Title: Development of sustainable prefabricated housing system by small-scale experimental model

Author 1

Ravijanya Chippagiri, Research scholar

Department of Civil Engineering at VNIT, Nagpur, India

ravijanya991@gmail.com (Corresponding Author)

ORCID Number: 0000-0002-1698-8282

Author 2

Ana Bras, PhD

Built Environment and Sustainable Technologies (BEST) Research Institute, Liverpool John Moores University, UK

a.m.armadabras@ljmu.ac.uk

Author 3:

Rahul V. Ralegaonkar, PhD

Department of Civil Engineering at VNIT, Nagpur, India

sanvan28@yahoo.com

Abstract

Utilisation of unused industrial wastes and need for rapid volumetric construction led to the evolution of sustainable prefabricated housing elements, particularly for urban slums. An agro-industrial by-product as raw material and waste expanded polystyrene beads as the insulation material are chosen to develop a lightweight prefabricated construction element. This bio-ash is used as a partial replacement, 20% and 10% for the fine aggregates to prepare concrete and lightweight mix respectively. A small-scale model of one-third scale is conceptualised as per standards that include precast columns and beams as framed structure, and prefab panels as walling and roofing elements. These elements are developed as per the desired mix proportions of the identified raw materials. The respective laboratory specimens are evaluated for the physico-mechanical, durability, and thermal properties. The developed walling end-product is found to be 27% lighter, 8% stronger, 24% less water-absorbent, and 62% less conductive when compared with the properties of commercially available fly-ash brick. A solar photovoltaic panel is embedded into the model's pitch roof that accommodates 71% of its generated energy to necessary electrical appliances. The material properties are found to be satisfactory for its on-site application and its final erection being 20% faster than conventional method.

Keywords: Sustainability; lightweight concrete; precast concrete; modelling; strength and testing of materials.

1. Introduction

Increasing population across the globe has resulted for housing shortage. World Bank has estimated a need of 300 million houses by the end of 2030 (Kulshreshtha *et al.*, 2020). Majority of the housing shortage lies with urban population that may increase up to 60% by the end of 2030 (Grandoliniede and Ijjasz-Vasquez, 2016). India is currently the second-most populous country with a population exceeding 1380 million at the end of 2020. The country's urban population is figured around 35%, which indicates the need of volumetric housing construction. The government has taken an initiative scheme "Housing for all" which targets the construction of 20 million urban houses by the end of 2022 (Department of Economic and Social Affairs, no date; Ministry of Housing & Urban Poverty Alleviation Government of India, 2017). This scheme is mainly focussed on the economically weaker section (EWS), and low income group (LIG).

Industrialisation and growing population have increased construction activities across the country. The construction sector continues as the second largest industry and is mostly accountable for 30% of CO_2 emissions, 32% of energy consumption, and 30-40% of waste generation (Ferdous *et al.*, 2019a). A report from the UN climate action summit 2019 mentions the nations to cut down their CO_2 emissions to 45% by 2030 (United Nations, 2019). Rise in advanced technologies and the requirement of proficient construction practices have led to rapid construction methods like prefabrication technology. Prefabrication (prefab), is defined as the manufacturing of the construction elements in a controlled industrial environment and installation of the same at desired site (Steinhardt and Manley, 2016).

Construction in the urban areas is challenging in case of conventional methods because of densely populated areas, cost, and time constraints (Dave, Watson and Prasad, 2017). Prefab technology found to be advantageous when compared to the conventional construction methods. The specific study resulted in 65% reduction in waste generation, 25% less manpower requirement, 15% time saving, 14% reduction in greenhouse emissions and 63% reduction for accidents (Li, Shen and Xue, 2014; Krishnanunny and K, 2018; Ferdous *et al.*, 2019b; Liu, Jia and Liu, 2019). However, the technology needs higher investment and expertise for planning and execution.

