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EVALUATING PERFORMANCE OF STEEL SLAG IN ECO-FRIENDLY BUILDING BLOCK

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ABSTRACT

Traditional burnt clay bricks substantially contribute to the world's most significant environmental problems, including climate change, emissions of greenhouse gases, the depletion of fossil fuels, and the release of hazardous substances. Therefore, it is necessary to explore alternative approaches that would adequately help to achieve Sustainable Development Goals (SDGs). This study aims to evaluate the mechanical and environmental properties along with the economic benefits of a machine-made non-fired pressurised hollow block made of cement, sand, and slag (CSS) incorporating induction furnace slag (IFS) which is an industrial waste. The prepared CSS blocks have been demonstrated to have a maximum compressive strength of 10 MPa. The Life Cycle Assessment (LCA) of the produced CSS block and conventional clay bricks was carried out in seven environmental impact categories. The environmental performance of CSS block was found to be 2-3 times better than conventional bricks in all environmental impact categories. The economic comparison found that the CSS blocks could save approximately 50% more material cost than burnt clay bricks. Despite relatively lower compressive strength, the hollow CSS blocks' have promising environmental and economic outcomes. Therefore, the industrial waste incorporated CSS block has a huge potential to be used as a non-load-bearing or load-bearing unit in limited settings.

Keywords: *Induction Furnace Slag (IFS), Non-fired, Environmental Impact Assessment, Life Cycle Assessment (LCA), Economic comparison.*

1. INTRODUCTION

Brick is a common building material, especially in South Asia, contributing to 85% of the world's production (Eil et al., 2020). It has been estimated that the global output of fired bricks reached 1.5 trillion units in 2015, with 806 brick kilns currently operating across five districts within the Chittagong division (DoE, 2017). The number of kilns in Chattogram, Cox's Bazar, Noakhali, Feni, and Lakshmipur districts is 410, 83, 113, 107, and 93, respectively (The Dhaka Tribune, 2019). The brick industry in Bangladesh produces roughly 25 billion units per year, eliminating hundreds of millions of tons of topsoil, significantly affecting agricultural production and sustainable development. Furthermore, by 2050, 50 million people in the country may face food shortages due to rapid urbanization and increasing population (The Daily Star, 2016). Bricks made from waste materials and cement-based building blocks are two substitutes for conventional clay bricks that are currently being researched. These alternative techniques seek to reduce environmental pollution and carbon emissions (Islam et al., 2011; Sjunnesson, 2005).

One potential approach is to utilize the waste (slag) produced during the purification of steel scrap in steel mills for brick production. The use of waste components in concrete blocks, such as ground granulated blast furnace slag (GGBS) and demolition garbage, has demonstrated favourable environmental outcomes (Siddique, 2014). Over 400 different steel industries in Bangladesh, varying in size and category, produced 5.2 million tonnes of steel in 2022. In this process, more than 200 thousand tonnes of induction furnace slag (IFS) are produced annually, as the majority of these industries employ induction furnaces.

According to Rahman et al. (2017), industrial parks globally have been exploring supply chain solutions, particularly focusing on turning waste into resources. The steel industry has been actively seeking ways to repurpose the waste it generates. Unfortunately, current practices often involve disposing of steel waste through traditional dumping or landfilling methods, which can lead to adverse environmental impacts and increased costs for disposal (Rashad, 2019). Therefore, waste from steel mills might be used to produce bricks as a potential solution to these issues. This strategy might assist businesses in seizing market chances and thwarting risks brought on by environmental concerns. In addition, the hyper-pressing process offers a water and money-efficient way to produce chemically bound building blocks (Ahmed et al., 2022). By incorporating these innovative practices and materials, the brick industry can mitigate its environmental impact and move towards sustainable development by reducing its carbon footprint and supporting a cleaner environment.

