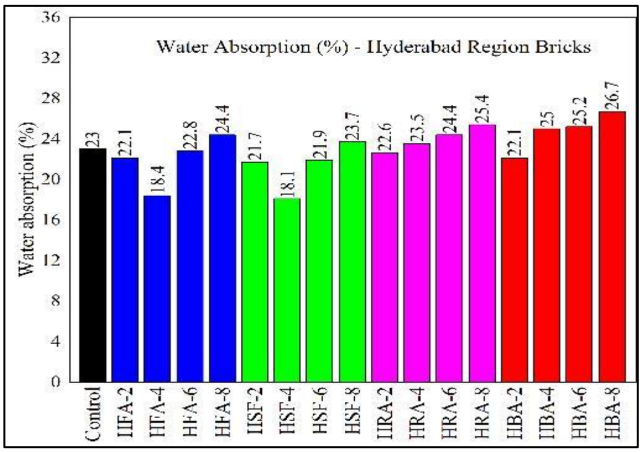

Fig. 17. Water Absorption of Hyderabad Bricks

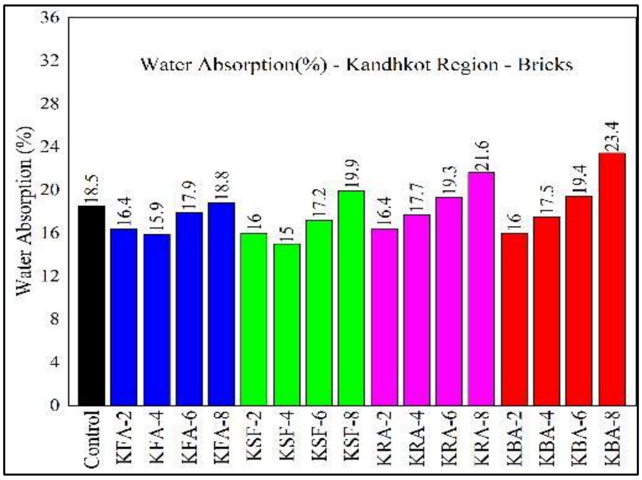

Fig. 18. Water Absorption of Kandhkot Bricks

1) Fly Ash:

Adding fly ash to clay bricks reduces water absorption significantly. The lowest water absorption rates of 18.4% and 15.9% were achieved with 4% fly ash for Hyderabad and Kandhkot, respectively (Fig. 17 and 18). However, when the fly ash content exceeds this level, water absorption gradually increases. This suggests an optimal range for fly ash content in reducing water absorption, as shown in Fig.19.

Fig. 17 and 18 highlight data points for different fly ash percentages in blue, making it easy to compare water absorption values. These graphs illustrate how fly ash affects brick water absorption and offer insights into the relationship between fly ash content and water resistance.

2) Silica Fume:

Adding silica fume to fired clay bricks significantly reduces water absorption. The optimal water absorption rates of 18.1% and 15.0% were achieved with 4% silica fume for Hyderabad and Kandhkot bricks, as mentioned in Figs. 17 and 18. However, as the silica fume content exceeds this level, water absorption increases. An optimal range of silica fume content exists for the desired reduction in water absorption in both regions, as shown in Fig.20.

Fig. 17 and 18 distinguish data points for different silica fume percentages in green. Labelled as HSF-2, HSF-4, HSF-6, HSF-8, KSF-2, KSF-4, KSF-6, and KSF-8, they represent bricks from Hyderabad and Kandhkot with silica fume added at 2%, 4%, 6%, and 8%. This graphical representation facilitates an easy comparison of water absorption values for each silica fume percentage, offering insights into its impact on water resistance.

3) Rice Husk Ash:

Introducing RHA to fired clay bricks reduces water absorption, especially at a 2% concentration.

However, as RHA content surpasses this level, water absorption increases. An optimal range exists for achieving the desired water absorption reduction with RHA.

Fig. 16 and 17 highlight data points for various RHA percentages in purple. Marked as HRA-2 to HRA-8 and KRA-2 to KRA-8, they represent bricks from Hyderabad and Kandhkot with 2%, 4%, 6%, and 8% RHA content. This graphical distinction facilitates effortless comparison of water absorption values at different RHA percentages, offering insights into RHA's impact on water resistance.

4) Sugarcane Bagasse Ash:

Adding SBA to fired clay bricks moderately reduces water absorption, especially at a 2% concentration, as noted in Fig. 17 and 18. Sometimes, there may be no significant change in water absorption compared to control bricks. However, surpassing this SBA level results in increased water absorption, indicating an optimal range for achieving the desired water absorption reduction. Fig. 16 and 17 display data points for different SBA percentages highlighted in red. These segments represent bricks with SBA additions, visually demonstrating the connection between SBA content and water absorption values.