Major materials involved in the traditional construction activities include steel, concrete, timber, and bricks. One ton of manufacturing steel, cement, and burnt clay bricks each release around 2 tonnes, 0.95 tonnes, and 0.05 tonnes of CO_2 respectively in the environment (Van Ruijven *et al.*, 2016; Nath, Lal and Das, 2018; Gavali *et al.*, 2019). An increase in the construction activities and industrialisation has led to the increase in exploitation of natural resources and generation of industrial wastes. Managing these industrial rejects is considered as one of the major challenges. [Industrial rejects is an alternate terminology for the industrial by-products or industrial wastes (Kumar *et al.*, 2021)]. Thus, to balance these two aspects, the alternative to the natural resources (sand) was explored by researchers using the by-products having the origin either as agro-based (rice husk) or industrial based (coal residue), collectively termed as agro-industrial by-products for the construction industry. The prior research encourages the application of sustainable construction materials for the energy conservation inside the structures (Bras *et al.*, 2020). The rejects like fly ash, silica fume, ground granulated blast furnace slag (industry-based), and rice husk ash (agro-based) were already considered as mineral admixtures by the Indian standards. Cement has been the major material in the construction industry and cement-based materials were widely used all over the world for various cast in-situ and precast techniques. Three grades in ordinary Portland cement (OPC), grades 33, 43, and 53 were approved in India for their applications and specific standards were set up namely IS 269, IS 8112, and IS 12269 respectively. Along with these, there were a few other types of cement partially mixed with fly ash and blast furnace slag called as Portland pozzolana cement (PPC) and Portland slag cement (PSC) respectively for its use at specific locations (Kumar Gangaram Singh and Kizhakkumodom Venkatanarayanan, 2020; Singla, Kumar and Alex, 2020). Apart from these, many other researchers have developed sustainable masonry products from sugarcane bagasse ash (SBA), bio-briquette ash (BBA), re-cycled paper mill waste (RPMW), construction and demolition waste (C&DW), and co-fired blended ashes (Raut *et al.*, 2012; Dakwale and Ralegaonkar, 2014; Madurwar, Mandavgane and Ralegaonkar, 2015; Sakhare and Ralegaonkar, 2016a; Ram, Ralegaonkar and Pradhan, 2017; Gavali and Ralegaonkar, 2020; Rathod *et al.*, 2020). In order to conserve the operational energy demand of the structures, it is appropriate to design the building materials with low thermal conductivity. The insulating materials like expanded polystyrene (EPS), extruded polystyrene (XPS), polyurethane (PUR), polyisocyanurate (PIR), mineral wool, MgO boards, foamed concrete, etc. are some of the examples that helped to improve the thermal resistance of the building elements (Einea *et al.*, 1991; Correia, Ferreira and Branco, 2006; Naito *et al.*, 2012; Shams *et al.*, 2015; Amran *et al.*, 2016; I. Goh *et al.*, 2016; Lopez and Froese, 2016; Daniel Ronald Joseph, Prabakar and Alagusundaramoorthy, 2018; Flansbjer *et al.*, 2018).

In order to meet the increasing demand for the development of sustainable mass housing schemes, it is apt to promote faster construction technology. From the reviewed literature, it is evident that the manufacturing of construction materials using industrial ashes and insulation materials is a feasible and sustainable solution. However, the development of sustainable prefab walling technology using industrial ashes and insulation materials that are light in weight and having better thermal insulation properties is one of the aspects to be researched. Thus, the present study highlights the design and development of lightweight prefab walling material using agro-industrial ash, CFA along with insulation material in a view to satisfy both sustainability and energy-efficiency objectives. The small-scale modelling technique is used to demonstrate the prefabricated housing technique.

2. Materials and Methodology

2.1 Materials

The locally available agro-industrial ash (located 31 km from the city of Nagpur, India), obtained by co-firing coal and saw dust (CFA) was identified as a raw material (Fig. 1). Research related to this ash was carried out in various experimental studies by previous researchers. As the source being the same, the material was found consistent with its properties even though acquired through various seasons. The products like bricks (Ram, Ralegaonkar and Pradhan, 2017), mortar (Shelote *et al.*, 2021), concrete (Chippagiri *et al.*, 2021), and alkali-activated masonry products (Gavali *et al.*, 2019) were developed earlier. The design of modular prefabricated construction elements using CFA is aimed in the present study. Fine aggregates are partially replaced with CFA to develop precast components and lightweight prefab elements in this study. This raw material found in compliance with the specified material characteristics as per section 7/part 6 of National Building Code (NBC-2016) (BIS, 2016) to be used in prefabrication such as its easy availability, light in weight, and better thermal insulation as compared to river sand.

Physical properties and chemical characterization are provided in Table 1. The specific gravity is determined with the volume displacement method as per IS 1727: 1967. The bulk density test is performed as mentioned in IS 2386 (Part 3): 1963. The chemical characterization of this raw material is determined from the chemical analysis done using X-ray fluorescence (XRF) scan which provides the oxides present in the material.

Figure 1. CFA

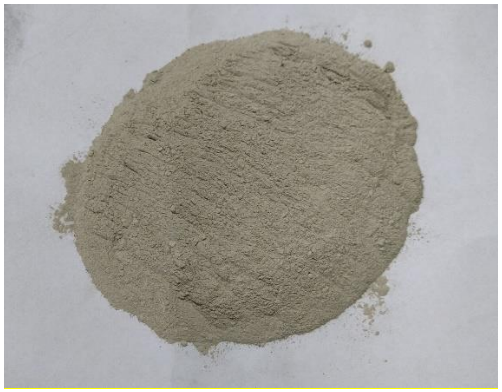

Figure 2. Fly Ash

Table 1. Properties of raw material – CFA.

