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Investigating the thermal properties and structural integrity of fly-ash bricks with varying rice straw proportions for sustainable

ABSTRACT

The purpose of this research is to investigate the thermal properties and structural integrity of a fly-ash brick that is layered with varying proportions of rice straw, specifically denoted as SB-1, SB-2, SB-3, SB-4, and SB-5 (representing 0%, 1%, 2%, 3%, and 4% of rice straw content, respectively). New urban areas built with straw bales give comfort at a low cost and reduce pollution generated by straw incineration Egyptians employed adobe blocks [composed of earth material (clay) and biological material (straw)] for architecture in ancient times. The performance of straw sandwiched clay brick is experimented in this study by analyzing the chemical property of straw to be utilized in brick, microstructure analysis, and mechanical and thermal conductivity of straw sandwiched clay brick. When the mechanical and thermal properties of the specimen were taken into account, 1 percent (SB–2) produced better results in both areas. Because it helps to meet the three dimensional aspects of sustainable development: environment, economy, and society, the concept of creating Eco-straw bale brick is an environmentally sustainable sound strategy.

Keywords: *Fly ash brick; mechanical properties; thermal properties with sandwiched clay; compressive strength; thermal conductivity*

1. INTRODUCTION

The building industry plays a significant role in the economy of any nation, but, it exerts a significant environmental footprint. The construction industry is a significant consumer of energy, material resources, and water due to its large scale, and it also contributes significantly to pollution. In response to these effects, organizations have made a commitment to environmental performance targets. They increasingly recognize the need for adequate policies and actions to make building activities more sustainable [1-3].It is projected that by 2056, worldwide economic activity will have grown by a factor of five, global population will have increased by over 50%, global energy consumption will have risen by almost three times, and global industrial activity will have at least nearly tripled [4-5].

Without a doubt, the construction industry is among the most resource-intensive sectors worldwide. In comparison to other sectors, the building industry has generated significant apprehension regarding its rapidly expanding worldwide energy consumption and depletion of finite fossil fuel resources. This has led to concerns regarding energy resource scarcity, supply disruptions, and severe environmental repercussions, including depletion of the ozone layer, carbon dioxide emissions, global warming, and climate change. [5]. The Fly Ash Brick is one kind of environmentally sustainable construction material derived from fly ash, a by-product of coal combustion. It is combined with cement or lime and water throughout the manufacturing process.

The textures of the bricks containing Fly Ash exhibited a striking resemblance to those composed of clay. Specifically, the brick sample incorporating the addition emphasized the presence of spherical Fly Ash particles. The incorporation of Fly Ash particles resulted in a decrease in the density of the bricks and a significant enhancement in their strength and durability. The utilization of this additive possesses practical consequences in terms of recycling and

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cost savings within the context of brick manufacturing [6].

The creation of building materials requires energy, as like the construction phase, and the operation of a completed building literally consumes energy for heating, lighting, power, and ventilation purposes. Aside from energy use, the construction sector is regarded as a major polluter of the environment [7-10], raw material use is significant, accounting for 3 billion tonnes per year, or 40% of global usage [9, 11,12] and generates a huge amount of waste [13,14]. The sustainable building strategy is perceived as a method by which the construction sector can endeavour to achieve sustainable development by considering socioeconomic, environmental, and additional factors. It also serves as an indication of the industry's dedication to safeguarding the environment. [3,15,16,17]. In contemporary construction practices, there has been a notable increase in the utilization of organic fibres. There exists a wide variety of materials, with bamboo, straw, and hemp being commonly observed as illustrative examples. Utilizing cellulose-based materials, including fiber, bamboo, hemp, and timber, provides a direct method for reducing the overall carbon footprint of newly constructed buildings. [18].

