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NON-FIRED BUILDING BLOCKS USING INDUSTRIAL WASTES

G. M. Sadiqul Islam*[1], Sudipta Sarker[1], Monower Sadique[2] and Ali Abdulhussein Shubbar[2]

[1]*Department of Civil Engineering, Chittagong University of Engineering & Technology, Bangladesh*
[2]*Department of Civil Engineering, Liverpool John Moores University, Liverpool L3 3AF, UK*

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ABSTRACT

Bricks produced from traditional techniques and agricultural clay contribute considerably to the air pollutions in the world. Therefore, an urgent need to start using an environment-friendly alternative material/approach to save the fertile topsoil and conserve a clean environment. This research is aimed to produce non-fired bricks incorporating industrial solid waste from steel and power plants, including Fly ash and Ladle Furnace Slag (LFS), as a partial replacement of CEM I and lime. Induction Furnace Slag (IFS) is used as a partial/full replacement of natural fine aggregate (local sand) in the laboratory scale manufacturing process. The prepared building blocks conform to the minimum compressive strength requirement of 10.3 MPa per ASTM C62 and BDS 208 while the maximum compressive strength was 40.6 MPa. This highly promising performance pronounced the use of industrial waste materials in non-fired brick production to achieve a cleaner environment for a sustainable society..

Keywords: *Ladle Furnace Slag (LFS), Induction Furnace Slag (IFS), Fly Ash, Industrial Waste management, Building block, Sustainability.*

1. INTRODUCTION

People have been using bricks as an essential building construction material for thousands of years for their manifold superiorities over other earthen construction materials. Clay bricks dating back to 10,000 BCE, was found in Egypt, which was hand-moulded and sun-dried. The historic city Ur adopted clay bricks as the primary construction materials around 4000 BCE. Archaeological evidence has been found traced back 5000 BCE on the use of fire to produce clay-based bricks for better performance. The brick industry has been on continuous development using modern machinery, such as powerful excavation equipment, motors, tunnel kilns. One thousand five hundred billion units fired brick production was estimated in 2015 globally (Climate and Clean Air Coalition, 2016). Despite the workability of conventional brick production, fired clay brick production consumes a considerable amount of virgin resources and energy. In the production of 1-tonne brick, an estimated 706 kWh energy is required, and 0.15-tonne carbon dioxide (CO_2) is being emitted (Carbon Trust, 2011). This considerable energy consumption and carbon footprint is a barrier to achieve sustainable development.

Apart from that, the construction contributes to a loss of 1% of agricultural land annually in Bangladesh. Approximately 80% of this loss is due to unplanned rural housing also over 17% for brick kilns. Excavation per hectare of fertile topsoil could cause up to Tk. 3.1 million economic loss (Ahmed, Hassan and Islam, 2021). The brick industries in this country produce approximately 25 billion units every year by eliminating 100 million tons of topsoil, considerably affecting agricultural production and achieving sustainable development. About 50 million people might face food shortages by 2050 when the population of the country is expected to reach 245 million (Correspondent, 2018). An annual 80 million tonnes of CO_2 emission is estimated for this country, of which ¼ is accounted for only 7,900 registered (constructed following proper design and environmental rules) conventional brick kilns. The unregistered traditional brick kilns are even higher than the reported numbers. These kilns also consume three million tonnes of wood and 5 million tonnes of coal annually (Hossain, 2017). In Dhaka, 58% of air pollution is accounted for conventional brick kilns.

A survey by the Department of Environment (DoE) of Bangladesh during 2013-18 found brick kilns were contributed highest air pollution in seven major cities of the country. Narayangonj has the most polluted air, followed by Dhaka. During the production (dry) season, November-April, the air quality of these metropolises becomes extremely unhealthy by emitting a lot of particles into the air. Another study with Norwegian Institute for Air Research (NILU), DoE conducted during 2013-16 in Dhaka, and Chattogram city found that 58% of the primary air pollutants (Particulate Matter 2.5) originate from the conventional brick kilns. Therefore, the country

*Corresponding Author: *gmsislam@cuet.ac.bd*
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requires an immediate urgent need to use environment-friendly alternative bricks to conserve the environment and save its fertile topsoil. Furthermore, turning to alternatives like compressed or thermal blocks incorporating waste residues is crucial in ensuring food security and sustainable development.