This study aims to optimize the cost of building blocks incorporating industrial waste. The produced block is expected to be a low-cost, environmentally friendly alternative to burnt clay bricks using cement, sand, and induction furnace slag (IFS). The evaluation includes the mechanical, environmental, and economic performance of the developed eco block and compares it to traditional clay bricks using life cycle analysis. By addressing environmental issues such as carbon emissions and resource depletion and assessing structural and financial benefits, this study is intended to provide an ideal mix design for eco-blocks and guide the adoption of sustainable and economically viable materials for the construction industry.

2. METHODOLOGY

2.1 Materials

The raw materials used in this study include cement, fine sand, coarse sand, and induction furnace slag (IFS). CEM I cement was chosen due to its higher compressive strength and faster initial setting. The fineness modulus of fine sand was calculated to be 1.65, while coarse sand had a fineness modulus of 2.67. The slag, also known as iron-free slag or induction furnace slag (IFS), is a non-metallic substance made up mostly of fused oxides of silicon, aluminium, manganese, calcium, and magnesium, as well as calcium silicates and ferrites. IFS, obtained from BSRM Steel, was selected as a replacement for fine sand to reduce the effect of salinity from local sand. The IFS had a water absorption capacity of 2% and California Bearing Ratio (CBR) of 120% (BSRM, 2022). Figure 1 illustrates the particle size distribution of the fine sand, coarse sand and IFS used in this study.

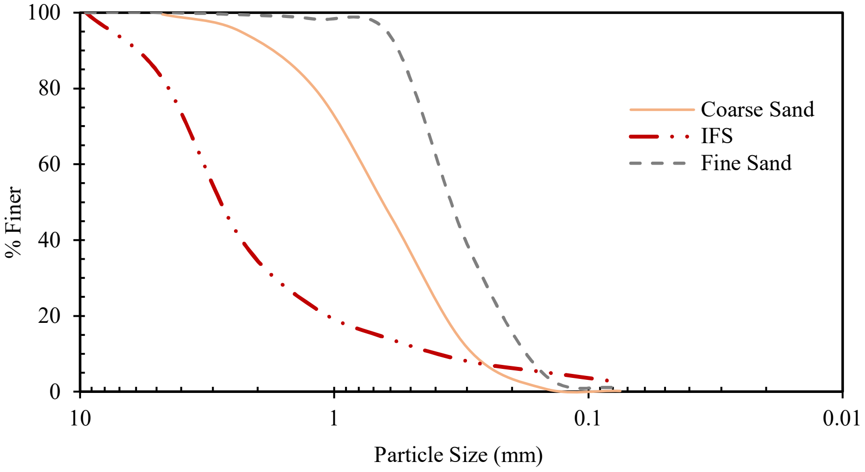

Figure 1: Particle size distribution (PSD) of Fine Sand, Coarse Sand and IFS

2.2 Mix design

The research methodology was adopted from the literature. Materials selection and proportioning were adopted with a modification from published literature. Mix design process gradually replaced fine sand with IFS and adjusted cement content to find the optimum combination of materials. Several studies, such as those conducted by Ahmed et al. (2022) and Islam et al. (2021), have adopted a comparable approach by substituting IFS with fine sand in varying proportions and had found favourable outcomes. Specimens are prepared for compressive strength, water absorption, shape and size, chloride content, and efflorescence test. Cost and environmental analysis are also conducted. The research design includes four mix designs (C16S24, C16S30, C16S36, and C18S30) with varying proportions of cement, IFS, fine sand, and coarse sand given in Table 1.

Table 1: Mix designs of building blocks used in this study

Mix ID	Cement (%)	Induction furnace slag (%)	Fine Sand (%)	Coarse Sand (%)
C16S24	16	24	25	35
C16S30	16	30	19	35
C16S36	16	36	12	35
C18S30	18	30	17	35

2.3 Laboratory Tests

The laboratory tests were performed on hollow CSS blocks after subjecting them to a concrete curing process involving water spraying twice a day for seven consecutive days. The compressive strength was determined using a compression testing machine, while efflorescence was evaluated following standard guidelines (BDS 208, 2009). Water absorption capacity was measured by comparing between oven-dry weights and after immersion underwater for 24 hours. The blocks size was measured and shape, colour, and overall appearance were assessed visually. The chloride content concentration was determined using ASTM Standard (2020). These tests provided valuable insights into the quality and performance of the hollow CSS blocks for different applications.