Straw is a natural fibre obtained as a by-product of agricultural production. The plant structure is formed from the root crown to the grain head, consisting of cellulose, hemicellulose, lignin, and silica. Photosynthesis, a natural and non-polluting process powered by solar energy, is responsible for its production. Wheat, rice, oats, hops, and barley are all good sources. Rice straw, with its high silica concentration, is the roughest of the bunch. It is a yearly renewable agricultural residue that is abundantly produced in most countries. It is also regarded a waste product that is disposed of by burning or any other method that has a direct or indirect environmental impact. It is evident that using this in construction would be environmentally friendly and beneficial to our quality of life. Burning straw produces a black haze that causes major chronic chest ailments, and the carbon released affects the environment's quality. Until now, the world's largest straw producers, such as China, India, and other agricultural countries, have been unable to use it for productive purposes. It is utilised in paper mills in India for the production of papers and other uses, but this is insufficient for optimal utilisation, and these countries continue to waste a significant portion of it. The pioneers of Nebraska's sand hills region were the first to employ straw bales. Nebraska began employing straw bale to construct buildings, churches, schools, government, and grocery stores in the 1890s. They concentrate on the bale wall system's stability, structural stability, plastering, and moisture management at that time [19]. As a result, straw bale construction has exploded as a cost-effective and environmentally friendly building option. Straw bale walls can offer a variety of physical benefits, including acoustic and temperature insulation [20]. The fact that straw can sustain relatively high transitory moisture content without incurring substantial degradation when utilised as the external envelope of structures provides reasons for broader embrace of this method of construction. [21]. At temperatures below 10 degrees Celsius, a straw bale can withstand 25 percent wetness for extended periods of time without degrading [22]. The inclusion of rice husk straw has the potential to enhance the insulating characteristics of bricks by reducing their weight. The utilization of agricultural waste in this manner is considered to be environmentally friendly. The deployment of alternative materials diminishes the need for conventional clay bricks, hence mitigating the extraction of clay from natural sources. [23].

Some academics have attested to the use of straw bales in building after thorough data collection, but none of the studies has focused on the use of straw sandwiched in fly ash brick manufacture. The key goal of this study is to improve the thermal insulation qualities of bricks. Straw is frequently incorporated as a filler material with properties of being lightweight and having low thermal conductivity, hence enhancing the insulation capabilities of the brick.

2. MATERIALS AND METHODS

Cement, Fly ash, m-sand, Lime, straws and water were employed in this experiment. The trials were conducted using fly ash from a local thermal power plant. Fly ash's properties are listed in Table 1. The lime reactivity of fly ash is 4.52MPa and it comprises 88 percent silica and alumina. As stated by IS. 3812 code [24], fly ash is Grade I, and according to ASTM C618 [25], it is Class F. As a sandwich material, rice straw was used. Straws obtained in Vasudevanallur, Tirunelveli, India, average 15 *cm* to 17 *cm* in length. SEM-EDX is a versatile technique offering high-resolution imaging and elemental analysis, with accuracy influenced by various experimental parameters and sample characteristics. The SEM and EDAX examination was conducted at Gandhigram Rural university in Dindugal, India. The instrument utilized for this analysis was the Carl ZEISS Microscopy, Germany, and model - ZEISS SIGMA. The cathode frequently employed for electron emission is typically a tungsten filament or a field emission gun

(FEG). The voltage used for acceleration normally falls within the range of 5 to 30 kilovolts. Electromagnetic lenses concentrate and guide the electron beam towards the sample. The range of diffraction angles can vary depending on the exact configuration, although it often spans from a few degrees up to approximately 70 degrees. The scanning electron microscope (SEM) operates in a high vacuum environment to minimize electron scattering and absorption caused by air molecules.

Table 1. Fly ash characteristics

Sl. No	Name of the Properties	Values
1.	SiO_2	61.7 (% by mass)
2.	Al_2O_3	26.32(% by mass)
3.	CaO	1.65(% by mass)
4.	MgO	0.63(% by mass)
5.	Fe_2O_3	6(% by mass)
6.	Na_2O	0.17 (% by mass)
7.	SO_3	0.0016 (% by mass)
8.	pH	10.9
9.	Lime reactivity	4.52 MPa
10.	Loss on ignition	1.57 %
11.	Specific gravity	2.5

Scanning Electron Microscopy (SEM) offers a comprehensive perspective of the surface, enabling scientists to examine intricate features, such as particle dimensions and morphology, as well as material texture. The Scanning Electron Microscope (SEM) image of straw is given in Figure 1 and the Energy Dispersive X-Ray Spectroscopy (EDAX) images are given in Figure 2. The specimen is prepared in clean water that is devoid of oil, dust, and solid particles. The concrete specimens are cast and cured using portable water from the laboratory in Eco Brick Tech, Madurai.