Studies have been conducted to produce sustainable bricks to minimize the enormous carbon footprint from this conventional clay brick making industry, considering environmental and economic issues (Preethi and Venkatarama Reddy, 2020). An alternative to conventional bricks could be cement-based building blocks from Ordinary Portland Cement (OPC). However, cement clinker production is highly energy-intensive; 1 kg clinker requires 1.5 kWh energy and releases about 1 kg of CO_2 to the atmosphere (Islam *et al.*, 2011). In addition, the aggregates are obtained from quarrying and thus have the same issues as a clay-based brick. Current global waste generation volumes are approximately 1.3 billion metric tons per year and are expected to increase to 2.2 billion metric tons by 2025. To reduce environmental pollution, decrease the amount of generated wastes and preserve virgin materials, thereby contributing to sustainability; researchers have made remarkable efforts to develop different bricks from various types of waste materials.

In the near future, coal-burning power plants will be the primary source of power generation in Bangladesh. The current power generation of the Barapukuria coal power plant is 525 MW, and approximately 1,09,200 Metric tonnes of fly ash is being generated every year (Tamim, Dhar and Hossain, 2013). Few of the local cement companies use fly ash to produce blended cement. However, they use imported fly ash as the local fly ash cannot be transported cheaply, and the ash management is not good. The situation will worsen once three other under-construction coal-burning power plants come into the complete generation of 3840 MW. Considering a linear interpolation, the annual production of fly ash will rise to 865,000 MT per annum from 2024 onwards. For a densely populated country like Bangladesh, this volume of fly ash is an enormous amount to dispose of. Considering the chemical composition of Fly ash, incorporating it in non-fired eco-friendly brick can be a two-way solution for this problem (Petrillo *et al.*, 2016).

Bangladesh has over 400 steel mills of different categories and sizes with over 4 million tons annual production. Most of the Bangladesh steel industries use induction furnaces that produce approximately 3.2 million tons of steel every year and 250 thousand tons of Induction Furnace Slag (IFS) (Rahman *et al.*, 2017). About 60–80 kg of Ladle Furnace Slag (LFS) is recovered to refine each ton of steel (Papayianni and Anastasiou, 2012). Some of this amount reintroduce in the production process. However, a considerable amount of LFS is dumped as a landfill. In addition, the chemical composition of the powder-like material indicates its potential as a supplementary cementitious material.

The supply chain, e.g., waste-to-resources, has been thoughtfully considered in many industrial parks around the globe (Rashad, 2019). However, conventionally dumping or landfilling the steel waste as management practice would negatively impact the surrounding environment, including further pollution. This practice also requires the excess cost to dispose of. The incorporation of steel mills waste materials in brick production could be a potential solution for managing these hazardous residues. Thus, strategic industries can take advantage of market opportunities and neutralize threats arising from environmental issues. This research aims to explore different options to produce non-fired brick/building blocks from several industrial solid wastes, including fly ash, LFS by complete or partial replacement of cementitious media such as Portland-based cement and lime powder. In addition, IFS is used to replace sand in the medium.

2. MATERIALS AND METHODS

2.1 Materials

Characterization of the raw materials is described, and then the performance of the material composition in the pressurized building block preparation system was evaluated in terms of compressive strength. Industrial wastes- LFS and fly ash is used as a supplementary binder in the production of the building block. Another steel industry waste material, IFS is used as filler/fine aggregate. CEM I, building lime, and local sands are other associated materials used in this research.

CEM I of strength class 52.5N with fineness 99.3% (#200 sieve) and building lime (passing through 1mm sieve) obtained from local sources. Fly ash is obtained from the Barapukuria coal-burning power plant in Bangladesh, while the LFS and IFS are collected from BSRM Steel Mills Ltd., Bangladesh. The building block is prepared using a maximum of 73% fly ash (of total binder content). The LFS passing through a 2mm sieve is used as a binder. Induction furnace slag (IFS) of two different sizes (0-4 mm; FM 2.33 and 4-8 mm; FM 3.54) is collected from BSRM steel mills Ltd. It is used as a full or partial replacement of sand. A maximum of 60% IFS (both same size proportion) of the total dry mix is used in the building block preparation. The local sand used for the study was prepared according to graded sand requirements ASTM C778-17.

