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Quantifying Sustainability and Energy Benefit by Recycling of Ground Granulated Blast-Furnace Slag (GGBS) on Replacement of Natural Fertile Topsoil Using for Fired Clay Brick Making Process – An Experimental Study

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ABSTRACT

Gross energy requirement during the life cycle of a building is a growing research field. The embodied energy calculation and its planning having significant role on optimization the total energy used in the building. Recycling of industrial waste materials to reduce the embodied energy is a sustainable approach to mitigate climate change and global warming. This paper discusses the quantification of indirect embodied energy consumption for recycling solid waste, such as granulated blast furnace slag (GGBS) in the brick making process, representing state of the art technology towards sustainable development. Traditional burnt clay brick consumes a huge amount of energy per brick itself. Due to the shortage of traditional resources and keeping in mind energy conservation, we felt we could re-use industrial process wastes, and contribute towards sustainable development. It may be noted herein that re-using industrial waste in construction materials has-been gaining great prominence around the Globe. GGBS is one of the few industrial waste products, which could be used as a construction material through multiple processing layers. In this study, we experimented with brick preparation by using GGBS with cement as a binder. The mechanical property of the sample, such as its compressive strength, is promising, ranging between 13.18MPa–25.48 MPa. The process does not require sintering the material; therefore, it helps in reducing the generation of CO_2 and other greenhouse gas (GHG), most importantly, it is almost carbon neutral. Energy consumption for preparation of brick by using GGBS calculated and makes comparison with the process of burnt clay brick, which found beneficial in respect of energy conservation, environment, and sustainability. The study reveals that recycling GGBS for production of brick having significant potential for reducing indirect embodied energy in the building. The Construction and building sector can benefit from using GGBS for brick processing.

1. Introduction

1.1. Background

Globally, we all are in a transition phase from linear economy to circular economy, sustainability and environmental impact is a key driver for this transition (Jabbour et al., 2020; Tcvetkov et al., 2019; Sillanpää and Ncibi, 2019). For a circular economy and sustainable resource management it is also essential to recycle industrial by-products (IBPs) in order 'to close the circularity loop (Campos et al., 2020; Smol et al., 2020). Among the IBPs such as slags from steel industries is one of the major by-products which are produced at large scale. (Humbert and Castro-Gomes, 2019; Matkarimov et al., 2020).

Worldwide around 400 million tonnes of steel slag are produced annually from smelting plant of steel industries (Branca et al., 2020; Feng et al., 2019). Slags, produced from steel industries, is the glass-like coproduct left over after a desired metal has been separated, it has been estimated that on an average the production of one tonne pig or crude iron and one tonne of liquid steel produced blast furnace (BF) slag ranges about 300 to 540 kg and 150 to 200 kg respectively (Slag-Iron & Steel, Indian Minerals Yearbook 2018, 57 editions, 2018). Huge amount of by-product (Slags) from steel industries remain dumping at open environment causing serious environmental hazards, ecological damages, occupy vast arable land area and incurring high economic cost. Since over the past few decades, major issues on huge amount of IBPs such as slag from steel industries have received increasing attention among the R&Ds, institute, and corporate sector around the world. There have been a lot of R&Ds and research efforts to develop technology for recycling and utilization of slag waste generating from steel industries (Zhang et al., 2020; Pan et al., 2019).

However, in spite of rigorous R&Ds on “recycling and utilization” slag waste, the comprehensive utilization of slag yet has not been emerged of its proliferation. Presently slag waste is mostly used in civil engineering application viz. road construction, cement & aggregates, bricks, tiles, geopolymer materials and other application such as recovery of valuable materials from slag (Liu et al., 2020; Kinnunen et al., 2020; Zhu et al., 2020; Zhou et al., 2019; Humber tans Castro-Gomes, 2019; Hoque and Hosse, 2019; Oge et al., 2019). On the flip side continuous extraction of virgin raw materials causing fast depletion of natural resources, recycling of IBPs (waste) has become a core element of sustainable development and which can replenish the depletion of natural resources and increase sustainability on natural resources. There is an urgent need to develop process technology and move to more sustainable approach towards managing IBPs such as slag etc. so that we can get rid from the multiple problems with the one solution that is recycling and reuse of slag waste for different application to success the “Mission Zero Waste” and increase sustainability.

