Improved burnt clay brick masonry: lowering upfront embodied carbon, improving thermal comfort and climate resilience of new housing in the Indo-Gangetic Plains

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Abstract

The urban residential building footprint is expected to increase four-fold during 2020-2050 in the Indo-Gangetic Plains region of India. The business-as-usual construction technology of RCC frame with solid burnt clay brick as the walling material uses large quantities of steel, concrete and solid brick and is highly resource and carbon intensive. The region produces 110-140 billion solid burnt clay bricks per year. Brick production is associated with large energy consumption, carbon dioxide emission, air pollution and degradation of agricultural land. The study presents an innovative new burnt clay product – vertically cored interlocking burnt clay block- being manufactured by a brick manufacturer in the region. The study presents the results of the life cycle analysis (as per EN 15804) and quantifies reductions in carbon and resource consumption for the product and the building element (wall). The analysis is based on the data collected from the industry. The cradle to gate analysis shows a reduction of 31% in the CO2 emissions (kgCO2/m^3 of burnt product) and 58% in soil consumption (m^3 of soil/m^3 of burnt product) for the vertically cored hollow block. A 150 mm thick wall made of vertically cored hollow block results in 55% reduction in the CO^2 emissions (kgCO2/m^2 of wall) when compared to a 230 mm thick wall of solid brick. In addition, the cement consumption in mortar reduces by 66% and sand consumption by 62% per m^2 of wall area. The study further indicates a significant reduction in concrete and steel consumption by extending the analysis to the building level.

Keywords - Low-carbon housing, hollow burnt clay block, life cycle analysis, Indo-Gangetic plains, resource efficient clay brick industry

1. Introduction

The Indo-Gangetic Plains (IGP) region covering the states/Union Territories of Punjab, Haryana, Chandigarh, NCT of Delhi, Uttar Pradesh, Bihar, West Bengal and Assam, has high population density and accounts for 42% of the total population of the country [1]. Several major states of the region have low rates of urbanisation e.g. Uttar Pradesh (22.3%), Bihar (11.3%) [2]. A large growth in

Table 1 Percentage of census housing reporting burnt clay brick as walling material in Indo-Gangetic Plains [4]

	% of census houses reporting burnt clay brick as walling material		
	Rural (%)	Urban(%)	Total (%)
Punjab	86.97	88.31	87.5
Haryana	87.83	86.52	87.36
Chandigarh	84.36	88.78	88.65
NCT of Delhi	84.82	86.27	86.24
Uttar Pradesh	63.57	83.04	67.87
Bihar	44.52	71.15	47.46
West Bengal	33.09	72.22	45.72
Indo-Gangetic Plains	51.53	78.80	58.68
India	40.47	64.00	48.06

urban population and housing is expected in the coming decades. The total urban residential built-up area in the region is expected to increase four-fold from 1.88 billion m^2 in 2020 to 7.35 billion m^2 by 2050 [3].

As per Census 2011, burnt clay brick is the main walling material for housing construction in the region. In 2011, 78.8% of the urban census houses in the IGP region reported burnt clay brick as the walling material [4]. In several of the states the percentage was more than 85% (refer Table 1).

The IGP region is rich in alluvial soil deposited by the major rivers, Indus, Ganges and Brahmaputra originating from the Himalayas. The bricks made from the alluvial soil in the region are of good quality and continue to remain the most widely available and preferred walling material for residential housing construction [5]. Reinforced Cement Concrete (RCC) frame, RCC slab and solid burnt brick infill is the dominant construction technology despite the introduction of several new building materials and construction technologies. For multi-storey housing projects in the National Capital Region (NCR) and other metropolitan cities, there is an increase in the use of Autoclaved Aerated Concrete (AAC) block masonry. Recently, some of the mass-housing, particularly high-rise residential projects have been constructed using monolithic concrete construction technology. The use of fly-ash bricks is limited to a few pockets, particularly in housing constructed by the government agencies.