3.1.1 Water absorption comparison

1) Fly Ash:

Fig. 19 demonstrates consistent trends in brick sample results across different Fly Ash percentages for both the Hyderabad and Kandhkot regions. Notably, Kandhkot outperforms Hyderabad, highlighted in blue for Kandhkot and purple for Hyderabad.

Analyzing this data provides insights into brick sample performance, showing Kandhkot's consistent advantage over Hyderabad. This difference may arise from various factors, including raw materials and regional conditions.

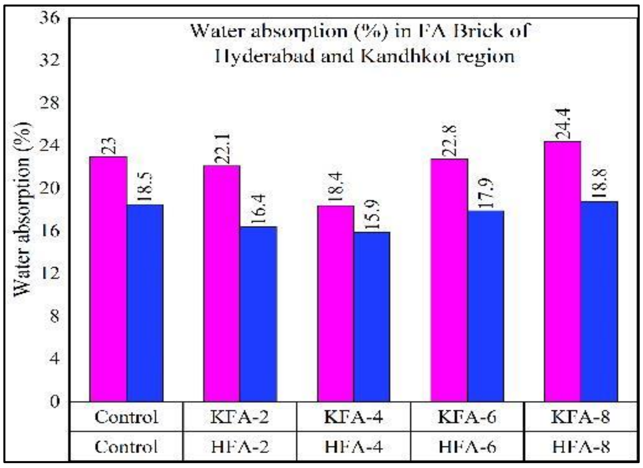

Fig. 19. Water Absorption (%) Comparison Of Fly Ash-Based Bricks

2) Silica Fume (SF):

In Fig. 20, results from both the Hyderabad and Kandhkot regions are compared across various levels of Agro-Industrial waste usage in brick samples. Remarkably, both regions exhibit consistent trends. Notably, Kandhkot consistently outperforms Hyderabad, with red data points for Kandhkot and green for Hyderabad. This analysis of Fig. 20 highlights that, regardless of waste percentages, Kandhkot consistently achieves better results than Hyderabad in brick sample performance. This trend persists despite variations in waste incorporation levels, providing valuable insights into the behavior of such brick samples.

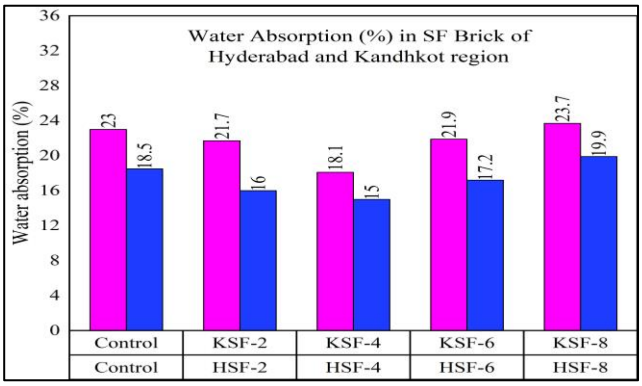

Fig. 20. Water Absorption (%) Comparison Of Silica Fume-Based Bricks

3) Rice Husk Ash:

Fig. 21 reveals a detailed comparison of results between the Hyderabad and Kandhkot regions, across various levels of Agro-Industrial waste usage in brick sample production. Interestingly, both regions exhibit consistent trends, with Kandhkot consistently outperforming Hyderabad. Blue data points represent Kandhkot, while purple denotes Hyderabad. This analysis of Graph 14 highlights the remarkable consistency in results across both regions, irrespective of variations in waste incorporation levels. Kandhkot consistently achieves more favourable outcomes than Hyderabad in brick sample performance.

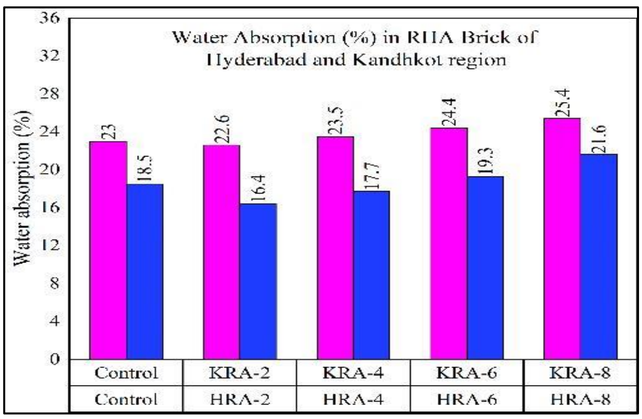

Fig. 21. Water Absorption (%) Comparison Of Rice Husk Ash-Based Bricks

4) Sugarcane Bagasse Ash (SBA):

Fig. 22 presents a detailed comparison of outcomes between the Hyderabad and Kandhkot regions, encompassing various degrees of Agro-Industrial waste utilization in brick sample production. Both regions consistently display similar trends, with Kandhkot consistently outperforming Hyderabad. Purple data points represent Kandhkot, while blue represents Hyderabad. This analysis of Fig. 22 highlights the remarkable consistency in results across both regions, regardless of variations in waste incorporation levels. Kandhkot consistently achieves more favorable outcomes compared to Hyderabad in terms of brick sample performance.

