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AN INVESTIGATION OF THE DURABILITY AND SUSTAINABILITY OF FLY ASH AND STEEL SLAG BASED BRICKS

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Abstract

Clay brick production can lead to environmental concerns as a result of extensive clay extraction and the high-temperature firing of kilns. This study investigates an alternative form of brick that incorporates the industrial by-products of fly ash and steel slag as substitutes for clay. The physical, mechanical, and durability properties of fly ash-steel slag bricks with various mix proportions were evaluated as per ASTM standards. The bricks displayed reduced water absorption of 6.63% and adequate efflorescence resistance, hardness, and soundness. Increasing the steel slag replacement of cement from 0% to 15% enhanced the brick's compressive strength from 11.4 MPa to 12.5 MPa, owing to the steel slag's cementitious properties. The mass loss from any acid attacks was only 1-2% for the fly ash-steel slag bricks compared to 5% for clay bricks due to the pozzolanic reactions. The fire endurance was also superior with a peak temperature of 300°C on the unexposed face at a 1100°C flame temperature. The optimal mix design was identified as a 15% steel slag replacement based on its strength and durability performance.

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Key words

- Fly ash,
- Steel slag bricks,
- Compressive strength,
- Water absorption,
- Durability properties.

1 INTRODUCTION

Bricks are one of the most commonly used building materials in construction projects around the world. They are manufactured by shaping a plastic mass of clay and water, which is then fired in a kiln to induce hardening (Fiala et al., 2019). Conventional clay bricks have been used for centuries, but there are some drawbacks to using this traditional material. Firstly, clay extraction causes environmental damage (Lozano-Miralles et al., 2018). Secondly, the firing process requires high temperatures and thus consumes a significant amount of energy (Yüksek et al., 2020). These sustainability issues have motivated research into alternative brick materials that utilize waste by-products from other industries (Zhang, 2013).

Two such by-products showing potential are fly ash and steel slag. Fly ash is a fine powder generated as a waste product from coal combustion in thermal power plants (Joshi and Lohita, 1997). Steel slag is a by-product of steel manufacturing. It is created when impurities are separated from the raw inputs of iron ore, coke, and limestone during the steelmaking process (Lim et al., 2016). These materials are underutilized and often sent to landfills (Guo et al., 2018). However, studies have shown that fly ash and steel slag possess cementitious properties and can be used as a building material (Gencel et al., 2021; Zhang et al., 2020).

The use of waste by-products to manufacture bricks can provide environmental and economic benefits. This research explores the feasibility of producing durable and sustainable bricks using fly ash and steel slag. These alternative bricks demonstrate a suitable performance; they can potentially replace clay bricks in many applications. This would reduce clay exploitation, minimize landfill waste disposal, lower brick manufacturing emissions and energy use, and create a value-added product from two underused industrial by-products (Chen et al., 2023; Nim and Meshram, 2020). These findings could guide other efforts to utilize fly ash and steel slag more effectively with a minimal environmental footprint (Priya et al., 2020).