2.4 Environmental Assessment

The construction industry's environmental impacts and the need for sustainable methods and materials are driving the use of Life Cycle Assessment (LCA) to evaluate environmental indicators. Accurate conclusions depend on high-quality Life Cycle Inventory (LCI) data. Clay brick production depletes topsoil and emits carbon, while CSS blocks utilize cement, sand, and slag, reducing CO_2 emissions in cement plants. The study assessed seven environmental impact categories: aquatic acidification, aquatic ecotoxicity, global warming, energy consumption, eutrophication, respiratory inorganics, and terrestrial ecotoxicity.

2.5 Cost Analysis

A comparative analysis assessed the economic viability of CSS (cement slag) blocks compared to clay bricks. A wall with dimensions of 50 feet (15.24m) by 10 feet (3m) was used for the analysis, considering four scenarios: CSS block, S-grade clay brick, machine-made clay brick, and machine-made 10-hole clay brick. Material costs and price of bricks were obtained from (PWD, 2022), reflecting current market prices.

3. RESULTS AND DISCUSSIONS

3.1 Compressive Strength Test

The compressive strength test evaluates the load-bearing capacity and structural integrity of building blocks. Figure 2 shows the increase in compressive strength over time. The samples gave varying strengths on different days. C16S36 had the highest strength increase trend, likely due to decreased fine sand and increased IFS content (Ahmed et al., 2022). The compressive strength of all specimens continued to increase until day 28, indicating that longer curing times led to stronger concrete. Furthermore, the compressive strength of the C16S24 and C16S30 differed significantly over time. The presence of moisture and salt together may contribute to the relatively reduced strength of CSS blocks, as previous studies have shown that their combination can inhibit strength gain (Foraboschi & Vanin, 2014). Water absorption, efflorescence, and chloride ion concentration tests provided additional insights. Alternatively, the better hardness of IFS compared to the sand might enhance the compressive strength.

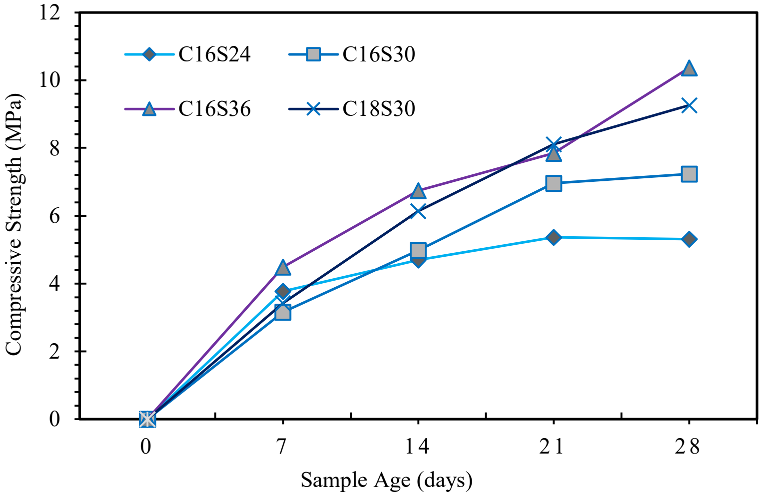

Figure 2: Improvement of compressive strength with sample age

3.2 Water Absorption Test

The specimens showed decreasing water absorption capacity as fine sand decreased and IFS increased. C16S24 had 11.1% water absorption, while C16S30 had 11.0%. C16S36 had 8.0% water absorption. According to BDS Standard (2009), the C16S36 and C16S30 mixes meet the water absorption standard for S grade blocks (<10%), while the others meet the B grade block standard (<15%).