The annual production of burnt clay bricks in the IGP region is estimated to be 110 -140 billion bricks per year, which is around 60% of the national production [6,7]. The number of manufacturing units is estimated to be around 60,000. Except for around 20 manufacturing units equipped to manufacture perforated or hollow bricks, almost all the other manufacturing units are producing only solid bricks. The brick making involves baking the brick at high temperature (~1000 ºC) in a kiln. The brick kilns in the region employ either Fixed Chimney Bull's Trench Kiln Technology (FCBTK) or an efficient version of FCBTK known as zig zag kiln technology. Large quantities of Coal and biomass fuels are used in brick kilns making them an important source of both carbon-dioxide emissions as well as local air pollution (particulate matter). To reduce particulate matter emission from brick kilns, the new environment standards issued by the Ministry of Environment, Forests and Climate Change (MoEFCC) for brick kilns in February 2022, mandate that all the FCBTK must shift to zigzag kiln technology or other cleaner technology/fuels in two years' time, i.e. by early 2024 [8]. As per information collected from the industry, around 30,000 or 50% brick kilns of the IGP region have converted to zig-zag kiln technology by June 2023. The brick kilns in the region use topsoil from the agricultural fields and degradation of agricultural fields is another area of concern.

Given this background, it is critically important to find new scalable low carbon and resource efficient building materials and construction technologies for the construction of housing in the IGP region. In this context, recently a brick manufacturer located at Varanasi has started manufacturing an innovative vertically cored interlocking hollow burnt clay block, which potentially can have large application in new residential construction. In this paper we apply the Life Cycle Analysis (LCA) approach and quantify the upfront carbon and resource savings at the product stage, at the building element (wall) stage and at the full building stage due to use of this new type of block.

2. Methods

2.1. Cradle to gate (A1-A3) carbon emissions for solid burnt clay brick & vertically cored interlocking hollow blocks

Following the standard EN 15804 [9], the project life cycle is shown in Figure 1. The analysis of cradle to gate (A1A3) carbon emissions for the vertically cored interlocking hollow blocks and solid burnt clay brick manufactured in the IGP region was carried out. As shown in Figure 1, A1 is raw materials extraction and supply; A2 is transport of raw material to the manufacturing plant and A3 is the manufacturing. The declared unit for the analysis is 1 m^3 of the burnt clay product. Based on the analysis, the results are presented in $kgCO^2/m^3$ of burnt clay product.

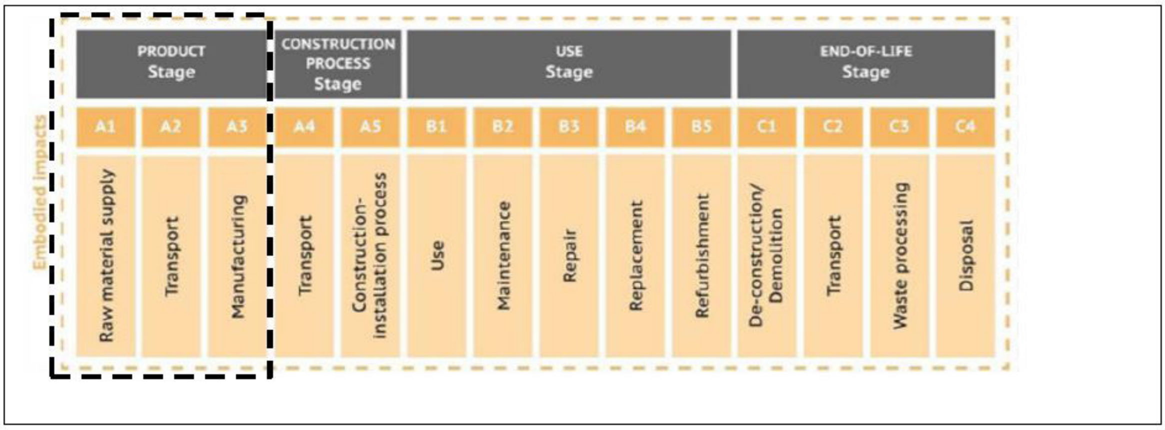

Figure 1: Project Life Cycle

2.1.1 Solid Burnt Clay Brick

The process flow diagram of solid brick manufacturing process in the IGP region is shown in Figure 2