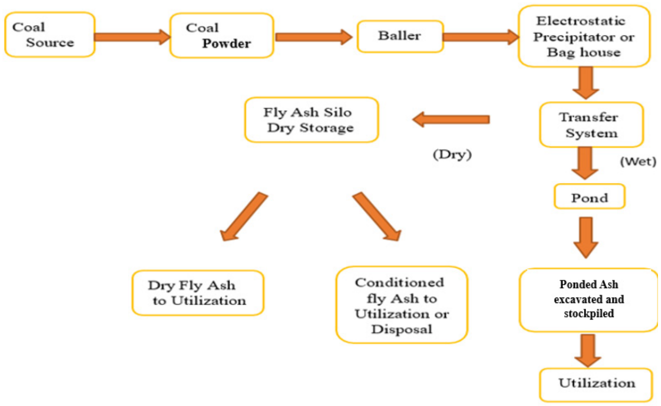

Fig. 1 *Transfer method of f y ash (dry, wet, and both)*

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Fly ash is a by-product generated from the combustion of pulverized coal in thermal power plants (Jagadish, 2007). It is a fine powder consisting of spherical, glassy particles that rise with flue gases and are collected by electrostatic precipitators (Hemalatha and Ramaswamy, 2017; Pandey et al., 2022). Fly ash has pozzolanic properties, which means it reacts chemically with lime to form cementitious compounds (Siddique, 2007). Approximately 75% of fly ash is silicon dioxide and aluminum oxide, while most of the remainder consists of iron, calcium, magnesium, sulfate, and carbon (Ward and French, 2006).

Fly ash is classified into two types based on the coal source. Class F fly ash comes from anthracite and bituminous coals, while Class C fly ash is from lignite or sub-bituminous coals (Goodarzi, 2006). Class F fly ash generally has higher amounts of silica, alumina, and iron compared to Class C (Karayannis et al., 2017). The chemical and physical characteristics of fly ash are key factors that determine its performance in bricks.

Steel slag is a by-product generated during iron and crude steel production processes. During these processes, impurities such as silicon, phosphorus, sulfur and excess carbon are removed from iron ore, coke and limestone feed materials (Lim et al., 2016). The impurity removal steps produce molten slag, which is tapped off and cooled to form a steel slag aggregate (Caijun, 2004).

The chemical composition of steel slag depends on the furnace type, steel grades, and input materials used. Major components are calcium oxide, iron oxide, silicon oxide, and magnesium oxide (Jing et al., 2020). Steel slag contains high amounts of free lime (CaO), which has cementitious properties (Tossavainen et al., 2007). After suitable processing, steel slag aggregates demonstrate good mechanical strength, resistance to abrasion and stability (Pribulová et al., 2016).

Research shows that fly ash and steel slag have shown potential to be used as replacements for natural clay in the production of bricks. Both by-products exhibit cementitious and pozzolanic properties that can impart strength and durability to bricks (Gencel et al., 2021; Zhang et al., 2020).

Studies have investigated the effects of different proportions of fly ash and steel slag on brick properties. Key parameters tested include compressive strength, water absorption, porosity, density, efflorescence, and microstructure (Nath and Sarker, 2014; Omur et al., 2022). The results show that fly ash and steel slag bricks can attain sufficient compressive strength and water resistance when optimal mixtures are used. Their improved durability is attributed to the pozzolanic reactions and filler effects of the ash and steel slag.

Researchers have also explored integrating other materials like lime, gypsum, and aggregates with fly ash and steel slag to further enhance brick properties (Demir, 2006; Rashad, 2014). The addition of binders and stabilizers aid pozzolanic reactions and the densification of the brick body. Overall, the literature demonstrates that fly ash and steel slag are technically feasible substitutes for conventional clay bricks.

The sustainability advantages of utilizing fly ash and steel slag for brickmaking have also been highlighted in various studies. Using these by-products reduces resource extraction and landfill disposal (Guo et al., 2018). Low firing temperatures and energy use also decrease greenhouse gas emissions compared to typical clay brick kilns (Kalaw et al., 2016; Yüksek et al., 2020). The conversion of waste into usable bricks is aligned with the principles of the circular economy and zero waste concepts (Duan et al., 2017).

However, there are some limitations around heavy metal leaching and expansion due to free lime in steel slag (Vaverka and Sakurai, 2014). These need to be addressed by selecting appropriate feedstock, steel slag weathering, and process control to avoid environmental issues. Overall, this research shows prudent use of fly ash and steel slag by-products, which produce sustainable and eco-friendly bricks.

This research focuses solely on analyzing fly ash and steel slag bricks. The different mixing ratios of these two materials are tested to determine the optimal mixture design. The durability tests conducted are limited to fire resistance, acid resistance, and pH exposure. Their sustainability is evaluated by comparing the waste utilization and energy consumption of fly ash-steel slag bricks versus traditional clay brick production. Their environmental impacts beyond these factors have not been studied.