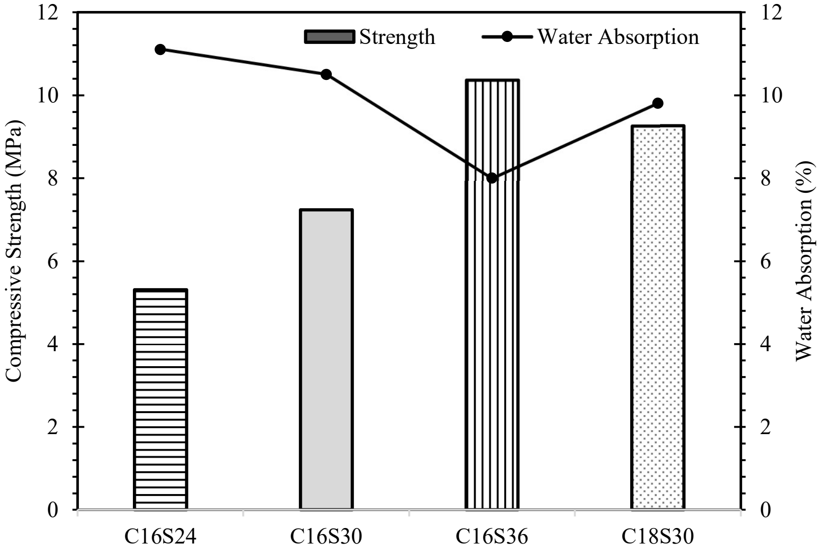

Figure 3: Water absorption compared to 28 day compressive strength of each mix design

3.3 Efflorescence and Chloride Content Test for Aggregates

The efflorescence resistance of building blocks C16S36 and C18S30 showed slight efflorescence. The other two designs exhibited moderate efflorescence (30-40%). Blocks were examined after 56 days. The efflorescence test results are given in Table 2, indicating the level of efflorescence observed for each mix design. Three 100g samples were taken from fine sand, coarse sand, and IFS for the chloride content test. The results of the chloride ion test are shown in Table 3. The fine sand showed a significant amount of chloride content due to its source proximity to the sea Bay of Bengal.

Table 2: Efflorescence test results

Mix Design	Efflorescence after Day 7	Efflorescence after Day 56
C16S24	Nil	Moderate
C16S30	Nil	Moderate
C16S36	Nil	Slight
C18S30	Nil	Slight

Table 3: Concentration of Chloride ion in fine, coarse sand and IFS

Material	Chloride Ion in ppm
Fine Sand	150
Coarse Sand	15
Induction Furnace Slag	26

3.4 Appearance Test

The shape, size, and colour test randomly selected 12 blocks from the sample pool. Measurements and visual inspections were conducted to evaluate the conformity and uniformity of the blocks. The dimensional measurement results demonstrated satisfactory outcomes, with minimal variations in size (below 5% from expected dimensions) and consistent colour. Only 4 out of 120 samples showed cracks or defects, possibly caused during transportation of around 30 km from the industry to the laboratory. The appearance test indicated that the building blocks produced in the study had an excellent physical appearance and dimensional accuracy, making them suitable for construction. Figure 4 shows samples of hyper-pressed blocks produced in a factory using an automatic machine.

Figure 4: Appearance of CSS Blocks

3.5 Effect of salt and moisture

It was observed that the water absorption capacity increased with higher fine sand content, which also contributed to the presence of chloride ions and salt content in the blocks. The salts could lead to sub-florescence and efflorescence, posing long-term mechanical risks (Foraboschi & Vanin, 2014). Furthermore, moisture absorption can adversely affect the compressive strength of masonry (Sathiparan & Rumeshkumar, 2018).

Notably, most of the bricks showed moderate to high levels of white efflorescence during compressive strength testing. This factor could explain the relatively low strength obtained, as previous research has shown that replacing some aggregate with IFS can result in higher compressive strength levels (Ahmed et al., 2022). However, significant strength gain was not observed in this case, emphasizing the importance of considering the effects of moisture, salt crystallization, and efflorescence on block mechanical behaviour (Peng et al., 2013). The source of salt in the specimens could be the water used and the IFS, with the block manufacturing plant located about 4 km from the sea.

Despite this, according to the relevant IS codes (2185-2 and 3952) and ASTM C129 (2022), the compressive strength of the blocks met the minimum requirements for load-bearing and non-load-bearing structures, making them suitable for two-story buildings as load-bearing units and all types of non-load-bearing units.