Global interest in sustainable development along with a growing demand for resource optimization, energy conservation has compelled industries to develop sustainable construction materials, which are more energy-efficient, environmentally friendly, and supplement natural construction materials. Researchers across the globe are striving to develop process technologies for recycling solid waste materials, which would be driven by sustainable practices (Turgut, 2012; Pappu et al., 2007; Papargyropoulou et al., 2011; Raut et al., 2011). Due to the rapid infrastructure development, the rate at which industrial solid waste increasing is phenomenal. Consider this, about a decade ago, in 2011, the amount of industrial solid waste was 9.2 billion tons, while the per capita was 1.74 tons/year (Song and Zeng., 2015).

On the other hand, the worldwide annual production of traditional burnt clay bricks is just about 1391 billion units, which hardly suffices the bursting population growth and economic development, due to which, the demand for brick has continuously been on the rise (Sutcu et. al., 2015). While there’s already a shortfall of demand vis a vis supply, another challenge looms large, meeting the demand sustainability while conserving energy for making these building materials. The process of constructing a building consumes huge energy depending upon the materials used for production, manufacturing processes, and transportation (Reddy and Jagadish, 2003). The process of preparing burnt clay brick itself consumes a huge amount of good quality soil and energy (Reddy and Jagadish, 2003; Chen et al., 2011; Chel and Kaushik, 2018). If we are to drill down further, the sintering process itself requires a huge amount of energy and releases a considerable amount of CO_2 in the atmosphere (EI-Attar et. al., 2017). If we could recycle the waste material to prepare the bricks, it would reduce the total quantity of embodied energy in the building, as well as reduce GHG (Schneider et al., 2011). A building constructed with burnt clay brick consumes about 4.03 GJ/m^2 of embodied energy (Dissanayake et. al., 2017).

Moreover, traditional burnt clay brick is being produced in the kiln, which in turn consumes a lot of natural resources and energy, causing severe environmental damage, one of the salient ones being massive carbon emissions (Oka et al., 1993; Buchanan and Honey, 1994; Koomey et al., 1998; Reddy and Jagadish, 2003). To save the clay from fertile lands, we must consider recycling solid wastes such as GGBS, generated from steel industries by developing process technology for brick processing. Several studies have recommended ways of using this waste for producing construction materials, it has been observed that in the construction sector, the predominant applications used so far include brick processing, concrete, and mortar, etc. (Zhang, 2013; Sabir and Bai., 2001).

Optimization of energy utilization becomes more important in the context of reducing greenhouse gas emissions into the atmosphere and optimization of natural resources also. Uses of GGBS in brick making processing without sintering is one of the sustainable approaches as it can reduce total embodied energy in the building and can save natural resources a lot.

1.2. Energy quantification for processing of building materials

Embodied energy calculated for a building while considering the sum of all energy used at every step, such as processing, transportation, and construction. Energy consumption for building materials has a huge impact on the total embodied energy of a building; thus, proper selection of energy-efficient building materials could reduce the quantity of embodied energy within the building. Analyzing embodied energy is a key tool to assess the environmental sustainability of a building. To build an energy-efficient building, we must have the transparency of the lower embodied energy construction material used for constructing the building construction and their comparison about energy consumption (Reddy and Jagadish, 2003; Dakwale and Ralegaonkar, 2014; Oti and Kinuthia, 2012).

Table 1 represents the specific building materials of different energy values. CO_2 and GHG may be reduced through the optimizing the quantification of embodied energy in the building. Proper selection of building materials, which are low energy-intensive, would help in reducing the total embodied energy in the building. From the data presented in Table 1, it seems that the values of burnt clay brick is quite high in comparison with other brick produced by recycling different kinds of solid waste material.