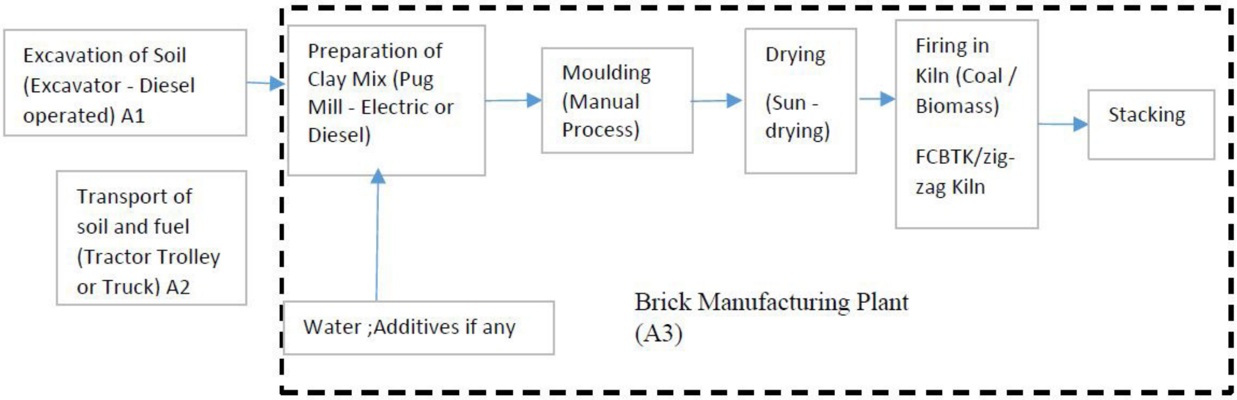

Figure 2: Process of solid burnt clay brick manufacturing in the Indo-Gangetic Plains

The data on energy used during A1-A3 was collected from the industry and literature. While there are many similarities in terms of the brick production across the IGP region, there is also some diversity in terms of size of brick, fuel, etc. Based on the industry data an average energy use pattern for solid clay brick production in the IGP region was developed.

For the analysis, the average size of the solid burnt clay brick is taken as 230mm x 110 mm x 70 mm and the weight of single fired brick is taken as 3.0 kg, which translates into the bulk density of 1694 kg/m^3. A typical brick kiln was assumed to fire 50,000 bricks per day (150 tons of burnt clay brick/day or 88.55 m^3 of burnt clay brick/day).

The process and energy data used for LCA is presented in Table 2.

Product life cycle stage	Description
A1	The soil for manufacturing bricks is surface soil excavated from nearby agricultural fields. A JCB excavator is used for excavating the clay. The typical diesel consumption in excavation is taken as 7 l/h and the excavation rate as 45 m^3 of soil/h. The specific diesel consumption of excavation is 0.225 l of diesel/m^3 of burnt clay product. The carbon emission factor for diesel is taken as 2.68 $kgCO_2$/l [10]
A2	a) Both trucks and tractor trolleys are used for transporting the soil from the agricultural fields to the brick manufacturing unit. For the analysis, the transportation is considered by 10-wheeler truck, which transports 20 tons of soil/trip. As soil is mostly procured from nearby agricultural fields, the distance of the place of excavating the soil to the brick kiln is taken as 10 km. b) The coal is assumed to be transported using trucks from the coal mine to the brick kiln. For the analysis, the transportation is considered by 10-wheeler truck, which transports 18 tons of coal/trip. It is assumed that all the coal which is being used is indigenous and the average distance from the place of mining to the brick kiln is taken as 500 km. The total travel distance taken for the analysis consists of both to-and-fro travel of the truck. The emission factor for the 10-wheeler truck is taken as 0.7375 $kgCO_2$/km [11]
A3	a) The soil mix is prepared in a machine known as pug-mill, which is mostly operated using the tractor (diesel operated). During the soil-mix preparation, water is added to the soil. In some cases, additives like fly ash are also added, but for the analysis no additives are assumed. It is assumed that on average the pug-mill per hour produces soil-mix sufficient to mould 12,000 15,000 bricks. The specific diesel consumption of pug-mill is 0.225 l of diesel/m^3 of solid burnt clay brick. The carbon emission factor for diesel is taken as 2.68 kgCO2/l [10] b) The moulding of brick is done manually. c) The bricks are dried in the open under the sun. d) The bricks are fired in a kiln. Both FCBTK and zig-zag kilns are used in the IGP region. The major fuel used is coal, with biomass fuels like mustard stalk, saw dust, and firewood used in small quantities. For the analysis, the base-line Specific Energy Consumption for FCBTK is taken as 1.34 MJ/kg-brick and 1.06 MJ/kg-brick for zig-zag kiln [12]. As the two types of kilns are present in almost equal numbers in the IGP region, an average SEC of 1.2 MJ/kg-brick or 2033 MJ/m^3 of burnt clay product is used for further calculations. For estimating the carbon emission, it is assumed that all the energy comes from burning coal. The carbon dioxide emission factor for bituminous coal is taken as 94.6 tCO_2/TJ [14]