3.6 Environmental Impact

A life cycle assessment (LCA) was conducted in this study to evaluate the energy and environmental performance of the block and traditional brick. The LCA considered seven impact categories and found that CSS blocks have environmental benefits compared to clay bricks. The details of LCA analysis process can be found in (Islam et al., 2023). Clay bricks, widely used for their durability and aesthetic appeal, undergo energy-intensive processes, including mining, milling, extrusion, drying, and firing.

The production of clay bricks has various environmental impacts, such as releasing harmful substances into the environment and consuming land, fossil fuels, and energy (Vosloo et al., 2016).

CSS blocks are made from CEM I, locally sourced fine sand, coarse sand, and IFS. The C16S36 mix was used as a reference to evaluate the environmental footprint of CSS blocks. An ecological advantage comparison was made between CSS blocks and clay bricks of equivalent dimensions. Since the dimensions of the two materials differ, the equivalent size of a brick was considered. CSS blocks offer environmental benefits by reducing industrial waste, carbon dioxide emissions and using less natural resources compared to clay bricks. IFS used in CSS blocks, contributes to waste reduction and provides a sustainable solution for the production of construction material. The environmental impacts are shown as percentages compared to equivalent clay bricks in Table 4 and Figure 5. The figure illustrates a significant reduction in environmental impact across various categories, including terrestrial and aquatic ecotoxicity, respiratory inorganics, and aquatic acidification. There is a moderate reduction in global warming and energy consumption, along with the least reduction in eutrophication compared to clay bricks. It is important to note that the environmental impact reduction occurred in all seven categories, representing a significant step toward reducing the environmental impact of the construction sector and achieving sustainability (Islam et al., 2023)

Table 4: Comparison of environmental impact of CSS block and equivalent clay brick

Impact Category	Unit	1000 Equivalent Clay Bricks	1000 CSS Block
Aquatic acidification	kg SO_2 eq.	9.63	3.22
Energy consumption	MJ primary	21716	13564
Global warming	kg CO_2 eq.	1696.7	1268.9
Eutrophication	kg PO_4	0.426	0.413
Respiratory inorganics	kg $PM_{2.5}$ eq.	1.061	0.099
Aquatic Ecotoxicity	kg TEG water	192526	51969
Terrestrial Ecotoxicity	kg TEG soil	52341.9	142.4

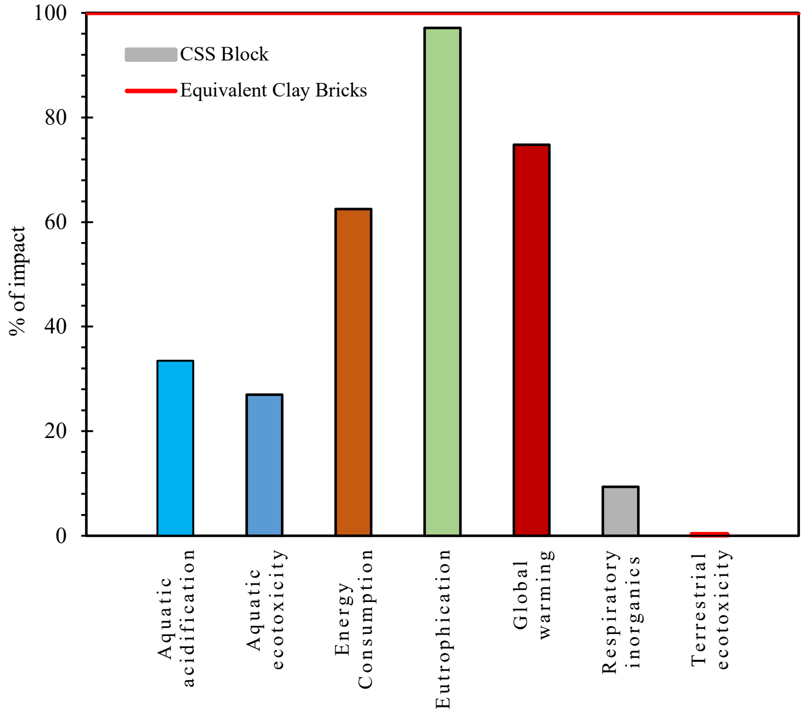

Figure 5: Comparison of CSS Blocks vs Clay bricks in all seven environmental impact categories