In this study, attempted has been made to develop process technology for brick production by recycling industrial by products such as GGBS, which can supplement traditional burnt clay brick and reduce embodied energy in the building, GHG emission, enhance resource optimization and increase sustainability.

Table 1. Specific building materials of different energy values

References	Type of materials	Size (mm)	Energy per brick equivalent (MJ)
Reddy and Jagadish, 2003	Stone block	180 x 180 x 180	0
	Burnt clay brick	230 x 105 x 70	4.25
	Soil-cement block	230 x 190 x 100 (6% cement)	1
		230 x 190 x 100 (8% cement)	1.35
	Hollow cement block	400 x 200 x 200 (7% cement)	1.32
	Hollow cement block	400 x 200 x 200 (7% cement)	1.62
	Steam cured block	230 x 190 x 100 (10% cement)	2.58
Dakwale and Ralegaonkar, 2014	Fly ash brick	230 x 90 x 90 (1% cement and 1% fly ash)	1.93-2.08
		230 x 90 x 90 (10% cement and 55% fly ash)	2.32
Oti and Kinuthia, 2012	Unfired brick (LOC – Lime - GGBS)	215 x 102.5 x 65 (1.4 lime, 5.4% GGBS)	1.70
	Unfired brick (LOC-PC-GGBS)	215 x 102.5 x 65 (1.4 lime, 5.5% GGBS)	1.73
IFC, 2017	Clay brick, Fixed Chimney Bull's Trench Kiln (FCBTK)		3
	Clamp kiln, Intermediate clamp kiln, Scotch kiln		5.6
	High draught zigzag		5.8
	Hoffman and hybrid Hoffman		2.9

2. Material

2.1 Physical and chemical properties of GGBS

Depending on the chemical composition of the input raw material used in the process of steel production, GGBS has different chemical and physical properties (Shrouty and Talodhikar, 2017). The microstructure between matrix and aggregate is the most important transition zone in the binder mix, like cement in this case. GGBS can contribute both to the chemical and physical changes, which in turn solidifies the microstructure of the brick (Suresh and Nagaraju., 2015). Most of the blast furnace steel slag consists primarily of SiO_2, Al_2O_3, and CaO. Table 2 represents the concentration of the chemical composition of these oxides in slag, which is in the range of 88-90% (Douglas et. al., 1991; Alshamsi, 1997; Konsta-Gdoutos and Shah., 2003; Li et al., 2018; Almeida and Klemm., 2018; Zhang et al., 2018; Shi, 2002). The typical physical and chemical property and chemical composition of different types of steel slag has been presented in the Table 3 and Table 4 respectively.

3. Methodology and experimental setup

The experimental setup and procedure involved in this study is mainly development of process technology to utilize and recycle of GGBS for preparation of brick sample specimens. Details of raw materials, sample specimens, test procedures, analysis, and the test results are presented phase-wise.

Table 2. Typical chemical property of GGBS

Compound	Douglas et al., 1991	Alshamsi, 1997	Konsta-Gdoutos and Shah, 2003	Li et al., 2018	Almeida and Klemm, 2018	Zhang et al., 2018
SiO_2	38	36.8	31.96	32.56	34.5	36.51
Al_2O_3	8.74	10	10.31	25.77	13.1	15.65
Fe2O	0.55	1.2	1.42	0.62	0.2	1.08
CaO	32	41.9	45.98	42.08	38.5	32.93
MgO	18.6	7.2	7.02	5.63	9.7	8.02
K_2O	0.76	0.5	0.31	0.96	0.6	1.11
Na_2O	0.22	0.3	0.26	1.22	0.2	0.81
SO_3	2.45	0.1	2.13	1.01	0.4	0.07
LOI	1.98	-	0.2	0.93	0.6	1.33