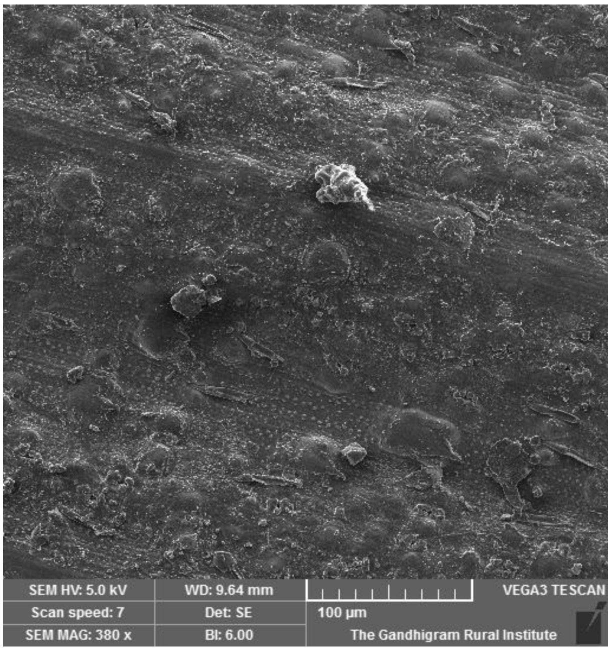

Figure 1. SEM image of Dry Straw

Rice straw was subjected to a scanning electron microscope (SEM) study to assess its surface morphology. The straw's smooth surface will not generate a link between the fly ash brick particles. As a result, the SEM examination was carried out on dry rice straw. The surface morphology of straw was observed to be little rough in the SEM image. So that the fly ash brick particles can bind together.

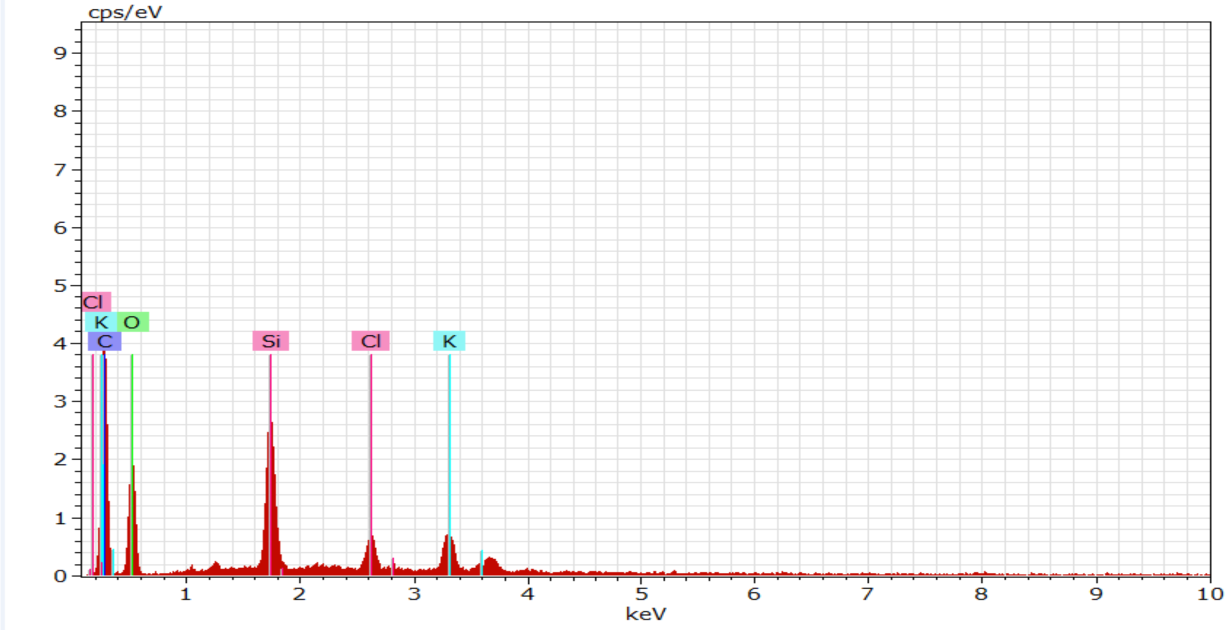

Figure 2. EDAX image of Dry Straw

EDAX data was used to obtain and map mineral components in rice straw. The EDAX image of straw revealed that Si and O are the major components of straw, while Cl and K are minor components [26].The presence of Si and O in the straw and fly ash could react to generate a SiO_2 component. This SiO_2 may improve the fly ash brick's stability and strength [27].