2.2 Particle size distribution (PSD)

The particle size distribution of binders (CEM I, fly ash, LFS, and building lime) is obtained using a LASER particle size analyser. Approximately 1g of sample (fly ash/LFS) is dispersed in water using an ultrasonic attachment in the sample vessel of the equipment. For CEM I and lime, the material is dispersed in propanol (to prevent reaction). Commercial software is used to create particle size distributions from the degree of scattering of a collimated, monochromatic, dual laser beam (red and blue) passing through the mixture of sample and solvent. At least three measurements are carried out for each sample. Although repeated distributions are similar for a given material, an average distribution result of these, created by the computer software, is reported. Figure 1 shows the combined PSD of CEM I, fly ash, LFS, lime, and IFS after 1-hour grinding. The mean size of CEM I (22.77 µm) and fly ash (20.1 µm) was found similar. However, the other two binders, building lime (49.37 µm) and LFS (59.2 µm), gave a much larger mean particle size.

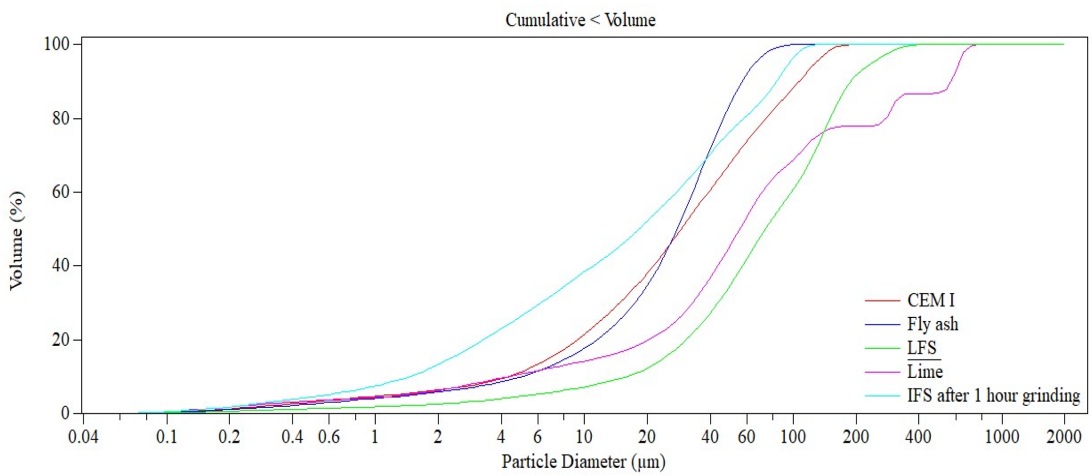

Figure 1: Particle Size Distribution of CEM I, Fly ash, LFS, Lime and IFS

2.3 Chemical compositions of materials

The chemical compositions of fly ash, steel slags (IFS and LFS) and other binders are determined using X-ray Florescence (XRF) technique. All these works are conducted at the Department of Pharmacy, Liverpool John Moore University, England. The chemical composition of fly ash satisfies the criteria of being low calcium fly ash (Class F) according to ASTM C618. In addition, the chemical composition of LFS shown in Table 1 conforms to that found in literature elsewhere.