2.1.2 Vertically Cored Interlocking Hollow Clay Block

The product vertically cored interlocking hollow clay block (Figure 3) is manufactured in a brick manufacturing plant located at Varanasi, Uttar Pradesh. The size of the vertically cored hollow block is 300mm x 150 mm x 200 mm and the weight of single block is 8.6 kg, which translates into the bulk density of of 956 kg/m^3. The product is fired in a zig-zag brick kiln which has capacity to fire 150 tons of burnt clay product/day.

Figure 3: Vertically Cored Interlocking Hollow Clay Block

The process flow diagram showing energy/fuel used in various stages of the production of vertically cored interlocking hollow clay blocks is shown in Figure 4.

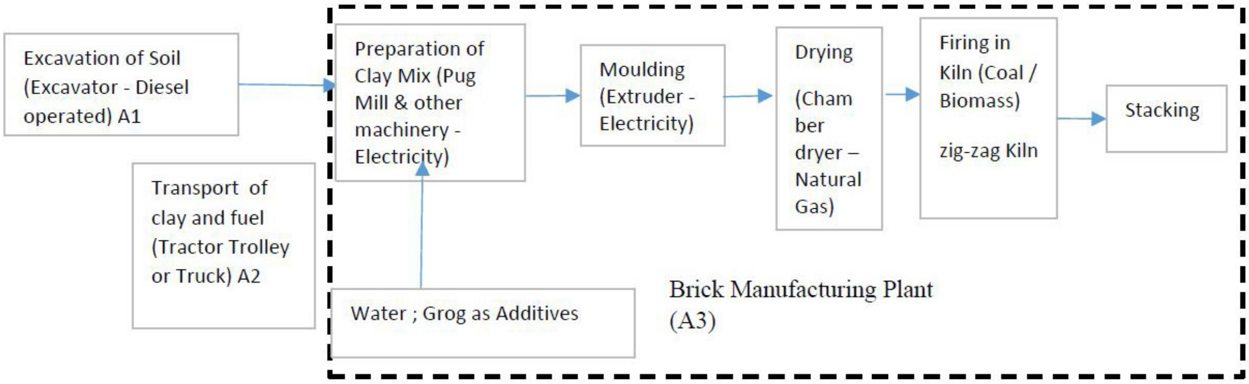

Figure 4: Manufacturing process of Vertically Cored Interlocking Hollow Clay Block

The process and energy data used for LCA is presented in Table 3.

Table 3: The process and energy data used for cradle to grate analysis of Vertically Cored Interlocking Hollow Clay Block

Product life stage	Description
A1	The soil for manufacturing bricks is surface soil excavated from nearby agricultural fields. A JCB excavator is used for excavating the clay. The typical diesel consumption in excavation is taken as 7 l/h and the excavation rate is 45 m^3 of soil/h. The specific fuel consumption of excavation is 0.095 l of diesel/m^3 of burnt clay product. The carbon emission factor for diesel is taken as 2.68 $kgCO_2$/l [10]
A2	a) Both trucks and tractor trolleys are used for transporting the soil from the agricultural fields to the brick manufacturing unit. For the analysis, the transportation is considered by 10-wheeler truck, which transports 20 tons of clay/trip. The distance of the place of excavating the soil to the brick kiln is taken as 10 km. b) The coal is assumed to be transported using trucks. For the analysis, the transportation is considered by 10-wheeler truck, which transports 18 tons of coal/trip. It is assumed that all the coal which is being used is indigenous and the average distance from the place of mining to the brick kiln is taken as 500 km. The total travel distance taken for the analysis consists of both to-and-fro travel of the truck. The emission factor for the 10-wheeler truck is taken as 0.7375 $kgCO_2$/km [11]
A3	a) The soil-mix is prepared in a series of electricity operated machinery including pug-mill and mixers. The specific electricity consumption of various machinery together is 4.03 kWh/m^3 of burnt clay product. b) The moulding of the block is done using an electricity operated extruder. The specific electricity consumption of the extruder is 5.04 kWh/m^3 of burnt clay product. c) The bricks are dried in a chamber dryer. The chamber dryer has multiple chambers. One chamber having capacity to dry 1848 blocks, has a cycle time of 14 hours and consumes 380 scm of piped natural gas. Taking 10,000 kcal/scm as the gross calorific value of the piped natural gas, the specific energy consumption for drying is 955 MJ/m^3 of burnt clay product. d) The blocks are fired in a zig-zag kiln. The kiln has a capacity to produce 150 tons of burnt clay product every day. The kiln uses mainly bituminous coal (4 tons/day), along with sawdust (1 ton/day) and dry cow dung (1 ton/day). Taking GCV of 5500 kcal/kg for the bituminous coal, 4000 kcal/kg for saw dust and dry cow dung, the specific energy for firing is calculated as 794.20 MJ/m^3 of burnt clay product. Weighted grid emission factor for electricity is taken as 0.71 $kgCO_2$/kWh [13]. The emission factor for natural gas is taken as 56.1 tCO_2/TJ [14]. For the carbon analysis, it is assumed that all the energy in the kiln comes from burning coal. The emission factor for bituminous coal is taken as 94.6 tCO_2/TJ [14].