3. EXPERIMENTAL PROCEDURE

3.1. Mix Proportion

The materials were quantified based on their mass percentage, and a consistent w/b ratio of 0.5 was maintained. The mix proportions are determined through the iterative process of trial and error. At a substitution rate of 0%, fly ash is considered to be 55%. Table 2 demonstrates a decrease in the percentage of fly ash when rice straw is added to the mixture. The mix's proportion is outlined in Table 2.

Table 2. Mix Proportion

Materials	SB-1 Proportion-1	SB-2 Proportion-2	SB-3 Proportion-3	SB-4 Proportion-4	SB-5 Proportion-5
Fly-ash	55%	54%	53%	52%	51%
M-sand	35%	35%	35%	35%	35%
Lime	10%	10%	10%	10%	10%
Straw	0%	1%	2%	3%	4%
W/B ratio	0.5	0.5	0.5	0.5	0.5

3.2. Specimen Preparation

The components are first weighted and fed into the mixing grinder in the proper proportions. The mechanical mixer is essential in the fly ash brick manufacturing process since it effectively combines the basic components to produce a consistent and manageable mixture. it comprises a revolving drum fitted with blades or paddles. During the operational phase, the mixer is loaded with fly ash, water, and additional substances like lime, M sand or cement. The drum's rotational movement guarantees extensive combination of various constituents, resulting in a uniform mixture that is crucial for the caliber and durability of the bricks. Belt conveyors have a changeable speed for both forward and reverse, as well as an adjustable reach and a travelling diverter. Where access is limited, a conveyor can quickly place a huge volume of items. The specimen cast by the mould is brought out by a roller belt when the mould is pressed over the container containing the mix. Adding 0%, 1%, 2%, 3%, and 4% straw to the fly-ash brick mixture. A single layer of the fly-ash brick mixture is laid, then straws are stacked on top of that layer. Sandwich stacking is comparable to this procedure. At the same time, the above-mentioned process fills 12 moulds with ingredients and prepares them for compression. After the bricks have been demoulded and the curing process has been completed. Before water curing, the bricks are air dried. After demoulding, the curing process continued for another 14 days [28]. The process of manufacturing straw sandwiched fly ash bricks is illustrated in Figures 3(a) to 3(g).

3a) Mixing Process

3b) Transportation

3c) Placing of materials

3d) Placing Rice- straw in Layers

3e) Compacting the brick

f) Bricks after compression

3g) Bricks arranged before curing

Figure 3. Manufacturing of Straw Sandwiched Fly ash Brick

3.3. Strength Test (Conforming to IS 12894: 2002)

The Straw Bale Sandwiched Fly Ash Brick was 230 *mm* X 110 *mm* X 70 *mm* in dimension. A total of 30 samples were created. Total of 6 specimens were prepared for each mix ratio on the 7th day of testing (3 specimens per mix) and the 14th day of testing (3 specimens per mix). Performing a compression test on a brick entails applying axial force to the brick using a Compression Testing Machine (CTM) with a maximum capacity of 1000 kN, until the brick fails. The process generally adheres to the following sequence of actions: The brick sample is prepared and positioned in the Compressive Testing Machine (CTM). The testing apparatus exerts a progressively escalating compressive force until the brick reaches its breaking point. The brick's compressive strength can be measured by the greatest load that it can sustain before failure. The strength test was conducted in the longitudinal direction of the sandwich brick.

3.4. Water absorption test (Conforming to IS 12894: 2002)

The porosity of bricks determines how much water it can absorb. Capillary action promotes absorption of water in bricks. Porousness and water absorption are insufficient indicators of whether brick can keep rainfall out and protect the inside from outside moisture. The absorption method is employed in this case. This procedure entails at 110 + 5 °*C,* dry bricks are stored in the oven. The weight of the bricks is recorded as M1 once they have been cooled to room temperature. Thereafter, at 27 °*C* the bricks are soaked in water for about 24 hours. The weight of the bricks is then calculated as M2 [29].

$$\text{Water absorption} = \frac{M2-M1}{M1} X\ 100 \quad (1)$$

Where,

M1 = weight of brick before soaking in water

M2 = Weight of brick after soaking in water

3.5 Thermal conductivity

A total of 15 circular specimens, each with a diameter of 112 *mm* and a thickness of 20 *mm*, were fabricated. Following the curing process, the heat conductivity of these specimens was assessed using Lee's disc method. Figure 4 illustrates the casting process of circular specimens intended to measure thermal conductivity.