Table 1: Chemical composition of materials used in this study

Materials	CaO %	SiO_2%	Al_2O_3 %	Fe_2O_3 %	MgO %	Na_2O %	K_2O %	TiO_2 %	MnO %
IFS	4.92	46.80	6.58	16.35	3.22	1.50	0.33	1.05	7.52
FA	0.71	52.92	17.12	2.58	0.43	0.32	0.77	2.78	0.01
Lime	93.26	1.085	0.56	0.66	0.75	1.93	0.09	0.11	1.01
LFS	47.44	29.35	5.57	0.74	2.27	1.57	0.09	0.89	1.61
Cement	64.38	22.36	4.59	2.81	2.08	1.52	0.72	0.63	0.04

2.4 Morphology analysis by SEM

Figure 2 shows high magnification ESEM micrographs of the materials used in this study. SEM mode with an accelerating voltage of 15 kV combined with a Links System Si(Li) X-ray detector is used. Selected samples are also analysed using the Energy-dispersive X-ray spectroscopy (EDX) mode at 20 kV voltage to identify the nature of crystalline deposits on their surfaces. Double-sided adhesive carbon tape is secured to a 10mm diameter aluminium stub, and the sample is sprinkled on it. Specimens are coated by Pd-Au alloy vapour to prevent charging during the test.

The SEM image of CEM I is shown with a scale bar. Rest images were capture with the same magnification. As shown in Fig. 2, building lime particles are much smaller than CEM I. The fly ash was spherical with a cleaner surface, while LFS has an irregular shape with whitish deposits on its surface. The IFS is showing broken surfaces as it is obtained through ball milling.

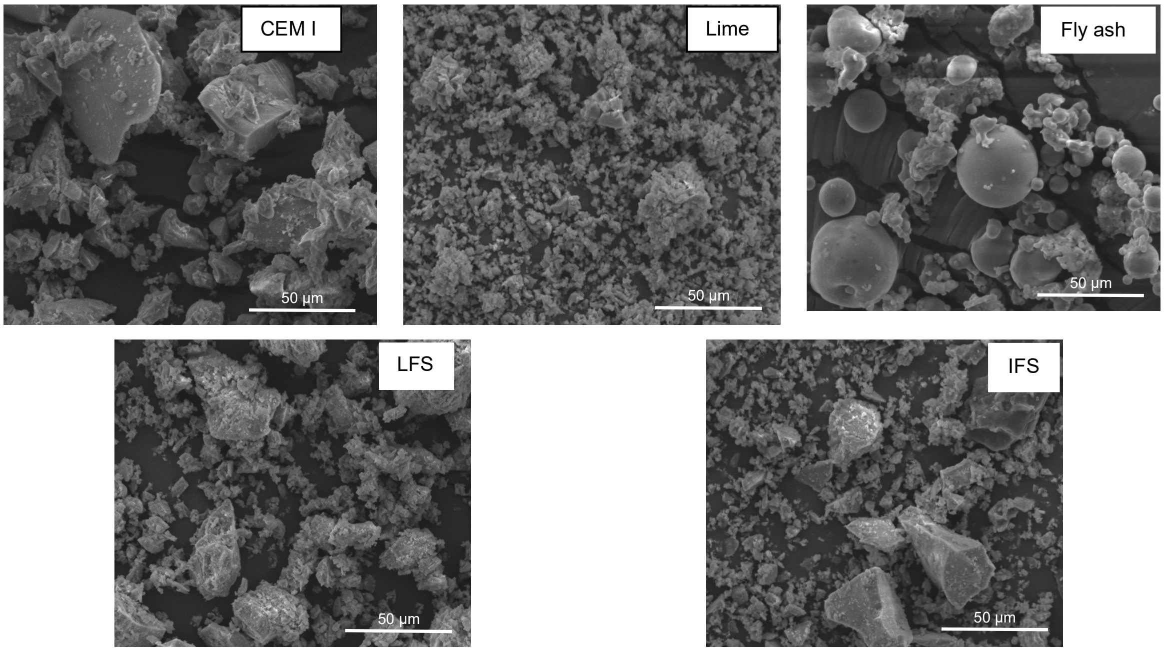

Figure 2: SEM images of materials used

2.5 Mix Details and Preparation of Building Blocks

Mix details of the fly ash-based and high-pressure building block are given in Tables 2 and 3, respectively. The required materials for building block preparation are first taken in an automatic pan mixer of 50 kg capacity. The mixer is kept rotating at a constant speed by a 1.5 kW motor. All the materials except water were mixed for 30 minutes. After adding water, the mixing process is continued for another 30 minutes. The quantity of water is added so that no water comes out after squeezing by hand from the mix, but moisture can be palpable in hand after finishing the mix. While the mixing continues, a further small quantity of water is also added if required (record also taken). As pressure is applied to compact the building blocks lowest possible amount of water (maximum amount of water used is 15.7% of total dry mix) is added in the mixing stage. An excess amount of water could bleed out while applying pressure.