<table>
<tr><td rowspan="3">Physical properties</td><td colspan="2">Specific gravity</td><td colspan="6">2.29</td></tr>
<tr><td colspan="2">Color</td><td colspan="6">Black</td></tr>
<tr><td colspan="2">Bulk density</td><td colspan="6">1430 kg/m^3</td></tr>
<tr><td rowspan="2">Chemical characterization</td><td>Oxides</td><td>SiO_2</td><td>Al_2O_3</td><td>Fe_2O_3</td><td>K_2O</td><td>SO_3</td><td>CaO</td></tr>
<tr><td>% Content</td><td>68.5</td><td>8.89</td><td>3.39</td><td>1.68</td><td>1.42</td><td>1.4</td></tr>
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Along with the by-product, several other conventional materials such as cement, fly ash (Fig. 2), river sand, crush sand, and coarse aggregates are used in this study. Additionally, mixes are trialled with a calcium-based accelerator, waste EPS beads, polymers such as hydroxypropyl methylcellulose (HPMC) and redispersible polymer (RDP), mineral, and chemical admixtures to obtain the targeted end-products.

2.2 Mix Design/Proportion, Preparation of specimen

Two different concrete mixes are proposed in this study. One for columns, beams & roof. The other lightweight (LW) concrete mix for the walling elements. Five trials for the concrete mix proportion (Table 2) and 11 trials for lightweight mix (Table 3) are performed by changing various combinations of the materials and their proportions. Each mix trial is tested for 6 specimens, 3 each for both 7 day and 28 day average strength. Density and compressive strength are considered the priority parameters and the final mix is derived based on these properties. A density of 2200 kg/m^3 and 1300 kg/m^3 was targeted for concrete and LW mix respectively. Similarly, an average compressive strength of 25 MPa and 7 MPa for concrete and LW mix respectively was chosen for the design. The LW mix is designed based on non-load bearing criteria and hence, the structural properties of this specific criteria was tested as per the codal provisions. The raw material is partially replaced with fine aggregate by 20% in concrete and by 10% in lightweight mix in the final mix proportion. Based on this, various samples are cast to test for physico-mechanical, durability, and thermal properties as per the codal standards (Table 4). The particle size graph of the materials used for LW mix are shown in the Figure 3.

Table 2. Mix design trials for concrete (All values in kg)

Trial No.	Cement	River Sand	CFA	20mm Gravel	10mm Gravel	Water	Aeration Agent ($\times 10^{-3}$)	Admixture

C1	4.32	7.46	0	6.45	6.45	2.05	-	-
C2	4.32	5.97	1.49	6.45	6.45	2.05	-	-
C3	4.32	3.73	3.73	6.45	6.45	2.05	-	-
C4	3.92	5.424	1.356	5.86	5.86	1.86	0.3	0.012
C5	3.92	5.424	1.356	5.86	5.86	1.86	0.5	0.016

Table 3. Mix design trials for LW mix (All values in kg)

Trial No.	Premix							Premix	EPS beads ($\times 10^{-3}$)	Crush Sand	CFA	Water	Accel-erator ($\times 10^{-3}$)	Admix-ture ($\times 10^{-3}$)
	Cement	Fly Ash	Latex ($\times 10^{-3}$)	HPMC Polymer ($\times 10^{-3}$)	RDP Latex ($\times 10^{-3}$)	Micro Silica ($\times 10^{-3}$)	Calcium based Accelerator ($\times 10^{-3}$)							
LW1								0.973	26.78	3.000	-	0.300	-	
LW2	1.136	1.136	12.5	5	-	-	-	0.409	11.247	0.702	0.078	0.190	-	
LW3								0.818	22.5	0.504	0.056	0.290	-	
LW4								0.818	22.5	0.504	0.056	0.250	-	6.21
LW5	1.410	1.416	-	3	45	45	-	0.818	22.5	0.504	0.056	0.250	-	7.8
LW6								0.818	22.5	0.504	0.056	0.235	-	6.21
LW7								0.818	22.5	0.504	0.056	0.240	-	4.05
LW8	0.966	0.960	-	2	-	-	20	0.818	22.5	0.504	0.056	0.242	8.18	4.05
LW9								0.315	-	0.194	0.022	0.082	-	1.57
LW10	0.966	0.960	-	2	-	-	20	0.818	11.25	0.504	0.056	0.242	-	4.5
LW11								0.818	5.65	0.504	0.056	0.242	-	4.5
LW12	2.125	2.112	-	4.4	-	-	44	4.000	27.6	2.464	0.274	1.183	-	22

Table 4. Performance evaluation of developed end-product

Physico-mechanical properties	Standard procedure
Density	IS 2185 : 1979 (Part I)
Compressive strength	IS 2185 : 1979 (Part I)
Tensile strength	IS 5816 : 1999
Flexural strength	IS 516 : 1959
Water absorption	IS 2185 : 1979 (Part I)
Durability	Rapid chloride permeability test (ASTM C1202)
Thermal properties	Lee's Disc apparatus test (ASTM C177)