Figure 4. Casting of circular specimens for thermal conductivity

Figures 5 and 6 exhibit Lee's disk with the specimen and the setup of Lee's disk apparatus. The rice straw is arranged in the same parallel orientation as the brick sample. The entire disc apparatus of Lee is suspended from a pedestal. In Lee's disc apparatus, the steam from the boiler passes through the steam chamber. Monitoring is done with an appropriate thermometer after the temperature of the steam chamber and Lee's discs are raised. The heat flow between the specimen's upper and bottom surfaces is measured and it is found that, the lower surface has a lower temperature than the upper surface, incorporating thermal gradient. The steady state temperature (indicated by the constant reading) in the thermometers T_1& T_2, which correspond to the steam chamber Θ_1 and the metallic disc Θ_2, is noted.

The specimen has now been removed, and the steam chamber has been put immediately on the metallic disc. As a result, Lee's disc temperature rises above the steady state temperature (Θ_2). When the Lee's disc temperature rises 10°*C* above Θ_2, the steam chamber is gently removed and the Lee's disc is allowed to cool. The temperature of Lee's disc is now falling, and a stop clock is triggered when it hits 5°*C* above its steady state temperature value (i.e.,Θ_2+ 5°C). For every 1°*C* drop in temperature, cooling time is recorded until the metallic disc reaches a temperature of (Θ_2– 5°*C*). A screw gauge is used to measure the thickness of the specimen and the metallic disc. A Vernier calliper is used to determine the radius of the Lee's disc. The mass of the metallic disc is likewise calculated using a common balance. Temperature is measured on the Y-axis, and time is measured on the X-axis, to create a cooling curve. Taking two points specifically, one point at a temperature of 1°*C* aboveΘ_2°*C* and another one at a point of1°*C* above Θ_2°C shall be utilized to obtain the rate of cooling. In relation to the above-mentioned points, a triangle is drawn. The rate of cooling of Lee's disc is then determined by the graph's slope. Based on the given readings, determination of thermal conductivity of the specimen is done: Figure 7 illustrates the Cooling curve for the relationship between time and temperature.

$$K=\frac{mst\ (r+2l)\ X\ (d\Theta/dt)}{\Pi r2\ (\Theta 1-\Theta 2)\ (2r+2l)} \qquad (2)$$

Where,

K = Thermal conductivity (W/mK)

m = Mass of the metallic disc (*kg*)

s = Specific heat capacity of Lee’s disc material (J/kg·K)

t = Thickness of the fly ash with rice straw specimen (*m*)

l = Thickness of the Lee’s disc (*m*)

r = Radius of fly ash with rice straw specimen (*m*)

Θ_1 = Steady state temperature of steam chamber in °*C*

Θ_2 = Steady state temperature of metallic disc in °*C*

dΘ/dt = Rate of cooling at steady state temperature (Θ_2) °C.

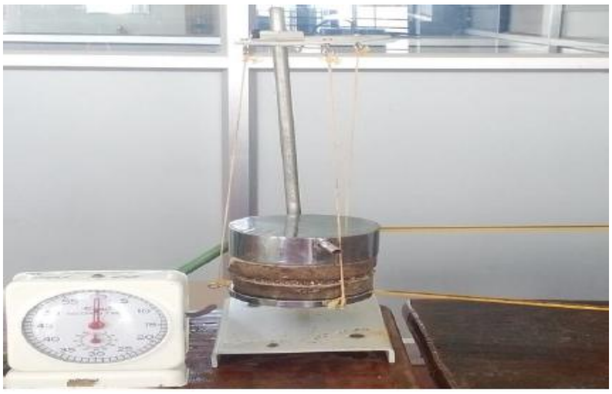

Figure 5. Photograph showing Lee’s disc with specimen

Figure 6. Lee’s Disc Apparatus Setup

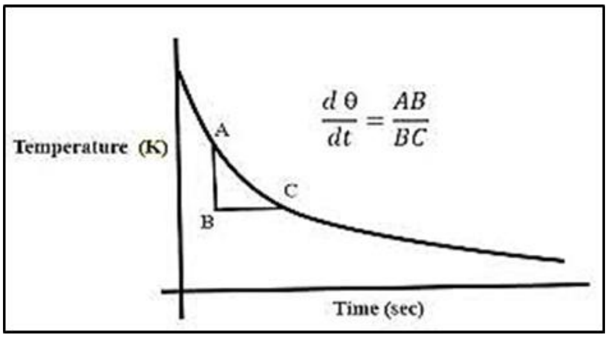

Figure 7. Cooling curve for time& temperature [30]

4. RESULTS AND DISCUSSION

The test findings of compressive strength, water absorption and thermal conductivity are summarized in Table 3.