Table 2: Mix details of fly ash building blocks (kg/m^3)

Batch ID	Water	Binder			Fine Aggregate	
		Fly ash	Cement	Lime	Local sand	IFS
IF100C7.5LP7.5	248.0	651.0	122.1	122.1	---	732.4
IF67C7.5LP7.5	254.7	648.3	121.6	121.6	240.7	488.7
IF33C7.5LP7.5	254.7	648.3	121.6	121.6	488.7	240.7
IF00C7.5LP7.5	248.0	651.0	122.1	122.1	732.4	---
IF100C5LP10	234.4	656.4	82.1	164.1	---	738.5
IF100C10LP5	234.4	656.4	164.1	82.1	---	738.5

(IF100C7.5LP7.5 contains 100% IFS as fine aggregate; 7.5% cement and lime each and 40% fly ash as a binder of the total dry mix by weight)

Table 3: Mix details of high-pressure building blocks (kg/m^3)

Batch ID	Water used	Binder		Fine Aggregate	
		LFS	Cement	Local sand	IFS
C10L05S25	159.6	111.4	222.7	556.9	1336.4
C10L10S20	163.1	222.4	222.4	444.8	1334.4
C10L15S15	163.1	333.6	222.4	333.6	1334.4
C7.5L7.5S25	149.2	167.8	167.8	559.5	1342.7

(C10L05S25: 10%, 5%, and 25% of the total dry mix are CEM I, lime, and local sand, respectively. 60% of total dry mix was IFS. All quantity as weight basis)

2.6 Casting and curing of the building block

A mould of surface dimension 9″×4″ (230mm×102mm) is used for building block casting. The finished height is around 75mm. About 3.3 kg of freshly mixed materials is required for each fly ash building block preparation. For a high-pressure building block, approximately 4.2 kg mix was required. Fly ash blocks are greyish while high-pressure block without fly ash is brownish. Figures 3 and 4 give the compaction machine with its application for building block preparation.

Constant bar pressure is applied by hydraulic jack three times, summing a total of 11 seconds (5s+3s+3s). In total, 70 and 200 bar pressure are used for fly ash and high-pressure building blocks. After casting, the blocks are taken from the mold instantly and kept at ambient temperature for 12 hours. Then those are kept underwater for seven days. On day eight, the samples are taken out of the water and kept at room temperature for the next 14 days. However, during this period, the blocks are immersed in water for 1 minute, at an interval of 8 hours. Then simple air curing was continued for the last seven days before testing at 28 days. Figure 5 shows the curing process of the building block samples. The pattern of curing was developed and followed to optimize curing cost considering strength gain patter earlier.

Figure 3: Building block casting machine

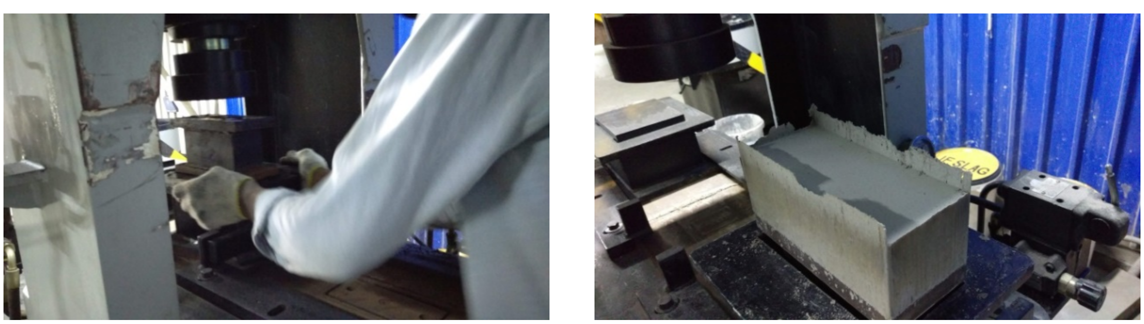

Figure 4: Pressure applying and casting

(a) Building blocks kept at ambient temperature (b)Water curing of Building blocks (c) Blocks after immersion in water for 1 minute