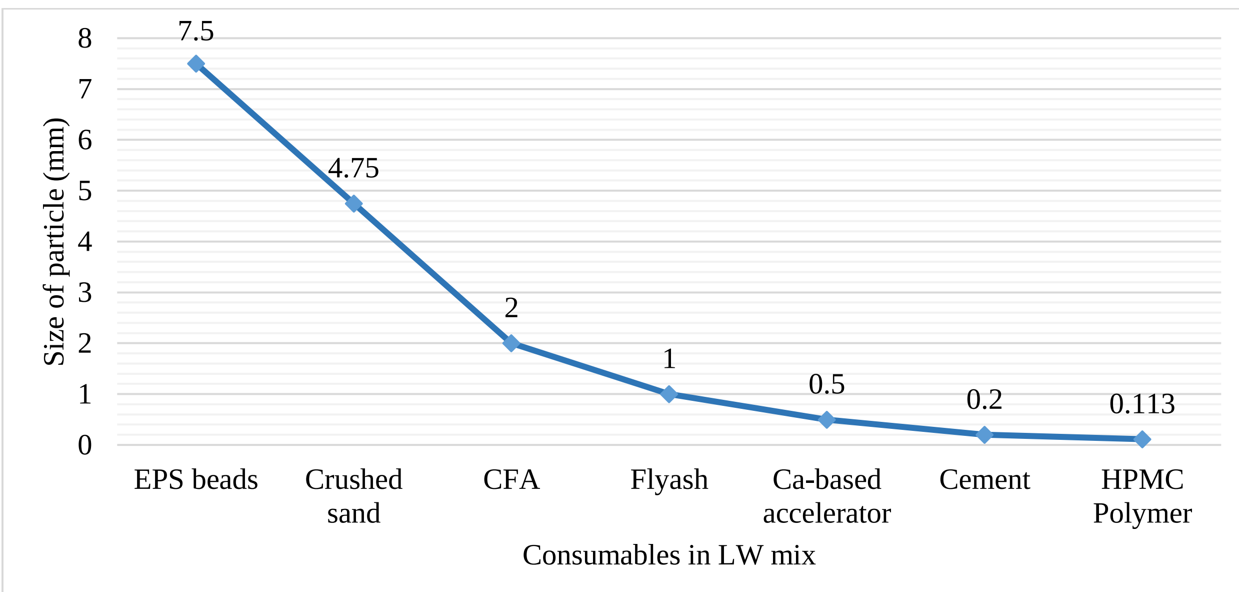


Figure 3. Particle size graph of the consumables of LW mix

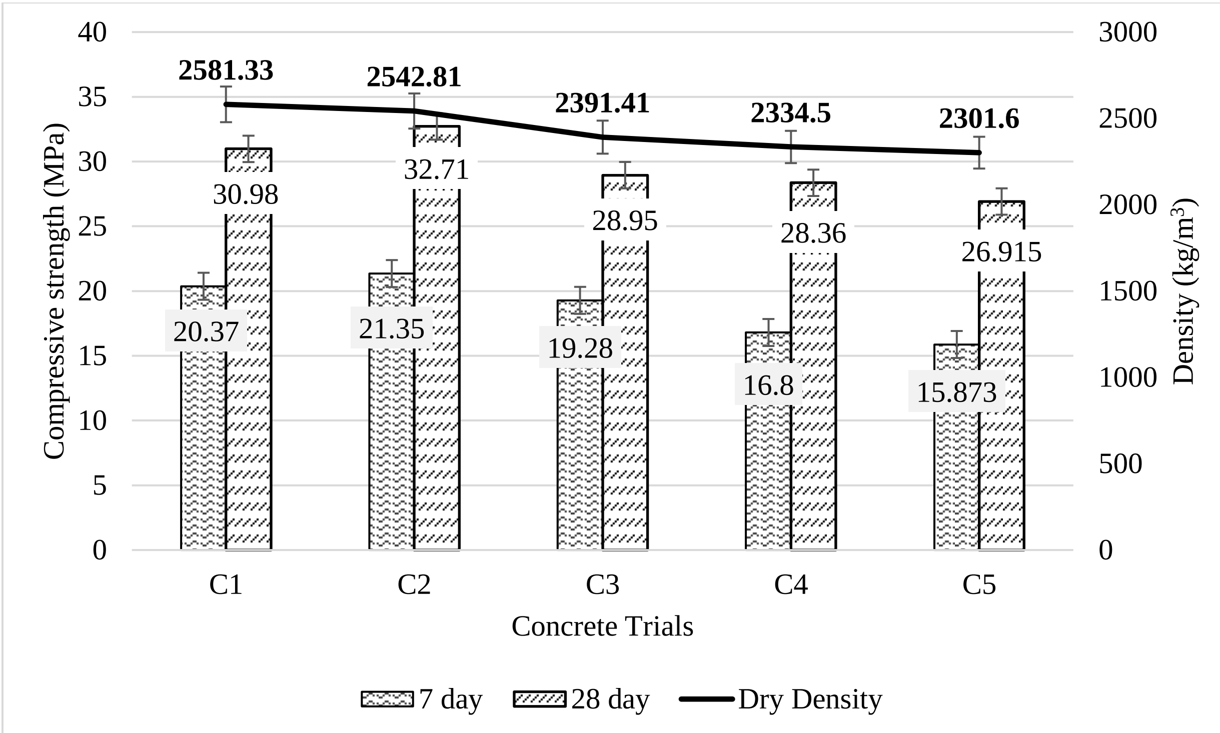


Figure 4. Concrete trials – Trade-off between compressive strength and density

The concrete trials C1, C2, and C3 are done to find out the optimum percentage of raw material that can partially replace the fine aggregates. Mix C2 with 20% replacement gave better results (Fig. 4). This mix is further experimented to bring down its density by around 10% by adding aeration agents. Mix C5 gave better results with desired strength and lesser density.

The LW mix trials are carried out using various materials with varying proportions as mentioned earlier. A premix of cementitious materials is prepared firstly and then a part premix is utilized for the mix trials. Figure 5 represents the comparison graph of strengths and density. Mix LW1 excludes the by-product to give an impression regarding the density and strength of the mix. Mix

LW9 excludes the EPS beads to realize the mortar's density and strength. LW11 was finalized as the mix and further LW12 is carried out for casting final specimens for testing.