Table 3. Summary of test findings

Mix/Properties	Compressive strength(N/mm^2)		Water absorption (%)	Thermal conductivity (W/Mk)
	7 days	14 days		
SB-1	4.7	8.27	9.6	0.93
SB-2	5.2	8.59	10	0.89
SB-3	4.2	7.63	10.6	0.82
SB-4	3.9	7.13	11.1	0.75
SB-5	3.1	6.84	11.7	0.68

4.1 Compressive Strength

Figure 8 depicts the influence of straw bale sandwiches on the compressive strength of fly ash bricks. The compressive strength of fly ash bricks should be greater than 3.5 N/mm^2 according to IS12894: 2002[27]. Straw sandwiched fly-ash bricks have compressive strengths ranging from 8.59 N/mm^2 to 6.84 N/mm^2 after 14 days of curing, which is significantly higher than the figure specified in IS 12894: 2002. [31]

A high compressive strength was achieved with a 1% addition of straw. This is owing to the fact that there is less straw present. The compressive strength gradually decreases when the percentage of straw is increased. Due to the dominance of straw content, there is weak bonding between the materials. As per IS 13757.1993 The minimum compressive strength of Fly-ash brick is 3.5N/mm^2 [32]. The compressive strength of fly ash brick is higher than the minimum need when 1 percent to 5% of straw is added, and 1 percent straw Sandwiched fly ash brick generated a high compressive strength of 8.59 N/mm^2. AS per IS 13757.1993, this satisfies the fly-ash brick class 7.5.

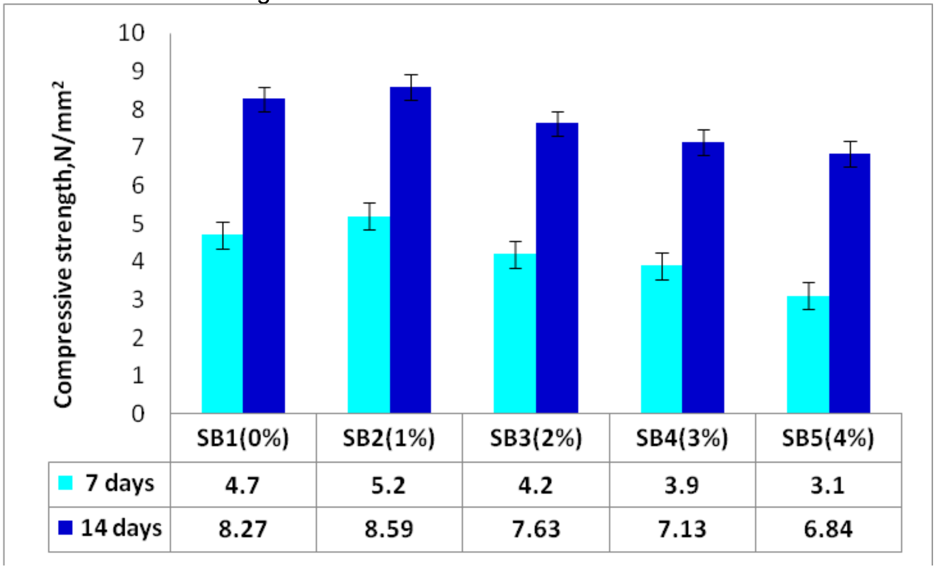

Figure 8. Compressive Strength of Straw Sandwiched Fly ash Brick

4.2. Water absorption test

Figure 9 shows the water absorption capacity of straw-sandwiched fly-ash bricks at various percentages of straw addition. The water absorption capacity is rather low at 1%, although the addition of straw boosted the water absorption capacity somewhat. The water absorption rate of fly ash bricks should not exceed 12% [33]. The fly-ash brick contains 1% straw. The water absorption by the fly-ash brick was 9.6%, and then gradually increased to 11.7 for 4 % of the addition of straw. Still, the value has not exceeded the allowable limit of 12%.

To produce fly ash bricks, fine particles like fly ash and lime powder are used. While moulding, to reduce voids in fly ash bricks, high compression is applied. When the percentage of straw content increases, the percentage of voids in fly ash bricks also increases. Since the fly ash brick contains fine particles, the increase in percentage of straw reduces the bonding between the particles.