2 METHODOLOGY

This chapter provides details on the materials, experimental methods, and test procedures used to investigate the durability and sustainability of fly ash and steel slag bricks.

2.1 Materials

The key materials used in this study are fly ash, steel slag, cement, sand, gypsum and alkaline activators. The fly ash was acquired from a local thermal power plant. As per the X-ray fluorescence (XRF) analysis conducted in a laboratory, the fly ash had a calcium oxide content of 8.24%, silica content of 49.55%, and alumina content of 28.02% (Table 1).

Tab.1 *XRF anaysis of fly ash*

Sr. #	Parameters	Percentage
1.	Calcium oxide (CaO)	8.24%
2.	Silica dioxide (SiO_2)	49.55%
3.	Aluminium oxide (Al_2O_3)	28.02%
4.	Iron oxide (Fe_2O_3)	4.39%
5.	Magnesium oxide (MgO)	1.86%
6.	Sulphur trioxide (SO_3)	0.48%
7.	Sodium oxide (Na_2O)	0.75%
8.	Potassium oxide (K_2O)	0.86%
9.	Alkali	1.32%
10.	Loss on Ignition	2.87%
11.	Phosphorus pentoxide(P_2O_5)	1.37%
12.	Water soluble phosphate pentoxide (P_2O_5)	0.008%
13.	Chloride (Cl)	0.019%
14.	Moisture	0.24%

The steel slag was obtained from a local steel manufacturing plant. It had a high calcium oxide content of 55% along with iron oxide (21.5%), silica (13.4%), and magnesium oxide (3.65%) as the other major components (Table 2).

Tab.2 *Chemica composition of steel slag*

Sr. #	Parameters	Percentage
1.	Calcium oxide (CaO)	55%
2.	Iron oxide (Fe_2O_3)	21.5%
3.	Silica dioxide (SiO_2)	13.4%
4.	Magnesium Oxide (MgO)	3.65%
5.	Phosphorus (P_2O_5)	1.84%
6.	Magnesium oxide (MgO)	1.75%
7.	Aluminium oxide (Al_2O_3)	1.51%
8.	Sulphur trioxide (SO_3)	0.51%
9.	Vanadium oxide (V_2O_5)	0.41%
10.	Titanium dioxide (TiO_2)	0.29%

Ordinary Portland cement (OPC) grade 53 conforming to ASTM C150 specifications was used as the source of calcium for activating the fly ash and steel slag (Kosmatka and Wilson, 2011). Locally available river sand was used as the fine aggregate after characterization of its physical properties like density, porosity and fineness modulus (Table 3). Gypsum was added as a set controlling additive. Sodium silicate and sodium hydroxide solutions were used as alkaline activators.

Tab.3 *Physical properties of the fine aggregates*

Physical Properties of the Fine Aggregates		
1	Density	1602 kg/m^3
2	Porosity	0.38
3	Fineness Modulus	2.7

2.2 Concentration of Alkaline activators:

A fixed ratio of 2.0:1 sodium silicate to sodium hydroxide was used, along with a sodium hydroxide concentration of 12 M.

2.3 Mix Proportions

As shown in Table 4, six different mixes were designed for this study. The reference mix S1 contained 0% steel slag. The mixes S2, S3, S4, S5 and S6 incorporated different proportions of fly ash and steel slag as partial replacements of cement; they ranged from 5% to 25%, according to the weight of the fly ash. The quantity of the total binding materials, sand, gypsum, and the cement and alkaline solutions were kept constant.

2.4 Preparation of Specimens

The dry constituents were first thoroughly mixed in a pan mixer for 3 minutes. The liquid components were then added, and the mixing continued for another 5 minutes to obtain a homogeneous mixture. The fresh mortar was filled in steel molds of a standard brick size (19 cm x 9 cm x 9 cm). The compaction was done on a vibrating table to remove air bubbles. The bricks were then removed from molds and cured by covering them with plastic sheets. The curing continued for 28 days at an ambient temperature prior to the testing.