Table 3. Typical physical properties of GGBS

Kumar et al., 2010		**Li and Zhao, 2003**		**Pal et al., 2003**	
Property	**Value**	**Property**	**Value**	**Property**	**Value**
Density, gm/cc	2.88	Specific gravity	2.79	Specific gravity	2.90
Glass content, %	93	Pozzolanic activity index, 28 days	106.3	Bulk density, kg/m^2	1200-1300
Specific surface area, m^2/gm	0.92	Specific surface, Blaine, m^2/kg	599	Specific surface, Blaine, m^2/kg	350-450
Characteristic					
Particle diameters, µm					
X10	1.11				
X50	25.75				
X90	84.24				

Table 4. Chemical composition of different types of steel slag

Compound (%)	**Zhang et al., 2019**	**Bing et al., 2019**	**NAR, 2018**			**IMY, 2018**		
			(BF Slag)	**(LD Slag)**	**(EAF Slag)**	**Bhilai Steel Plant (BF)**	**TATA Steel (BF)**	**JSW Ballari Plant (BF)**
CaO	45.043	40.30	40-45	45-48	25-35	32.43	34.3	34.90
SiO_2	20.924	15.38	30-35	13-16	15-17	34.52	34.5	35.20
Fe_2O_3	14.796	12.73	-	-	-	-	-	-
Al_2O_3	5.332	2.54	12-15	1-3	4-6	20.66	20.8	19
MgO	3.213	9.05	5-7	5-10	3-5	10.09	7.3	8.76
Na_2O	0.088	-	-	-	-	-	-	-
P_2O_5	1.727	1.01	<1	1-3	<0.05	-	-	-
SO_3	0.518	-	-	-	-	-	-	-
K_2O	0.201	-	-	-	-	-	-	-
TiO_2	0.98	-	-	-	-	-	-	0.14
MnO	1.347	1.88	<1	<5	<1	0.23	0.052	-
FeO	-	14.06	-	-	-	0.57	0.6	-
Fe	-	-	<1	15-17	20-25	-	-	0.039
LOI	4.665	-	-	-	-	-	-	-

3.1. Raw materials

GGBS is a non-metallic industrial by-product from steel making industries that is generated through the process of the steel melting at a temperature of 1500 °C. GGBS used in this study was collected from steel plants of Rourkela (Odisha, India). Ordinary Portland Cement (OPC) was procured from the local market. The chemical properties of GGBS and the cement used in this study were examined, the results are summarized in the Table 5.

3.2. Specimen processing

3.2.1. Sample specimen BSC made by GGBS and OPC

Blast furnace slag was collected from steel plants, while the cement was procured from the local market. For our study, we used GGBS ranges between sieve size 0.6 mm – 0.075 mm. GGBS was mixed with cement with proportion of 95%, 90%, 85%, 80% respectively. The mixing matrix of the material are presented in Table 6.

Table 5. Chemical properties of the GGBS and OPC (wt %)

Compound (%)	**GGBS**	**OPC**
SiO_2	33.01	22.67
Al_2O_3	18.98	3.89
Fe_2O	0.87	2.99
CaO	37.09	64.23
MgO	7.12	1.3
K_2O	0.76	0.81
Na_2O	0.22	0.23
SO_3	0.76	1.89
LOI	0.67	0.75

Table 6. Material proportion (%) for preparation of sample specimen GGBSC

Sample Id	**BSC1**	**BSC2**	**BSC3**	**BSC4**
GGBFS	95	90	85	80
OPC	05	10	15	20

GGBS and cement mixtures for sample specimen were prepared by thoroughly mixing predetermined quantities till uniform color were obtained, a specified quantity of water was required to mix the material to get the proper consistency. The casting of the sample followed the Indian Standard Code IS 516 – 1959. After gaining green strength, the sample was removed from the mold and placed into water curing pot for 28 days curing, post which the mechanical property of the sample was tested.