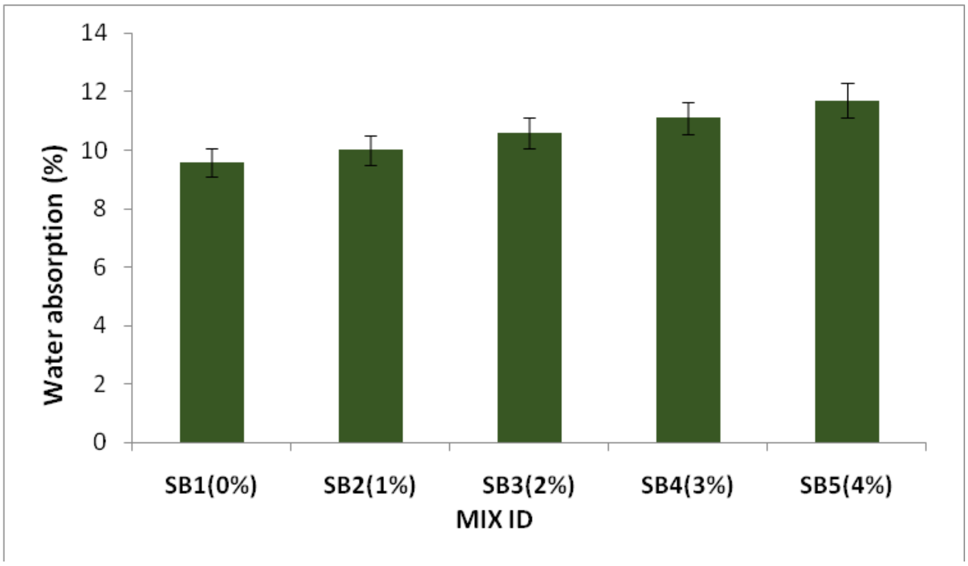

Figure 9. Water absorption of Straw Sandwiched Fly ash Brick

4.3. Thermal conductivity

Figure 10 depicts the thermal conductivity of straw-sandwiched fly-ash brick. Fly ash bricks have a thermal conductivity of 0.90–1.05 W/Mk [34]. SB1 to SB5 have thermal conductivities ranging from 0.93W/mK to 0.63W/mk. The thermal conductivity of the straw-sandwiched fly-ash brick falls when the straw % is increased. As previously explained in the section on water absorption, this is owing to the presence of straw. The incorporation of straw into fly ash bricks results in a reduction in the material's total thermal conductivity. Straw is regarded as an insulating material due to its integration into bricks, which effectively reduces their thermal conductivity. Consequently, fly ash bricks containing a greater proportion of straw exhibit enhanced insulating characteristics and reduced thermal conductivity [35].