Figure 5: Curing process of building blocks

2.7 Water Absorption and Compressive Strength Test

The water absorption is calculated as the difference in weight after seven days of water curing and its weight before water curing and expressed in percentage. The compressive strength of a material is the uniaxial compressive stress reached when the material fails. For building blocks, three blocks were tested in each case, and the average value of these three was reported as per ASTM C39-18.

(a) Compression test set up (b) Fly ash block (c) High-pressure block

Figure 6: Compressive strength test and failure planes of building blocks

3. RESULTS AND DISCUSSIONS

3.1 Fly Ash Based Building Blocks

Fly ash incorporated building blocks are prepared using a ternary combination of CEM I, fly ash, and lime as a binder with IFS and local sand as fine aggregate. Table 4 gives details of binder and fine aggregate combination and their corresponding compressive strength. Among these combinations mentioned, IF00C7.5LP7.5 gives the maximum compressive strength of 18.5 MPa and 40.6 MPa at 7 and 28 days. The sample incorporated 100% IFS (45% of total mix content) as fine aggregate, while the rest, 55% of the mix, includes 40% fly ash and 7.5% CEM I and lime each. With a gradual increase in CEM I content, 28 days compressive strengths are increased. For a fixed content of binder (fly ash, lime, and cement) highest strength is obtained with local sand as fine aggregate.

Table 4: Compressive strength of fly ash-based blocks

SAMPLE	Materials, % of total dry mix						Compressive Strength (MPa)	
	Binder			Fine Aggregate		water		
	Cement	Fly Ash	Lime	IFS	Fine sand		7 Days	28 Days
IF100C7.5LP7.5	7.5	40	7.5	45	---	15.2	11.8	19.1
IF67C7.5LP7.5	7.5	40	7.5	30	15	15.7	11.3	23.7
IF33C7.5LP7.5	7.5	40	7.5	15	30	15.7	14.1	26.6
IF00C7.5LP7.5	7.5	40	7.5	---	45	15.2	18.5	40.6
IF100C5LP10	5.0	40	10.0	100	0	14.3	9.2	14.4
IF100C10LP5	10.0	40	5.0	100	0	14.3	9.6	20.3

3.2 Effect of IFS and Lime in Fly ash Blocks

Figure 7 shows the variation of strength for 0%, 33%, 67% and 100% replacement of local sand by IFS. Approximately 40-50% strength is increased at 28 days from that obtained at seven days. With the gradual increase in IFS content, compressive strength decreased. At 28 days, the decrease of strength (14 MPa) is high between 0 to 33% replacements of sand by IFS. After that, the strength decreases at a slower rate, and 100% IFS (as aggregate) gives 47% strength of blocks with 100% sand (as aggregate). At seven days, the strength variation is relatively more minor. The lowest strength is obtained for building blocks with 67% IFS + 33% local sand aggregate. Building blocks used 100% IFS gives 11.8 MPa, which still satisfies the minimum strength requirement by ASTM C62-17 (standard specification for building bricks). Therefore, even if the compressive strength is lower than the local sand, 100% IFS could be used as fine aggregate to produce building blocks to apply in non-exposed weather conditions such as interior partition walls as per ASTM C62 (ASTM, 2017) requirements.