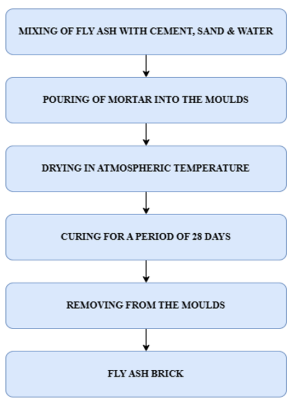

Fig. 2 *Manufacture of fly ash and steel slag brick (FASSB)*

Tab.4 *Mix Design*

Mix Design							
Sr. #	Fly Ash (kg/m^3)	Steel Slag (kg/m^3)	Sand (kg/m^3)	Cement (kg/m^3)	Gypsum (kg/m^3)	Sodium Silicate (kg/m^3)	Sodium Hydroxide (kg/m^3)
S1.	528.5	0	356.5	241	130	246.5	123
S2.	499.5	26.5 (5%)	356.6	241	130	246.5	123
S3.	473.5	52.5 (10%)	356.5	241	130	246.5	123
S4.	447	79 (15%)	356.5	241	130	246.5	123
S5.	422.9	105.6 (20%)	356.5	241	130	246.5	123
S6.	396.5	132 (25%)	356.5	241	130	246.5	123

2.5 Experimental Methods

A range of physical, mechanical and durability tests were conducted on the fly ash-steel slag bricks as per ASTM standards (ASTM 2021).

Physical properties like visual appearance, shape, size, soundness, hardness, and efflorescence resistance were evaluated. The water absorption capacity was determined as per ASTM C67 guidelines.

The compressive strength test was carried out on brick specimens as per the ASTM C62 standard to assess the mechanical performance. A minimum of three bricks was tested from each mix after 28 days of curing.

Acid and fire resistance tests were conducted to determine the durability of the bricks. Their resistance to acid attack was evaluated by immersing the bricks in a 5% sulfuric acid solution for 28 days as per the ASTM C267 method. Their structural integrity after fire exposure was tested using a furnace based on the ASTM E119 standard.

Additionally, the pH value of the bricks was checked using pH paper to detect the presence of excess alkalinity.

2.6 Analysis Methods

The results from the physical, mechanical, and durability tests were statistically analyzed to compare the performance of bricks containing different proportions of fly ash and steel slag. The mean and standard deviation values were calculated. The one-way ANOVA method was applied to determine any significant difference between the mix results. The suitability of fly ash and steel slag as clay substitutes was evaluated based on the achievement of minimum strength and durability requirements for bricks. Their environmental sustainability was assessed by comparing the raw material consumption, manufacturing energy needs, and waste utilization against conventional clay bricks.

3 RESULTS AND DISCUSSION

This chapter presents the key findings from the experimental investigation on fly ash and steel slag bricks. The results of various physical, mechanical, and durability tests are reported and discussed.

3.1 Physical Properties

Physical properties like soundness, hardness, efflorescence, water absorption, size, and shape were evaluated as per the ASTM test standards.

3.1.1 Soundness

The quality of the soundness evaluated based on a ringing sound when bricks were struck together was good for both the clay bricks and fly ash and steel slag brick (FASSB), which indicates adequate compactness (Table 5). This test demonstrates that fly ash bricks have to have a satisfactory degree of soundness (Koukouzas et al., 2011).

Tab.5 *Soundness test results*

Sr. No.	Clay brick	FASSB
1	Good	A clear ringing sound produced

3.1.2 Hardness

The hardness test made no impression on the FASSB with a finger nail similar to the clay bricks, which suggests a sufficient degree of hardness (Table 6). The surface hardness of the fly ash bricks was equivalent to that of the clay bricks (Wang et al., 2016).