4. Results and Discussion

4.1 Results

To determine the strength and durability of the brick, the testing, and analysis of mechanical property is an essential parameter to validate the brick sample (IS Code 1077-1992; IS Code IS 1077-1973; IS Code 2180-1988). The mechanical properties, such as compressive strength, water absorption, and bulk density were tested and are presented in Table 7, the average values of the test result have been summarized in Table 8 and Fig. 1, respectively. The brick sample prepared by GGBS materials and cement (binder) has been compared its mechanical properties with the traditional burnt clay brick specified in the Indian Standard code, and interpreted in the Table 9.

Table 7. Testing result of mechanical property for the sample specimen

Sample Id	GGBS:OPC	Compressive strength (MPa)			Water absorption (%)			Bulk density (gm/cc)		
BSC 1	95:05	13.45	14.01	13.95	11.41	11.03	11.45	1.81	1.83	1.79
BSC 2	90:10	17.45	16.67	16.09	10.05	10.34	10.99	1.88	1.9	1.91
BSC 3	85:15	21.67	20.76	22.08	9.78	9.85	9.44	2.12	2.14	12.15
BSC 4	80:20	24.78	25.78	25.89	9.01	9.00	9.07	2.21	.2.23	2.19

Table 8. Average mechanical property of the sample specimen

Sample Id	OPC	Average compressive strength (MPa)	Average water absorption (%)	Average bulk density (gm/cc)
BSC 1	5%	13.80	11.30	1.81
BSC 2	10%	16.74	10.46	1.90
BSC 3	15%	21.50	9.69	2.14
BSC 4	20%	25.48	9.03	2.21

Table 9. Compassion of mechanical properties with the traditional burnt clay brick specified in the respective Indian Standard Code

Description	IS Code	Limiting value specified by the IS Code	Experimental achievement in this study
Compressive strength of brick	IS Code 1077-1992 (Burnt clay brick)	3.5 MPa – 35 MPa	13.80 MPa - 25.48 MPa
Water absorption (Brick)	IS Code IS 1077-1973 (Burnt clay brick)	Not more than 20% by weight	9.03.% - 11.30%
Bulk density (Brick)	IS Code 2180-1988 (Burnt clay brick)	1.8gm/cc - 2.5 gm/cc	1.81 gm/cc - 2.21 gm/cc

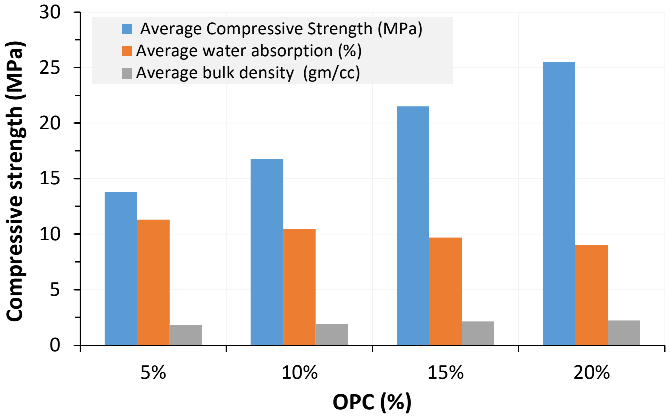

Fig. 1. Average mechanical property of the sample specimen

4.1.1. Quantification of indirect embodied energy for the production of brick by GGBS with OPC used as a binder

For energy calculation, considered a hundred no's of bricks measuring 240 x 115 x 65 mm, based on the material proportion, weight of the one brick sample was analyzed as 3.35 kg, it was found that 345 kg of material required for preparation of 100 no's of brick, the details has been summarized in the Table 10. The sample-wise energy quantification for the production of bricks has been presented in Tables 11 to 14.