2.2 Embodied carbon assessment of walls constructed using solid burnt clay brick & vertically cored interlocking hollow blocks

Referring to project life cycle (figure 1), this analysis covers product (A1-A3) and construction process stage (A4 -A5). A4 accounts for transportation of the materials from the manufacturing plant to the construction site and A5 accounts for construction and installation. The functional unit chosen is one square meter of wall and the results are presented in kgCO2/m² of wall area.

The analysis compares two walls a) 230 mm thick wall (unplastered) made from the solid burnt clay brick (230mmx 110 mm x 70 mm size) and b) 150 mm thick wall (unplastered) made from the vertically cored interlocking burnt clay blocks (300 mm x 150 mm x 200 mm). The average thermal conductivity of the manually moulded solid burnt clay brick produced in the IGP region is 0.6 W/m.K [15], which results in a computed Uvalue of 230 mm thick solid brick wall (un-plastered) as 2.6 W/m².K The U-value of the 150 mm wall constructed using vertically cored interlocking burnt clay blocks is 1.4 W/m².K as per the product specifications provided by the brick manufacturer. Thus, it can be observed that even with lower thickness, the U-value of the vertically cored block is expected to have lower U-value.

The quantity of bricks/blocks, cement and sand were determined by constructing two walls, each having an area of 38 ft2 (3.53 m²), one using the solid burnt clay brick and the other using the vertically cored interlocking hollow burnt clay blocks. The construction of the two walls was carried out at the site of a multi-family residential housing project at Varanasi. The quantity data used for the analysis is given in Table 4.

Table 4: Quantities of materials required for the construction of wall

		Wall with solid burnt clay brick (un-plastered)	**Wall with vertically cored interlocking hollow burnt clay block (un-plastered)**
Size of the brick/block		230 mm x 110 mm x 70 mm	300 mm x 150 mm x 200 mm
Thickness of the wall (mm)		230	150
Area of the wall (m²)		3.53	3.53
Brick/blocks	Number	370	54
	Weight (kg)	1110	464.2
	Volume (m³)	0.655	0.486
Cement in mortar	Volume (m³)	0.050	0.017
	Density (kg/m³)	1440	1440
	Weight (kg)	71.78	24.47
Sand in mortar	Volume (m³)	0.241	0.092
	Density (kg/m³)	1600	1600
	Weight (kg)	385.2	147.3

Table 5: The data used for carrying out life cycle carbon analysis (A1-A5) for walls

Product life cycle stage	**Description**
A4	Transport of building materials from the manufacturing plant to the construction site a) Brick and Block: For the analysis, the transportation is considered by 10-wheeler truck, which transports 18 tons of brick/trip. The distance of the brick manufacturing plant to the construction site is taken as 50 km. b) Cement: For the analysis, the transportation is considered by 10-wheeler truck, which transports 18 tons of cement/trip. The distance of the cement manufacturing plant to the construction site is taken as 250 km. c) Sand: For the analysis, the transportation is considered by 10-wheeler truck, which transports 18 tons of sand/trip. The distance from the sand mining location to the construction site is taken as 100 km. The total travel distance taken for the analysis consists of both to-and-fro travel of the truck. The emission factor for the 10-wheeler truck is taken as 0.7375 $kgCO_2/km$ [11]