Tab.6 Hardness test results

Sr. No.	Clay brick	FASSB
1	No impression after scratching with the help of a finger nail	No impression after scratching with the help of a finger nail

3.1.3 Efflorescence

While the clay bricks showed a slight to moderate degree of efflorescence, the FASSB had almost no efflorescence, which indicates a negligible amount of soluble salts [Table 7, Figure 3]. This improved efflorescence resistance in the fly ash bricks is due to the reduced free lime (Fatih & Ümit, 2001).

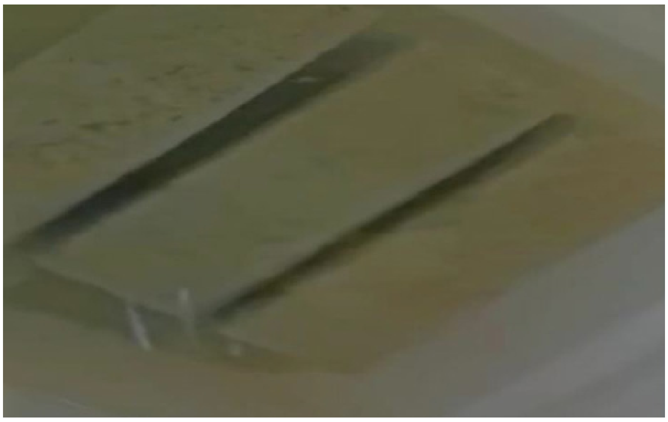

Fig. 3 Efflorescence test

Tab.7 Efflorescence test results

Sr. No.	Clay brick	FASSB
1	Slight to moderate	Almost none

3.1.4 Water Absorption

The average water absorption of the clay bricks was 11.83%, which complied with the less than 20% limit (Table 8). The FASSB exhibited a significantly reduced average absorption of 7.02% (Table 9). Lower absorption of water is beneficial to minimize dampness issues in masonry walls. The FASSB had decreased water absorption of around 8-12%, which could be attributed to filling the pores with fly ash (Nath and Sarker, 2014).

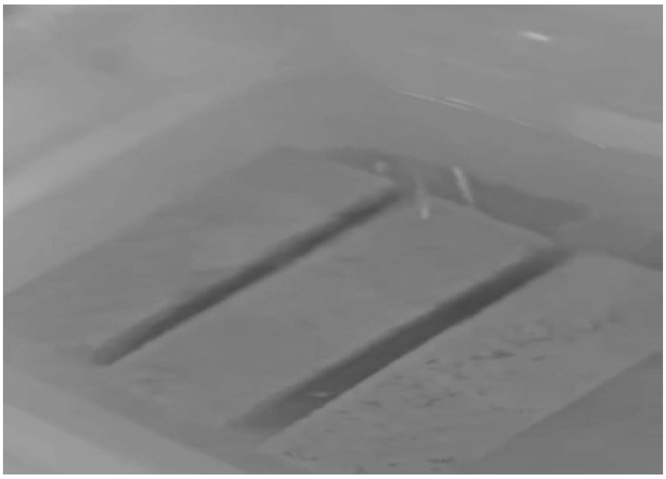

Fig. 4 Water absorption test

Tab.8 Water absorption of cay bricks

Sr. No.	Dry weight (kg)	Wet Weight (kg)	Water Absorption (g)	Water Absorption (%)
1	3.13	3.50	370	10.57
2	3.21	3.64	430	11.81
3	2.90	3.28	380	13.10
Average				**11.83**

Tab.9 Water absorption of FASSB

Sr. No.	Percentage of replacement	Average Dry Weight (kg)	Average Wet Weight (kg)	Average Water Absorption (g)	Average Water Absorption (%)
1	0 %	3.07	3.27	200	6.50
2	5 %	2.98	3.20	220	7.30
3	10 %	2.80	2.98	180	6.40
4	15 %	3.00	3.19	190	6.30
5	20%	2.95	3.18	230	7.8
6	25%	2.98	3.21	230	7.8
Average					**7.02**

3.1.5 Shape and Size

Visual observation showed the FASSB to have sharp edges and dimensional stability similar to that of clay bricks with standard lengths, widths and heights. The shape features of the fly ash bricks should have well-formed rectangular units (El-Mahllawy, 2008).