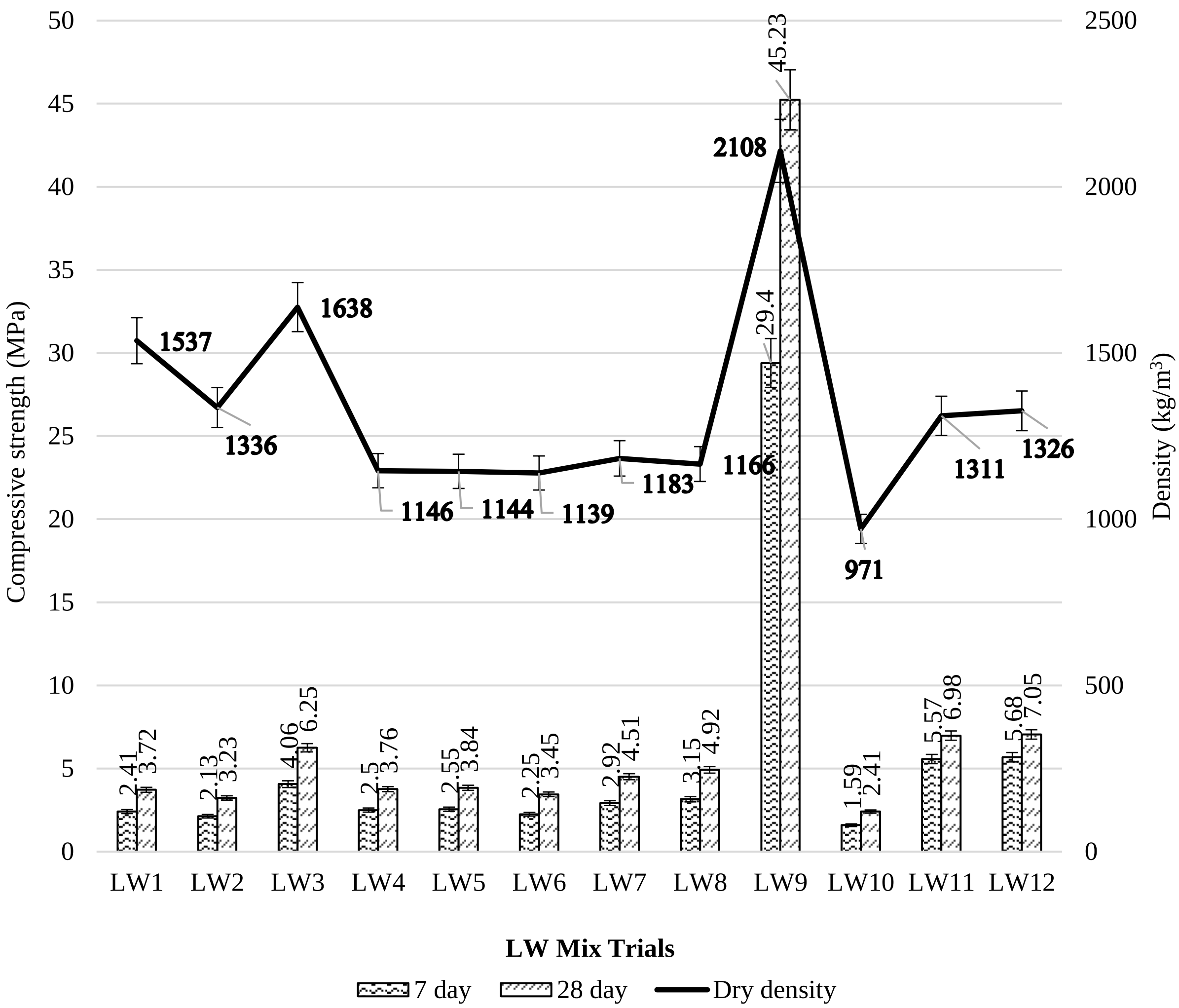


Figure 5. LW mix trials – Trade-off between compressive strength and density

2.3 Methodology

The cubes, cylinders, beams, and discs are cast and tested according to the procedures laid by the standards as mentioned earlier. The test images are also presented in the Figures 6-8. The mechanical properties are tested by casting cubes for compressive strength, cylinders for split tensile strength, and beams for flexural strength (Fig. 6 (a, b, c)). Discs of 100mm diameter and

50mm thickness (Fig. 7) are cast to check the durability and thermal properties. Rapid chloride permeability test (RCPT) is considered for checking the durability parameter of the end-products. Lee’s disc apparatus is used to evaluate the thermal conductivity of the products (Fig. 8).

(a) Compressive test (b) Split tensile test (c) Flexural test

Figure 6. Mechanical testing of concrete and lightweight mix

Figure 7. RCPT samples

Figure 8. Thermal Conductivity test

Based on the optimum mix proportion of the sustainable materials, a small-scale model house exactly to one-third of the original plan as shown in the Figure 9 is constructed. This particular model represents an urban slum house. As per the plan, structural elements such as beams and columns are made of precast concrete. The prefab walling and roofing elements are cast with LW mix. Roofing is experimented with the LW panels as the model is designed for a pitched roof with no loads exerting on its top surface. The process of prefabrication starting from the manufacturing of elements to the final erection is followed by considering section 10/part 7 of NBC (2016) – volume 1 (BIS, 2016). The 3D drawings and elevations from different directions of the experimental model house are as shown in the Figure 10.