Product life cycle stage	Description
A5	Construction and installation. The carbon emission factors considered for the analysis are: a) Solid burnt clay brick: 198.9 $kgCO_2/m^3$ of burnt product as computed in this study. b) Vertically cored interlocking hollow clay block: 137.3 $kgCO_2/m^3$ of burnt product as computed in this study. c) OPC cement: 0.996 $kgCO_2/kg$ [15] d) Sand: 0.009 $kgCO_2/kg$ [16]

3. Results

3.1 Cradle to gate (A1-A3) carbon emissions for solid burnt clay brick & vertically cored hollow block

The results of the cradle to gate carbon emissions for solid burnt clay brick manufactured in the IGP rgion is estimated as 198.87 $kgCO2/m^3$ of burnt product, while that for the vertically cored interlocking hollow burnt clay blocks is 31% lower at 137.27 $kgCO2/m^3$ (refer Table 6 for details).

Table 6: Results of Cradle to gate (A1-A3) carbon emissions for solid burnt clay brick and vertically cored hollow block

		CO_2 Emissions ($kgCO_2/m^3$ of burnt product)	
		Solid Burnt Clay Brick	Vertically Cored Interlocking Hollow Burnt Clay Block
A1	Excavation of Soil	0.60	0.25
A2	Transportation of soil	1.38	0.45
	Transport of coal	3.98	1.42
A3	Soil-mix preparation	0.61	2.86
	Moulding/Extruder	0	3.58
	Drying	0	53.58
	Firing of brick/block in the kiln	192.30	75.13
	A1-A3	**198.87**	**137.27**

It is interesting to note that in the case of the 230 mm solid brick wall, while the brick contributes to around 60% of the carbon emissions, almost 34% of the emissions are contributed by the cement used in the mortar. This points out to the fact that for low-carbon masonry, apart from attention on using bricks with lower carbon emissions, due attention needs to be paid to the quantity and carbon emission characteristics of mortar also.

3.2. Upfront embodied carbon (A1-A5) assessment of walls constructed using solid burnt clay brick & vertically cored interlocking hollow blocks

The upfront embodied carbon emissions (A1-A5) for a 230 mm unplastered solid burnt clay brick wall is calculated as 59.81 $kgCO2/m^2$ of wall, while that for a 150 mm unplastered wall made from vertically cored interlocking hollow burnt clay block is 55% lower at 27 $kgCO2/m^2$ of wall (refer Table 7 for details)

For the vertically cored hollow block, firing and drying operations contribute to 55% and 39% of the carbon emissions respectively. For the solid burnt clay brick the firing operation alone contributes to around 97% of the carbon emissions, there are no emissions from drying as bricks are dried in the open under the sun.

Table 7: Upfront embodied carbon (A1-A5) assessment of walls constructed using solid burnt clay brick & vertically cored interlocking hollow blocks

		CO_2 emissions ($kgCO_2/m^2$ of wall)	
		Solid burnt clay brick (wall thickness 230 mm)	Vertically cored interlocking hollow burnt clay block (wall thickness 150 mm)
A4 (Transportation)	Brick/Block	1.29	0.54
	Cement	0.42	0.14
	Sand	0.86	0.34
A5 (Construction & Installation)	Brick/Block	36.16	18.76
	Cement	20.24	6.90
	Sand	0.85	0.33
A1-A5	**Total**	**59.81**	**27.00**

4. Discussion

The housing in the IGP region is dominated by solid burnt clay brick masonry. The analysis shows that if the conventional solid burnt clay brick (230mm x 110 mm x 70 mm) is replaced with the vertically cored interlocking hollow burnt clay blocks (300 mm x 150 mm x 200 mm), then significant reduction in carbon dioxide emissions and resources is possible. The analysis shows that at the product level (cradle-to-gate), the CO^2 emissions ($kgCO^2/m^3$ of burnt product) for vertically cored interlocking hollow burnt clay blocks is 31% lower than that of solid burnt clay brick. In addition, it also results in savings of 58% in the consumption of soil which reduces from 1.44 m^3 of soil/m^3 of burnt product for solid brick to 0.61 m^3 of soil/m^3 of burnt product for the vertically cored blocks.