3.1.6 Brick Structure

The inner structure of the broken FASSB was homogeneous and compact without any defects, which was similar to the clay bricks. The dense microstructure improves the strength and durability properties of fly ash bricks (Anurag et al., 2021).

3.2 Compressive Strength

The compressive strength, which determines the load bearing capacity, showed enhancement when increasing the steel slag content in FASSB (Table 10). The maximum strength of 12.5 MPa was attained with 15% steel slag, which can be attributed to the cementitious properties of steel slag containing active free lime.

The pozzolanic reaction between the glassy silica of fly ash and the calcium from cement and steel slag binds the bricks (Gesoğlu et al., 2009). Finer steel slag also fills voids, which improves the bricks' strength. The reduced strength beyond a 15% replacement is likely due to excess free lime, which causes disruptive expansion (Wang et al., 2018). All the FASSB exceeded the minimum strength standard of 3.5 MPa for bricks.

The compressive strength values compare well with Poon et al., who reported a peak strength of 11.2 MPa with a 20% steel slag incorporation in fly ash bricks (Poon et al., 2001). The optimal steel slag content varies based on the characteristics of the specific fly ash and steel slag used. The strength enhancement validates fly ash and steel slag as effective clay substitutes.

Tab. 10 *Compressive strength results*

Sr. No.	Percentage of replacement material (Steel Slag)	Sample	Compressive strength (MPA)	Average (MPA)
1	Clay Bricks	C1.1	5.7	5.7
		C1.2	5.6	
		C1.3	5.7	
2	0 %	S1.1	11.3	11.4
		S1.2	11.5	
		S1.3	11.4	
2	5 %	S2.1	11.9	11.9
		S2.2	11.7	
		S2.3	12.1	
4	10%	S3.1	11.9	11.5
		S3.2	11.3	
		S3.3	11.5	
5	15 %	S4.1	12.4	12.5
		S4.2	12.9	
		S4.3	12.1	
6	20%	S5.1	11.2	11.2
		S5.2	11.4	
		S5.3	11.1	
7	25%	S6.1	10.8	10.7
		S6.2	10.6	
		S6.3	10.7	

3.3 Durability Performance

The durability of FASSB was evaluated through pH, acid attack, and fire resistance tests.

3.3.1 pH Test

To perform the pH test, the pH pencil test was adopted. Distilled water was sprayed on the surface of the bricks, and the dampened area was scratched with a pencil. The pH test detected negligible alkalinity in the FASSB with a pH of around 9, while the clay bricks had a slightly higher