4.1.2. Assumption

1. For energy calculation, consider 100 bricks of size 240x115x65 mm, weight 3.45 kg/brick
2. GGBS procured from 2.5 km distance
3. One lorry GGSB equal to 2000 kg
4. GGBS available free of cost
5. Fossil fuel to Energy conversion refers, 1 liter = 32.2 Mega Joules – LHV (Hofstrand, 2007).
6. Energy calculation for cement refers (Udawattha and Halwatura., 2016)
7. Energy for water consumption has not been considered, refer (Udawattha and Halwatura., 2016).

Comparison of total energy requirement per bricks produced by recycling of GGBS with the traditional burnt clay bricks has been summarized in the Table 15 and Fig. 2, respectively.

Table 10. The material requirement for 100 brick of sample Id (GGBS) of size 240 x115 x 65 mm

Raw Material	GGBS:OPC = 95:05	GGBS:OPC = 90:10	GGBS:OPC = 85:15	GGBS:OPC = 80:20
GGBS	322 kg	310.50	293.25	276.00
OPC	17.20 kg	34.50	51.75	69
Water	86.5 Lit	89.70	93.15	96.60

Table 11. Total energy requirement for the materials required for processing 100 nos of brick (GGBS:OPC/95:05)

Raw material	Fossil Fuel	Electricity	Total Energy (MJ)
GGBS	6.09 Liter	0.0 MWh	196.38
OPC	1.7 Litre	0.0 MWh	56.82
Molding	0.0	0.006 MWh	21.6
Total energy requirement for 100 nos brick			274
Energy requirement for 01 nos brick			2.74 MJ

Table 12. Total energy requirement for the materials required for processing 100 nos of brick (GGBS:OPC/90:10)

Raw material	Fossil Fuel	Electricity	Total Energy (MJ)
GGBS	5.78 Litter	0.0 MWh	186.23
OPC	3.4 Littre	0.0 MWh	109.48
Molding	0.0	0.006 MWh	21.6
Total energy requirement for 100 nos brick			317
Energy requirement for 01 nos brick			3.17

Table 13. Total energy requirement for the materials required for processing 100 nos of brick (GGBS:OPC/85:15)

Raw material	Fossil Fuel	Electricity	Total Energy (MJ)
GGBS	5.54 Litter	0.0 MWh	178.49
OPC	5.11 Littre	0.0 MWh	164.64
Molding	0.0	0.006 MWh	21.6
Total energy requirement for 100 nos brick			364
Energy requirement for 01 nos brick			3.64

Table 14. Total energy requirement for the materials required for processing 100 nos of brick (GGBS:OPC/80:20)

Raw material	Fossil Fuel	Electricity	Total Energy (MJ)
GGBS	5.22 Litter	0.0 MWh	168.18
OPC	6.81 Littre	0.0 MWh	219.41
Molding	0.0	0.006 MWh	21.6
Total energy requirement for 100 nos brick			409
Energy requirement for 01 nos brick			4.09

Table 15. Comparison of energy consumption per brick in this experiment with burnt clay brick from research reference

Sample Id	Total energy (MJ) per brick (from this experiment)	Reference-1 Total energy (MJ) per Burnt clay brick (Reddy and Jagadish, 2003)	Referance-2 Total energy (MJ) per Burnt clay brick (IFC, 2017)
BFSC1	2.74 MJ	Average 4.25 MJ	Average 4.32 MJ
BFSC2	3.17 MJ		
BFSC3	3.64 MJ		
BFSC4	4.09 MJ		

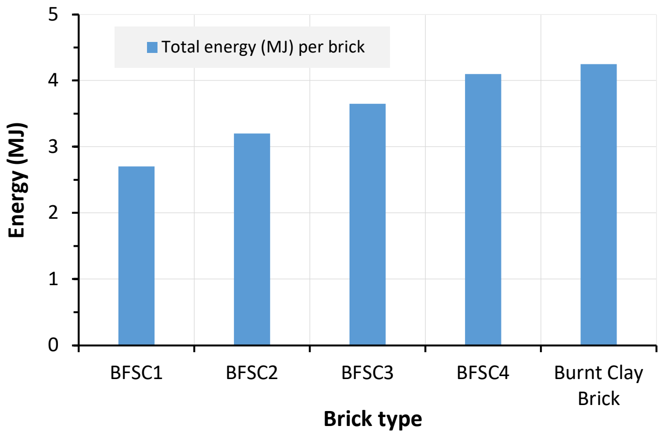

Fig. 2. Total energy consumption per brick (MJ) produced by recycling of GGBS and burnt clay brick