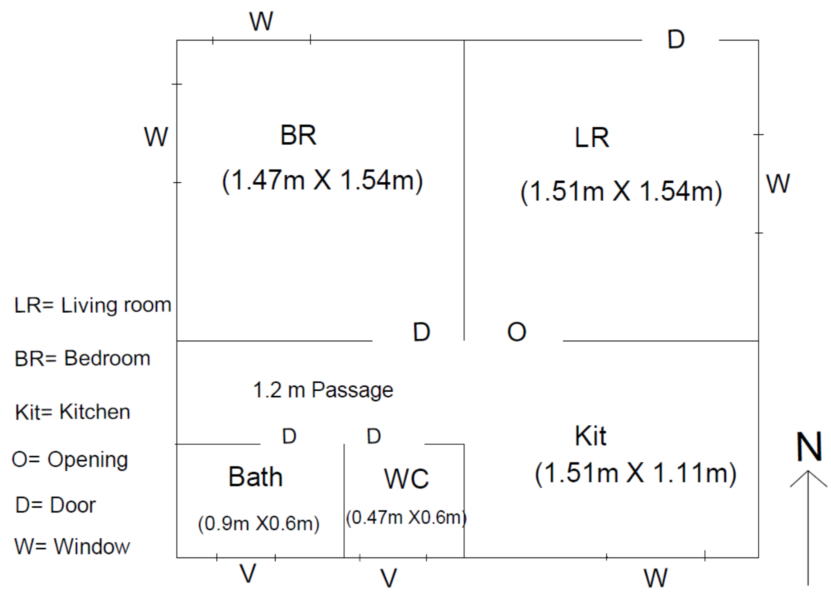


Figure 9. Line diagram of model house

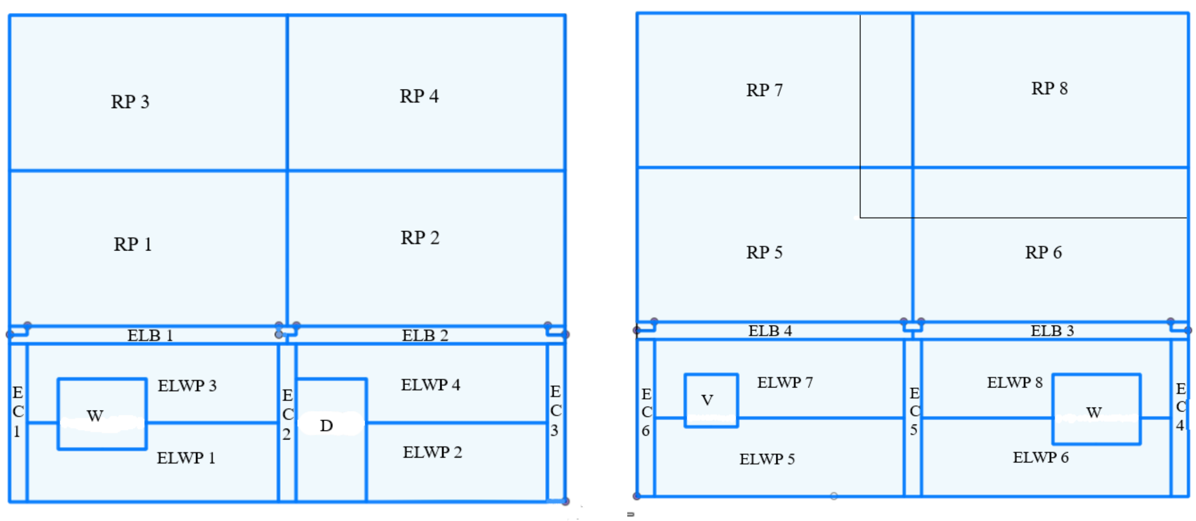
Figure 10. Model house - drawings

The structural elements and prefab panels are coded as per the Table 5 given below. Accordingly, the exterior elevations from four different directions along with their coded elements are presented as shown in the Figure 11 (a, b, c, d).

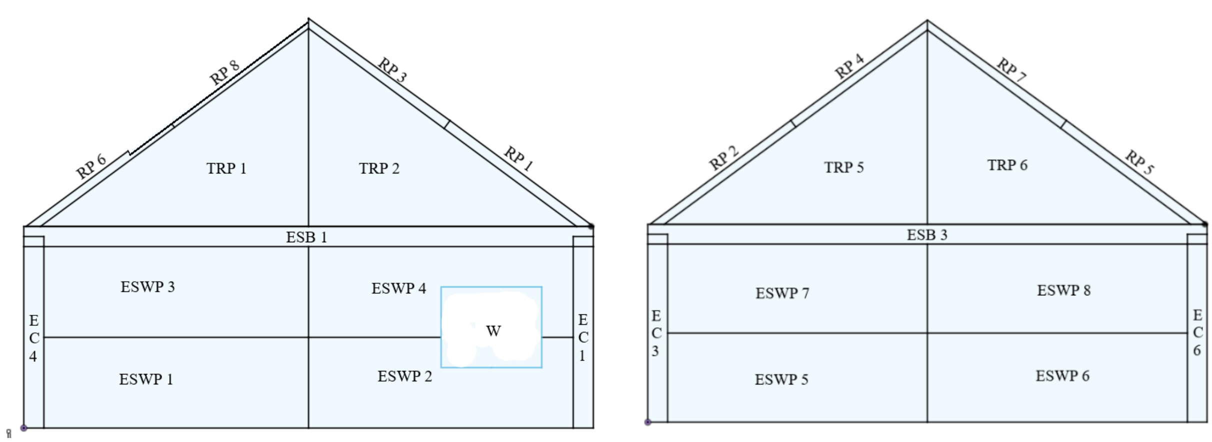
Table 5. Code, size and number of concrete and prefab elements

Type	Code	Name	Size (m)	Required Nos.
Concrete	EC	External Column	0.1×0.1×0.9	6
	ESB	External Short Beam	2.83×0.1×0.1	3
	ELB	External Long Beam	1.58×0.1×0.1	4
	ELWP	External Long Wall Panel	1.43×0.45×0.07	8

	ESWP	External Short Wall Panel	1.315×0.45×0.07	8
	RP	Roof Panel	0.885×1.58×0.05	8
Light weight Mix	TRP	Triangular Roof Panel	b=1.332, h=0.982, t=0.07	6
	ILWP	Internal Long Wall Panel	1.51×0.45×0.04	4
	ISWP	Internal Short Wall Panel	1.48×0.45×0.04	2
	LBRP	Long Bathroom Panel	1.45×0.45×0.04	2
	SBRP	Short Bathroom Panel	0.6×0.45×0.04	2



(a) North elevation (b) South elevation



(c) East elevation (d) West elevation

Figure 11. Exteriors of model house as per coding of panels

In order to meet the operational energy demand, it is proposed that the on-site built in decentralised energy generation approach be conceptualised for the model house. A pitch roof element is designed to have a solar PV panel embedded into the roof making it an integrated component. The angle of the roof was finalised at 37˚ as an optimum angle for generating maximum energy in the area of Nagpur, India (Sakhare and Ralegaonkar, 2018). A solar photovoltaic (PV) panel (Table 6), 6×12 polycrystalline cells capable of producing 1 kW energy within 6.22 sq. m. of panel area is integrated with a south-facing roof panel.