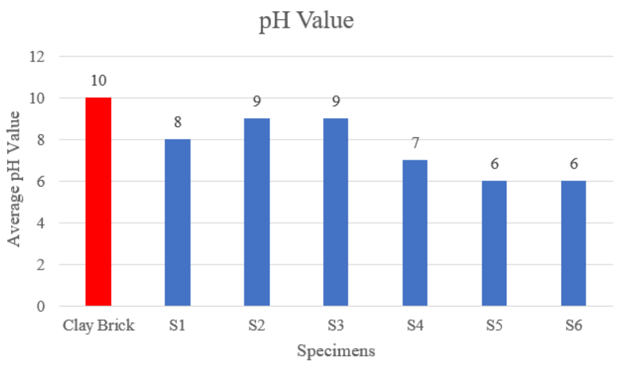

***Fig. 5** pH value of bricks*

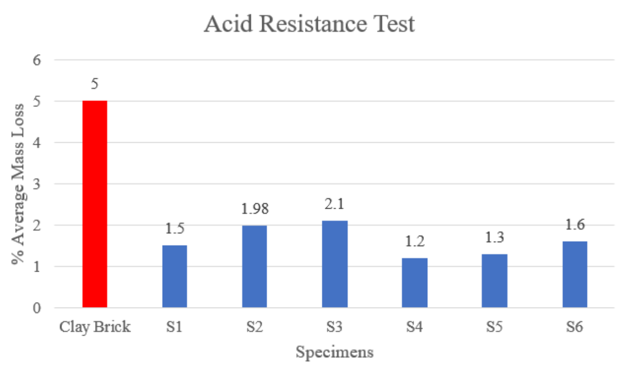

***Fig. 6** Acid resistance test*

***Fig. 7** Brick sample, acid resistance test*

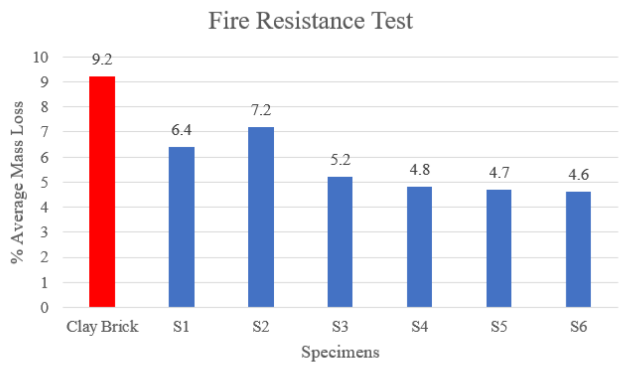

***Fig. 8** Fire resistance test*

pH of 10 (Figure 5). The minimal alkalinity in FASSB can prevent detrimental expansion and efflorescence associated with high alkali content (Pitarch et al., 2019).

3.3.2 Acid Resistance

Immersion in 5% sulfuric acid caused only a 1-2% mass loss in FASSB compared to 5% for the clay bricks after 28 days (Figure 6 and 7). The improved acid resistance of FASSB is due to the pozzolanic reaction products and polymerization formed with fly ash and steel slag (Wang et al., 2005).

The aluminum silicates combined with hydrated calcium aluminates resist acid attacks by forming insoluble compounds (Cultrone et al., 2005). The minimal acid degradation validates the durability of FASSB.

3.3.3 Fire Resistance

Exposure to a 1100°C flame increased the temperature to 500°C on the fire-exposed face of FASSB in 5 minutes. The unexposed face remained around 300°C and showed the amount of insulation (Figure 8). This exceeds the clay bricks; a 25% better thermal resistance for the fly ash bricks was observed (Pimraksa et al., 2011).

The glassy silicates, low organic content, and pozzolanic phases in fly ash enable stability at elevated temperatures (Chen and Brouwers, 2007). The results prove the fire safety benefits of FASSB.

3.4 Discussion

The physical properties of FASSB, including their soundness, hardness, efflorescence resistance, water absorption, size, and shape were found to be satisfactory and complied with the standards. As shown in Table 9, the water absorption was significantly lower at 7.02% compared to 11.83% for conventional clay bricks. Similar reductions in water absorption for the fly ash bricks of around 8-12% can be attributed to the filling of pores by the fly ash (Nath and Sarker, 2014).

The surface hardness, shape features, and ringing sound of FASSB were equivalent to those of clay bricks (Koukouzas et al., 2011; Wang et al., 2016). FASSB showed negligible efflorescence compared to the moderate efflorescence in clay bricks; the lower efflorescence in fly ash bricks was due to the reduced free lime (Fatih and Ümit, 2001).

The excellent compressive strength acquired by FASSB with increasing the steel slag content from 11.4 MPa to a peak of 12.5 MPa at a 15% steel slag replacement matches or exceeds the 5.7 MPa strength for clay bricks. Similar enhancements in strength observed with peak strength at 20% steel slag in fly ash bricks were due to the cementitious properties of steel slag (Poon et al., 2001).