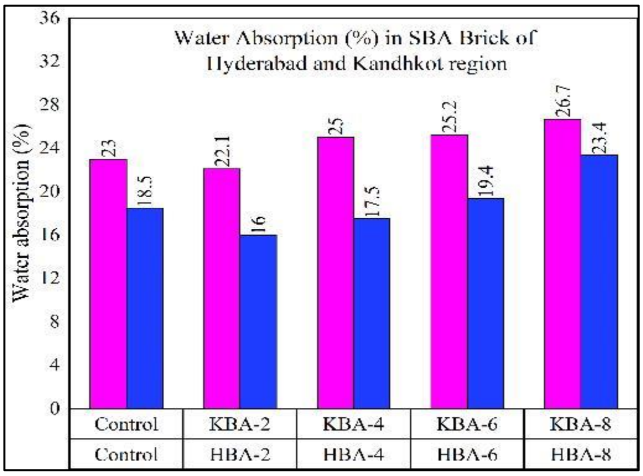

Fig. 22. Water Absorption (%) Comparison Of Sugarcane Bagasse Ash-Based Bricks

Generally, based on outcomes, water absorption of FA, SF, RHA, and SBA is different because of particle size, chemical composition (SiO2 and Al2O3 content), and sources. The maximum water absorption is attributed to fine particles and large surface area of silica fumes. Rice husk ash (RHA) and sugarcane bagasse ash (SCBA) are both porous in comparison to fly ash, which results in significant water absorption. RHA may absorb slightly more water than SCBA due to its particle characteristics; however, both have higher absorption rates than fly ash. In contrast, fly ash has the lowest water absorption because of its minimal surface area and porosity. As a result, silica fume is the most effective at absorbing water, followed by RHA and SCBA, while fly ash is the least effective[1] .

3.2 Efflorescence

In accordance with the ASTM C67-20 standard [28], an extensive evaluation of all brick samples was conducted to assess their efflorescence percentage, as shown in Fig. 23. This process involved randomly selecting five bricks from each of the prepared samples, each containing varying percentages of agro-industrial wastes. The objective was to determine the presence and extent of efflorescence, a common phenomenon in masonry construction characterized by the appearance of white, powdery deposits on the surface of bricks.

Fig. 23. Efflorescence Test

Based on experimental results, no efflorescence occurred on Kandhkot brick samples. This concludes that using agro-industrial waste materials in brick manufacturing is crucial for the visual and quality of bricks, which is also suitable for sustainability and economics. However, in the Hyderabad region, bricks showed 4% efflorescence, which is below the standard requirements as mentioned in the codes. However, bricks with 8% SBA in the Hyderabad region showed 4% efflorescence, which almost matched the control sample brick’s results. This may be due to SBA particle size, fineness, chemical composition, and physical properties such as water absorption [35, 36].

Based on the results, the efflorescence evaluation showed modifying results among both regions, but no efflorescence occurred in the Kandhkot region. These outcomes specify significant understandings of the potential low efflorescence factors related to using agro-industrial waste in brick manufacturing, specifically in various other geographical zones[38, 39].

3.3 Dimensional Stability/ Tolerance Test

Based on the IS-1077 standard, a dimensional tolerance test was conducted on all brick samples to confirm accordance with the specified dimensional tolerance limits, as shown in Fig. 24. The standard specifies tolerance limits of—/+ 80mm for length,—/+ 40mm for width, and—/+ 40mm for depth, which are critical parameters to evaluate the brick’s parameters as dimensional stability and uniformity.

Fig. 24. Dimensional Tolerance Test

Based on the outcomes of the dimensional tolerance test, incorporating fly ash (FA), silica fume, rice husk ash, and sugarcane bagasse ash resulted in slight dimensional variations that were all within IS-1077 standard limitations. Dimensions increased slightly with the addition of FA but within acceptable limits. Also, within reasonable limits, silica fume, rice husk ash, and sugarcane bagasse ash produced negligible variations[4, 6, 8]. These results indicated that brick dimensions were not significantly affected by agro-industrial waste materials. The bricks were stable and uniform. With all factors considered, they were satisfied with IS-1077 construction use standards, [20–24].