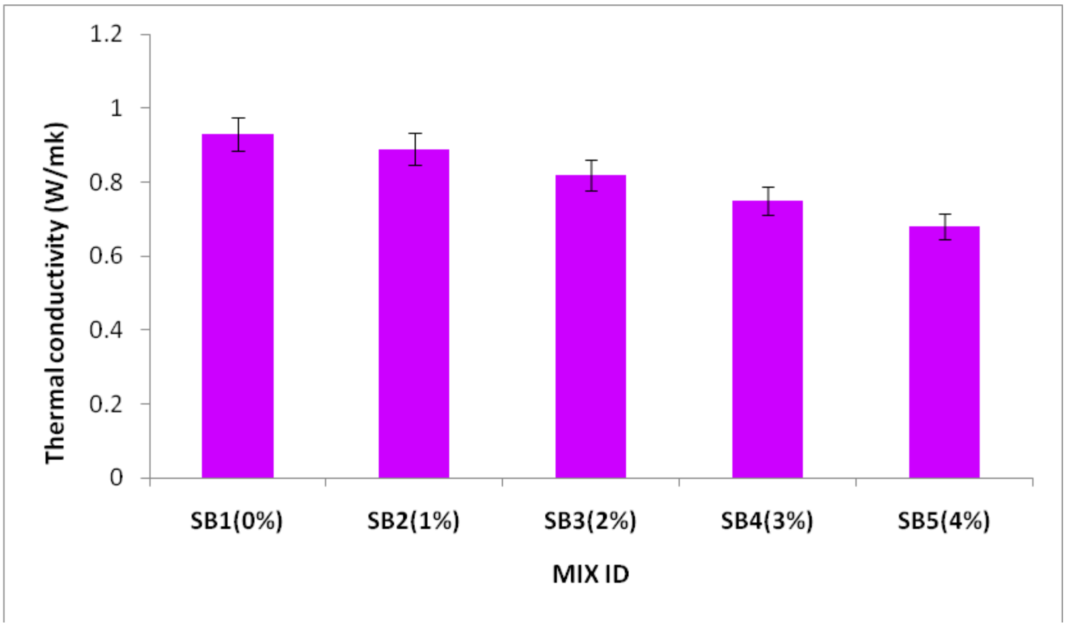

Figure 10. Thermal conductivity of Straw Sandwiched Fly ash Brick

5. CONCLUSIONS

A yearly renewable agricultural residue termed as straw bale is added to the fly-ash brick mixture and experimented in this study.Cement, Fly ash, m-sand, Lime, straws and water were employed in experimental work to determine the behaviour of straw-sandwich fly ash brick. The surface morphology of dry rice straw was little rough enough when observed through SEM examination, depicting that the fly ash brick particles can bind together.The presence of Si and O in the straw and fly ash could react to generate a SiO_2 component, which improves the stability and strength of fly ash brick's. A single layer of the fly-ash brick mixture is spread, followed by straws stacked on top of that layer, and the process is repeated three times, replacing the percentage of straw bale from 0%, 1%, 2%, 3%, and 4% with the mass of fly ash. Higher value on compressive strength of 8.59N/mm^2 is exerted by addition of 1% straw Sandwiched fly ash brick, which satisfies the fly-ash brick class 7.5, according to IS 13757.1993.

It is noticed that increase in percentage of straw addition reduces the bonding between the particles, since the fly ash brick contains fine particles. 4% of the addition of straw exhibits water absorption value of 11.7% which has not exceeded the allowable limit of 12%. SB1 to SB5 specimens have thermal conductivities ranging from 0.93 W/mK to 0.63 W/mK. As a result, while the percentage of straw grows leads to drop in heat conductivity. When the percentage of straw in the Sandwiched fly-ash brick is raised, the specimens will not transport the outside temperature to the interior environment of the building. Thus, the experimental results demonstrate the efficient application of straw bale in fly ash sandwich bricks as a sustainable alternative to conventional bricks concerning both thermal and mechanical properties.

Conflicts of interest

The authors have no conflicts of interest to declare.

Author's contribution statement

The conceptualization and design of the study were aided by all authors. The following people handled the preparation of the materials, the gathering and analysis of data: Dr.Ganeshprabhu Parvathikumar, Brintha Sahadevan, Mukilan K, Kavitha Eswaramoorthy. [Ganeshprabhu Parvathikumar] wrote the first draft of the manuscript, and the other writers provided feedback on it. The final drafts were read and approved by all authors.

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IZVOD

ISTRAŽIVANJE TERMIČKIH SVOJSTAVA I STRUKTURNOG INTEGRITETA CIGLI OD LETEĆEG PEPELA SA RAZLIČITIM PROPORCIJAMA PIRINČANE SLAME ZA ODRŽIVOST

Svrha ovog istraživanja je da se istraže termička svojstva i strukturni integritet cigle od letećeg pepela koja je obložena različitim proporcijama pirinčane slame, posebno označene kao SB-1, SB-2, SB-3, SB-4 i SB-5 (koji predstavlja 0%, 1%, 2%, 3% i 4% sadržaja pirinčane slame , respektivno). Nove urbane oblasti izgrađene balama slame pružaju udobnost uz niske troškove i smanjuju zagađenje izazvano spaljivanjem slame Egipćani su koristili blokove od ćerpiča [sastavljene od zemljanog materijala (glina) i biološkog materijala (slame)] za arhitekturu u drevnim vremenima . Performanse slame u sendviču cigla od gline je eksperimentisana u ovoj studiji analizom hemijskih svojstava slame koja će se koristiti u cigli , analizom mikrostrukture i mehaničkom i toplotnom provodnošću opeke od gline u sendviču . Kada se uzmu u obzir mehanička i termička svojstva uzorka, 1 procenat (SB–2) daje bolje rezultate u obe oblasti. Budući da pomaže u ispunjavanju trodimenzionalnih aspekata održivog razvoja: životne sredine, ekonomije i društva, koncept stvaranja opeke od eko-slame je ekološki održiva strategija.

Ključne reči: *cigla od letećeg pepela ; mehanička svojstva; termička svojstva sa sendvič glinom ; čvrstoća na pritisak; toplotna provodljivost.*

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