Thee negligible alkalinity of FASSB with a pH of around 9 prevents harmful expansion and efflorescence issues associated with a high alkali content (Pitarch et al., 2019). The 1-2% mass loss of FASSB in an acid attack was significantly

Tab. 11 *Comparison of FASSB properties with the literature*

Property	This Study	Literature
Water absorption	7.02%	8-12% (Nath & Sarker, 2014)
Surface hardness	Equivalent to clay bricks	Equivalent to clay bricks (Koukouzas et al., 2011; L. Wang et al., 2016)
Efflorescence	Negligible	Lower than clay bricks (Fatih & Ümit, 2001)
Compressive strength	11.4-12.5 MPa	11.2 MPa at 20% steel slag (Poon et al., 2001)
Alkalinity	pH ~9	Lower alkalinity prevents expansion (Pitarch et al., 2019)
Acid resistance	1-2% mass loss	Improved due to pozzolanic products (H. Wang et al., 2005)
Fire resistance	25% higher than clay bricks	Improved stability of fly ash (W. Chen & Brouwers, 2007; Pimraksa et al., 2011)

lower than the 5% loss in clay bricks owing to the pozzolanic reaction products (Wang et al., 2005).

The thermal behavior of FASSB was superior to the clay bricks with a 25% higher fire resistance (Pimraksa et al., 2011). This is attributed to the stability of the glassy silicates in fly ash at elevated temperatures (Chen and Brouwers, 2007)

Thus, the physical, mechanical and durability characteristics determined experimentally for FASSB are well aligned and comparable with previous studies on the properties of fly ash bricks. The results validate the feasibility of using fly ash and steel slag as environmentally friendly substitutes for conventional clay bricks.

4 CONCLUSIONS

This research has aimed at investigating fly ash and steel slag bricks as a sustainable alternative to conventional clay bricks. This study analyzes the physical, mechanical and durability characteristics of FASSB manufactured with different proportions of the two industrials by-products. The key findings are summarized below:

- The physical properties of FASSB, including hardness, soundness, size, shape and efflorescence resistance were found to be satisfactory and compliant with the standards. Water absorption was significantly reduced compared to the clay bricks.

- Increasing the percentage of steel slag from 0% to 15% enhanced the compressive strength of the bricks from 11.4 MPa to 12.5 MPa, while the compressive strength decreased as the steel slag percentage increased from 15%. Owing to the cementitious properties of the steel slag, the bricks exceeded the minimum strength requirement of 3.5 MPa.

- The durability tests demonstrated the excellent resistance of the FASSB to acid attack with only a 1-2% mass loss after acid immersion compared to 5% for clay bricks. The fire endurance was also superior with a peak temperature of 300°C on the unexposed face when subjected to a 1100°C flame.

- The FASSB showed minimal alkalinity with a pH of around 9, which prevents harmful expansion and efflorescence issues.

- Based on the results, 15% replacement of cement with steel slag produced optimal properties in terms of strength and durability. The improvement is attributed to enhanced pozzolanic reactions and the formation of additional calcium silicate hydrate gel.

- Fly ash and steel slag can be effectively utilized to manufacture bricks that exceed the various physical, mechanical, and durability requirements for masonry construction applications.

- The feasibility of substituting a significant portion of clay with these industrial by-products has demonstrated, as it reduces the need for virgin clay extraction for bricks.

- Reusing fly ash and steel slag landfill waste to make durable bricks aligns with circular economy and zero waste concepts, because they provide environmental benefits.

- The lower firing requirements compared to traditional clay brick kilns reduces greenhouse gas emissions and energy usage, further improving the eco-friendly credentials of fly ash- steel slag bricks.

In conclusion, this study successfully demonstrated the feasibility of fly ash and steel slag bricks as eco-friendly, durable and value-added substitutes for conventional clay bricks to achieve more sustainable construction practices.

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