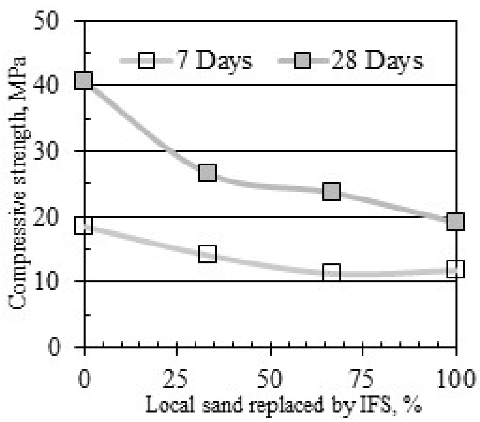

Figure 7: Compressive strength vs sand replaced by IFS (40% fly ash)

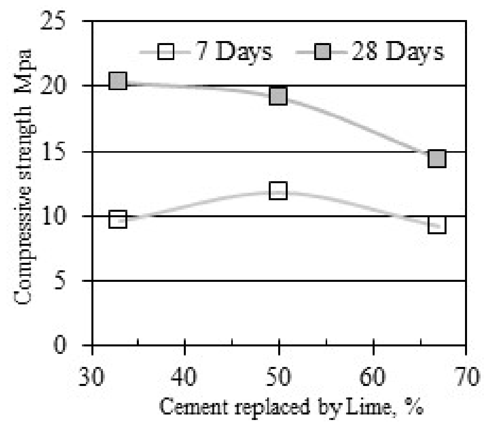

Figure 8: Compressive strength vs % cement replaced by lime (40% fly ash)

Considering 28 days compressive strength, it is evident from Figure 8 that with the increase in CEM I replacement by lime, compressive strength decreased. The 28-day compressive strength reduces to 14.4 MPa from 20.3 MPa, while cement replacement increases from 33% to 67%. However, the reduction for 50% cement replacement is minor, and therefore, it could be concluded that the lime and fly ash combination could work similar to that of cement and fly ash.

3.3 High-pressure Building Blocks

High pressure (200 bar) building blocks are prepared using 60% IFS with a limited amount of local sand (15-25%), and instead of lime and fly ash, LFS was used on a limited scale (5-15%). Table 5 shows mixed combination and their compressive strength at 7 and 28 days. Sample C10L10S20 gives the highest 7- and 28-days strength than all other batches. 10% LFS is found optimum considering the same amount of IFS (60%) and Cement (10%) are used. C10L05S25 shows the lowest 28 days strength of 29.4 MPa. Nonetheless, the average strength of high-pressure building blocks is higher than the average strength of fly ash incorporated blocks indicating a significant contribution of high pressure in obtaining compressive strength.

Table 5: Mix combination and compressive strength of high-pressure building block

SAMPLE	Mix combination, % dry mix				water content, %	water absorption %	Compressive Strength (MPa)	
	IFS	Cement	LFS	Fine sand			7 Days	28 Days
C10LRF05S25	60.0	10.0	5.0	25.0	7.2	2.6	25.2	29.4
C10LRF10S20	60.0	10.0	10.0	20.0	7.3	3.2	27.2	38.0
C10LRF15S15	60.0	10.0	15.0	15.0	7.3	3.2	25.6	34.1
C7.5LRF7.5S25	60.0	7.5	7.5	25.0	6.7	3.0	23.1	31.1

3.4 Effect of LFS content on the high-pressure building block

As shown in Figure 9, 10% LFS content gives better compressive strength performance both in 7 and 28 days. On the other hand, 5% LFS content gives the lowest compressive strength in 7 and 28 days. The strength increment rate for 10% LFS content is the highest among all the samples. For this, the 28 days compressive strength is 10.8 MPa greater than that of 7 days compressive strength.

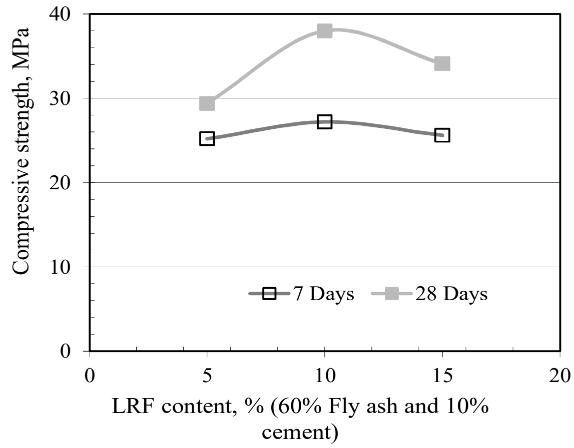

Figure 9: Compressive strength VS % LFS content

3.5 Excess water absorption and compressive strength of high-Pressure building block

The original total weight of the ingredients required to produce one building block is noted. After seven days of underwater curing, the samples were surface dried and weighted. Figure 10 and 11 shows the water absorption rate (%) and compressive strength of fly ash incorporated building blocks and high-pressure building blocks. For fly ash blocks, the highest 7-day compressive strength (18.5 MPa) is obtained for the IF00C7.5L7.5 batch, giving lower water absorption (2.8%). Generally, higher water absorption (above 3%) is obtained for the samples having low compressive strength (below 10MPa).