4.2. Discussion

This study has found that recycling of GGBS for production of brick having huge potential to save energy, reduce greenhouse gas, environmental pollution and increase sustainability as well. The current study workout indirect embodied energy quantification of the brick-making process by recycling of GGBS and compared it with traditional burnt clay brick. Overall, this study aimed to find ways to minimizing energy consumption in the construction phase of the brick making process, so that the overall embodied energy of a building could be reduced, thereby in the process reduce GHG emission as well. At the same time, the mechanical property and durability of the brick is an important concern, nevertheless, going by our tests, the mechanical property has been found to be promising, moreover, it satisfies the Indian standard code IS 1077: 1992, which has to mention the strength parameter of traditional burnt clay brick, which ranges from 3.5 MPa–35 MPa. Our experimental study achieved the compressive strength ranges from 13.18 MPa-25.48 MPa, it should be noted herein that the other two mechanical properties such as bulk density and water absorption have also been promising.

Table 6 presents the composition of the material consumption, strength, and energy requirement for each type of sample specimen. Material with 5% cement and 95% GGBS seems moderate, with lesser energy consumption as 2.74 MJ while compressive strength achieved 13.80 MPa, where as in IS code 1077-1992 specified that permissible compressive strength of traditional burnt clay bricks ranges from 3.5 MPa-35 MPa. The energy consumption for the production of each brick by GGBS seems less than that burnt clay brick (Table 9). Based on the results from our experimental study, it can be considered that the process is certainly more energy-efficient and sustainable and can supplement traditional burnt clay bricks produced by natural fertile clay soil.

5. Conclusion

This paper emphasizes the use of GGBS waste for making brick, this would address sustainable issues such as the energy conservation and recycling of industrial solid waste (GGBS) to useful and valuable construction material, emitting far lesser CO_2 and GHG in the atmosphere. The Mechanical Property of the bricks produced using GGBS is promising for sure and it satisfied the respective Indian Standard code and comparable to burnt clay brick, it is a good replacement for the traditional burnt clay brick. Energy consumptions of the production of the brick by recycling GGBS (curing process) with different proportion of binding materials found less than the process of burnt clay brick. As energy consumption for processing GGBS brick ranges from 2.74 MJ to 4.09 MJ, whereas to achieve the same mechanical property for the burnt clay brick consumed higher rate of energy as ranges from 4.25 MJ to 4.32 MJ. Material with 5% cement and 95% GGBS seems moderate, with lesser energy consumption as 2.74 MJ while compressive strength achieved 13.80 MPa, where as in IS code 1077-1992, specified that permissible compressive strength of traditional burnt clay bricks ranges from 3.5 MPa – 35 MPa. Thus, the brick prepared with GBBS would, therefore, be an energy-efficient and sustainable solution for constructing buildings, as the process helps in reducing the quantity of total embodied energy within the building. Unfired bricks produced by recycling GGBS were expected to perform well and provide a sustainable solution as a replacement to traditional burnt clay brick, save fertile topsoil, the environment, and ecology, and most importantly help to reduce GHG in the atmosphere. The findings of this study may be scalable in an entrepreneurial opportunity producing green and sustainable materials for construction industry.

List of Abbreviations

GGBS: Ground granulated blast furnace slag
IBPs: Industrial by products
GHG: Greenhouse gas
OPC: Ordinary Portland Cement
IS Code: Indian standard code
MJ: Mega Joule
MPa: Mega pascal
LHV: Lower Heating Value

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