4. Conclusions

Based on the experimental results of this research, the following conclusions can be drawn:

4.1 Fly Ash

The addition of fly ash in the manufacture of burnt clay bricks resulted in an optimum enhanced compressive strength and also a reduction in water absorption performance. In both regions, including the various proportions (2%, 4%, 6% and 8%) conducted, the most satisfactory results in terms of lower water absorption and higher compressive strength were achieved when incorporating 4% of FA. In contrast to the control brick from the Kandhkot region, the modified variant with 4% fly ash exhibited a substantial 24% increase in compressive strength and a concurrent reduction in water absorption by 2.6%. Likewise, when examining the Hyderabad brick prepared at 4% FA with the control brick, there was a notable 28% enhancement in compressive strength and a significant decrease in water absorption of 4.6%.

Furthermore, dimensional stability was observed to be within acceptable parameters across all four varying percentages, and no instances of efflorescence were detected in any of the samples prepared with Fly Ash.

4.2 Silica Fume

The inclusion of Silica Fume in the production of burnt clay bricks resulted in a significant increase in compressive strength and a decrease in water absorption. Among the different percentages (2%, 4%, 6% and 8%) investigated, the most favorable outcomes in terms of lower water absorption and higher compressive strength were achieved when incorporating 4% of Silica Fume, for both regions. In contrast to the control brick from the Kandhkot region, the modified variant with 4% Silica Fume exhibited a substantial 37% increase in compressive strength and a concurrent reduction in water absorption by 3.5%. Likewise, when examining the Hyderabad brick prepared at 4% SF with control brick, there was a notable 31% enhancement in compressive strength and a significant decrease in water absorption by 4.9%.

Furthermore, dimensional stability was observed to be within acceptable parameters across all four varying percentages, and no instances of efflorescence were detected in any of the samples prepared with Silica Fume.

4.3 Rice Husk Ash

The inclusion of Rice Husk Ash in the production of burnt clay bricks increased compressive strength and decreased water absorption. Among the different percentages (2%, 4%, 6% and 8%) investigated, the most favourable outcomes in terms of lower water absorption and higher compressive strength were achieved when incorporating 2% of Rice Husk Ash for both regions. Differing from the Kandhkot region's control brick, the altered version containing 2% Rice Husk Ash demonstrated a notable 23% surge in compressive strength and a reduction in water absorption by 2.1%. Similarly, upon comparing the Hyderabad brick produced with 2% RHA to its pristine counterpart, a noteworthy 15.5% improvement in compressive strength was evident, accompanied by a minor reduction in water absorption by 1.7%.

Furthermore, dimensional stability was observed to be within acceptable parameters across all four varying percentages, and no instances of efflorescence were detected in any of the samples prepared with Rice Husk Ash.

4.4 Sugarcane Bagasse Ash

The inclusion of Sugarcane Bagasse Ash in the production of burnt clay bricks resulted in a slight increase in compressive strength and a decrease in water absorption. Among the different percentages (2%, 4%, 6% and 8%) investigated, the favorable outcomes in terms of lower water absorption and higher compressive strength were achieved when incorporating 2% of Silica Fume, for both regions. Differing from the Kandhkot region's control brick, the altered version containing 2% Sugarcane Bagasse Ash demonstrated a 27 % increase in compressive strength and a reduction in water absorption by 2.5%. Similarly, upon comparing the Hyderabad brick produced with 2% SCBA to its pristine counterpart, a 7% improvement in compressive strength was evident, accompanied by a minor reduction in water absorption by 1%.

Furthermore, dimensional stability was observed to be within acceptable parameters across all four varying percentages, and 4% efflorescence was found when 8% of Sugarcane Bagasse Ash was added.

However, it is noteworthy that the Kandhkot region demonstrated more significant improvements in compressive strength and a reduction in water absorption compared to Hyderabad. Kandhkot soil is classified as A-6, while Hyderabad soil falls under the classification of A-7-5 following the AASHTO Soil classification system. These distinct soil classes provide crucial insights into the engineering characteristics of each region's soil, aiding in construction and design decisions. The A-6 classification signifies specific properties of Kandhkot soil, guiding its use in various projects. Meanwhile, the A-7-5 classification attributed to Hyderabad soil delineates its unique attributes, assisting in understanding its behavior under different conditions.

5. Recommendations

1) Conduct a comprehensive environmental impact assessment (LCA) and cost analysis of bricks made from different waste materials.
2) Investigate the compressive strength, water absorption, and efflorescence test of high- and low-calcium agro-industrial waste materials.
3) Evaluate the long-term durability of bricks under harsh conditions such as acidic environments, freeze-thaw cycles, shrinkage, and moisture exposure.
4) Investigate the thermal and acoustic properties of alternative bricks.

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