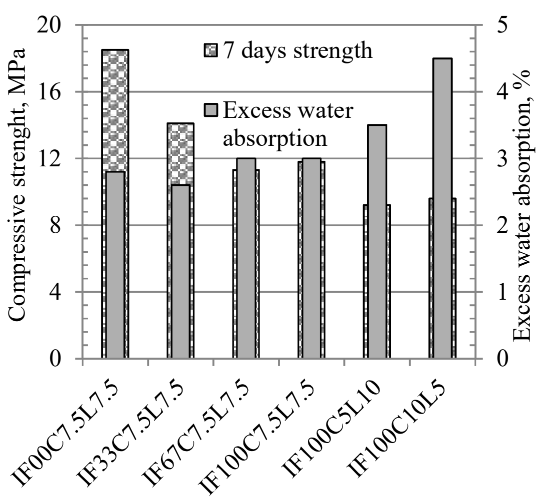

Figure 10: Water absorption (%) and compressive strength of fly ash-based building block.

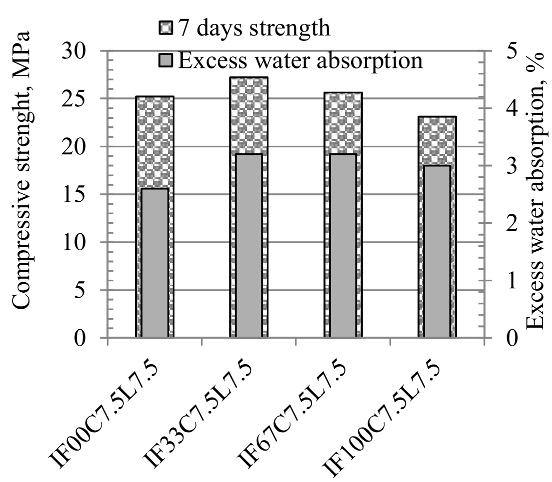

Figure 11: Water absorption (%) and compressive strength of high-pressure building block.

The water absorption is negligible (≤3%) for highly pressurized building blocks; however, no definite correlation was found between the seven days of excess water absorption and compressive strength. The highest compressive strength at seven days was found to be 27.2 MPa, for which excess water absorption is 3.2%. C10L05S25 sample gives the lowest water absorption (2.6%), for which the strength is 25.2 MPa. Though it is not the lowest seven days strength, its 28 days strength (29.4 MPa) is the lowest. The water absorption rate for every sample of the high-pressure system always gives a lower value than that of a fly ash based building block.

This is due to around 2000 psi higher pressure is applied to the high-pressure building block. In the mix, fly ash requires a higher level of water to make it workable

4. CONCLUSIONS

The research aimed to assess the feasibility of non-fired brick/building block production using waste materials. In this regard, the compressive strength of fly ash-based blocks (70 bar pressure) increases with the replacement of IFS by local sand, and maximum strength of 40.6 MPa was achieved. By applying a higher pressure (200 bar), the compaction level was improved, which increased the building blocks' compressive strength. Overall, the study with potential waste materials gave a promising indication that these materials could be used as an alternative to clay brick production with further modification. Researchers have considerable scope for further development to improve the quality of bricks. Durability tests such as chloride penetration/carbonation, water and gas permeability, dimensional performance/efflorescence, leaching of any heave metal/harmful constituents from the building blocks are required to carry out its efficient use. For pressurized building blocks, the effect of variable compaction pressures could be evaluated. Strength performance with other waste materials such as rice Husk Ash, ceramic waste could also be evaluated.

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