3.7 Cost Analysis

For economic analysis, the cost of a block was considered in four main sectors, viz. raw materials, energy consumption, maintenance and human resources, and marketing. Ahmed et al. (2022) considered electricity and labour accounting for around 18% and marketing expenses around 12% when estimating building block costs. In another study, energy and electricity were reported to be approximately 26% of brick costs, with labour and maintenance accounting for 11.5% (Youssef et al., 2020). Figure 6 shows the economic allocation and the total cost of the CSS block used in this study. The mix design C16S36 was considered as the reference block.

As shown in Figure 6, CSS blocks in the reference wall instead of traditional clay bricks can be 50% cost-efficient. Compared to the other two types of bricks, this savings could even go up to 130%. The choice of construction materials is crucial for the environment and long-term sustainability of a building. While cost may tempt the owner to use cheaper alternatives, the advantages of sustainable eco-blocks like hollow blocks could be achieved by setting government regulations for their use. Hollow blocks can also reduce heating and cooling needs due to their low thermal conductivity, resulting in a lower carbon footprint and energy savings (Caruana et al., 2017; Sathiparan et al., 2014). Moreover, their lightweight and manageable nature makes them ideal for efficient construction projects, and their durability reduces the need for frequent maintenance and repairs.

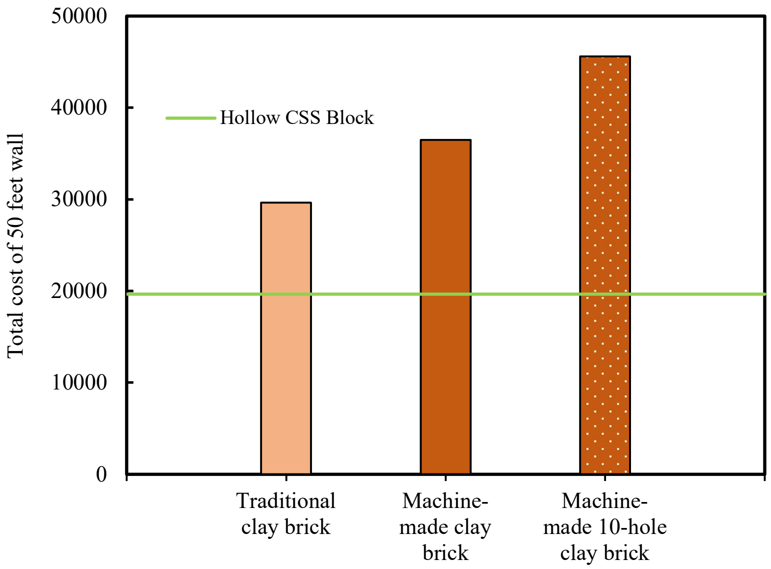

Figure 6: Cost comparison between different bricks and CSS block

4. CONCLUSION

This study evaluated the physical properties of non-fired hyper-pressed hollow CSS blocks compared to conventional fired clay bricks. The study also performed LCA and cost analysis. The strength of CSS blocks was found to improve with the IFS level. The water absorption is reduced with an increase in IFS level and improvement of compressive strength. CSS blocks are environment friendly, making waste to resources, reducing carbon dioxide emissions, and natural resource use. Compared to traditional bricks, CSS gave an average reduction of 56% in the seven environmental impact categories. With their larger size and lower density than regular bricks, CSS block requires less quantities, and approximately 50-130% overall cost reduction may be possible for masonry wall construction. In addition, the hollow blocks are expected to be more thermally efficient, reducing the cost of heating and cooling inside the building. Overall, CSS blocks are a sustainable alternative to fired clay bricks in terms of engineering, economic, and environmental aspects.

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