The savings at the product level are further enhanced when the bricks/blocks are used to construct a wall. A 150 mm thick wall made of vertically cored hollow block results in 55% savings in the CO^2 emissions ($kgCO^2/m^2$ of wall) when compared to a wall of 230 mm thickness made from solid burntclay brick. It is to be noted that the thermal transmission or U-value of the vertically cored hollow block wall is lower, thus improving the thermal comfort and reduction in operation energy. In addition to the CO^2 savings, there are additional savings in materials used in the mortar. The cement consumption in mortar reduces by 66% from 20.3 kg of cement/m^2 of wall for solid brick wall to 6.9 kg of cement/m^2 of wall for vertically cored hollow brick wall. The sand consumption reduces by 62% from 109.1 kg of sand/m^2 of wall for solid brick wall to 41.7 kg of sand/m^2 of wall for vertically cored hollow block wall.

As the scope of the study was limited to the product and building element level, the study has not analysed the impact on CO^2 emissions and other resources for the construction of a full residential building using the two types of bricks. Such an analysis will help in quantifying additional large savings in steel and concrete. An indication of the scale of savings is available in a recent study [17] that has compared the steel and concrete consumption in a four-storey residential building (built-up area of 500 m2 located at Kolkata). The study has compared three construction systems:

a) RCC framed structure, RCC slab, with solid brick masonry (brick size: 250 mm x 125 mm x 75 mm)

b) RCC framed structure, RCC slab with horizontally cored hollow burnt clay blocks (block size:300 mm x 200 mm x 200 mm)

c) Constrained masonry, waffle slab using vertically cored hollow burnt clay blocks (block size:300 mm x 200 mm x 200 mm)

The savings obtained in steel and concrete is shown in Table 8. It is seen that just by replacing the solid burnt clay brick with hollow burnt clay blocks, 32% reduction in steel and 20% reduction in concrete can be achieved. However, if the construction system is changed to constrained masonry using vertically cored burnt clay block and waffle slab, then 66% reduction in steel and 48% reduction in concrete is possible.

Table 8: Savings obtained in steel and concrete for three construction systems [17]

Construction system	Steel (kg/m² of built-up area)	M 30 Concrete (m³/m² of built-up area)	Savings (%)
RCC framed structure, RCC slab (150 mm), with solid brick masonry (brick size: 250 mm x 125 mm x 75 mm)	48.1	0.393	Nil
RCC framed structure, RCC slab (150 mm) with horizontally cored hollow burnt clay blocks (block size:300 mm x 200 mm x 200 mm)	32.9	0.315	32 % in steel and 20% in concrete
Constrained masonry, waffle slab (200 mm) using vertically cored hollow burnt clay blocks (block size:300 mm x 200 mm x 200 mm)	16.4	0.204	66% in steel and 48% in concrete

Overall, the study results show the large potential of carbon and resource saving by shifting from solid burnt clay brick to vertically cored interlocking hollow clay blocks. Further work can focus on:

b) Extending the analysis to full building level for various types of residential buildings

c) Exploring further the possibility of confined masonry and waffle slab construction system and other innovative low-carbon construction systems using the vertically cored blocks

d) Experimentally determining the U-value of the 150 mm wall made from the vertically cored blocks and studying the improvement in thermal comfort and reduction in operational energy through simulations.

e) Studying in detail the techno-economics of the vertically cored blocks and examining its scaling-up prospects in the IGP region.

5. Conclusion

The study presents an innovative new burnt clay product – vertically cored interlocking burnt clay block- being manufactured by a brick manufacturer in the IGP region. The study presents the results of the life cycle analysis (as per EN 15804) and quantifies reductions in carbon and resource consumption for the product and the building element (wall). The analysis is based on the data collected from the industry. The cradle to gate analysis shows a reduction of 31% in the CO^2 emissions ($kgCO^2/m^3$ of burnt product) and 58% in soil consumption (m^3 of soil/m^3 of burnt product) for the vertically cored hollow block. A 150 mm thick wall made of vertically cored hollow block results in 55% reduction in the CO^2 emissions ($kgCO^2/m^2$ of wall) when compared to a 230 mm thick wall of solid brick. In addition, the cement consumption in mortar reduces by 66% and sand consumption by 62% per m^2 of wall area. The study further indicates a significant reduction in concrete and steel consumption if the analysis is extended to the building level.

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