Table 6. Specifications of solar PV panel

Description	Specifications
Dimensions	1980 × 1010 × 14 ($\times 10^{-3}$)m
Weight of panel	45 kg
Max. power	320 W
Cell efficiency	18%
Units generated	215 units/sq.m./yr or 4.5 units/kW/yr
Thermal resistance	0.144 m^2K/W

3. Results and Discussion

Various tests revealed the suitability of concrete and LW mix. The physico-mechanical properties of both the end-products are mentioned in Table 7 and Figure 12. Along with these, durability and thermal properties are calculated and the final results of it are presented in Table 8.

Table 7. Physico-mechanical properties of developed end-products

S. No.	Property		Concrete	LW mix	Remarks (IS 456: 2000; IS:2185, 2005)
1	Density (kg/m^3)	Dry	2302	1312	LW mix falls under Grade B load bearing concrete masonry unit as per IS 2185 (Part 1) : 2005
2	Compressive strength (MPa)	7 day	15.87	5.68	
3		28 days	26.915	7.05	
4	Split Tensile strength (MPa)	28 days	1.83	1.275	-
5	Flexural strength (MPa)	28 days	4.02	2.16	Satisfies the condition mentioned in IS 456 : 2000
6	Water Absorption (%)	24 hrs	5.77	7.64	Falls less than 10% as per IS 2185 (Part 1) : 2005

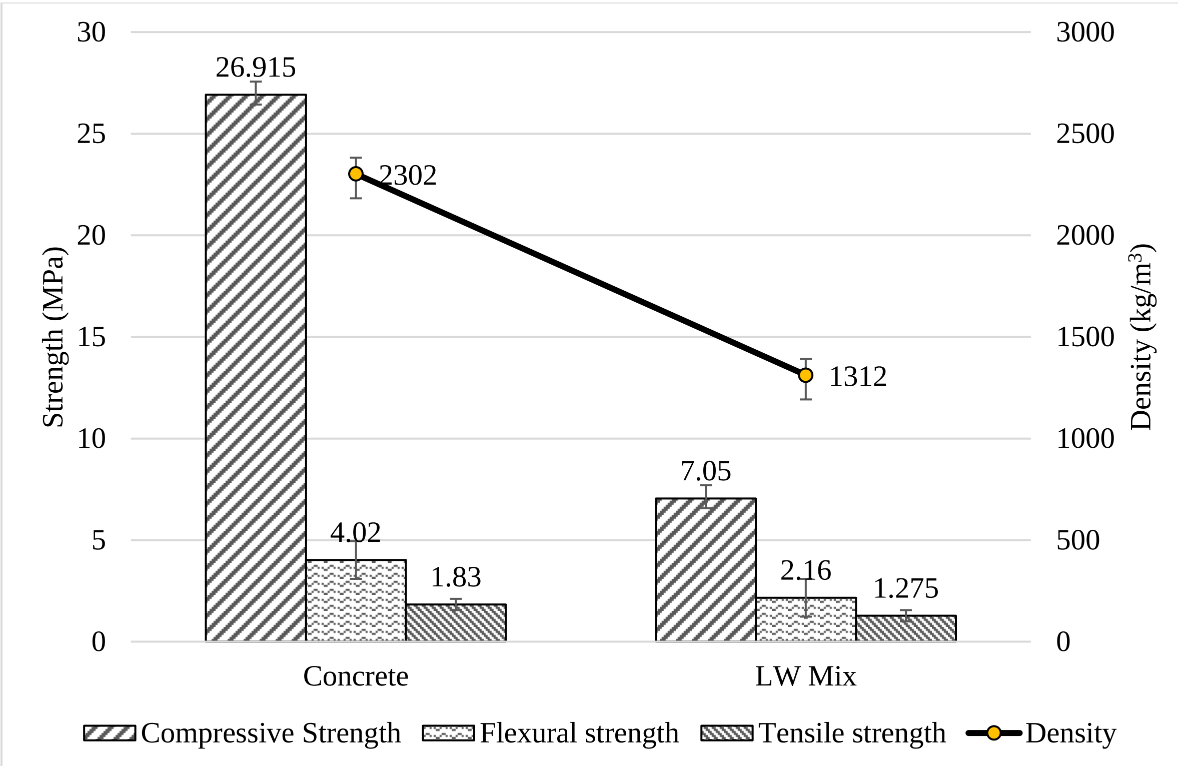


Figure 12. Physico-mechanical test results of developed mix

A study on stress-strain characteristics is conducted for the developed end-products. CFA-based concrete and LW mix cylinders are tested for compressive stress along with the strain values. Figure 13 indicates stress-strain plots for the developed products. Linearity in the curves is observed at the initial points of load followed by the non-linearity when the load increases further. After reaching their maximum stresses, a decline in the stress is observed with the increased strain value. The LW mix is designed as per the non-load bearing criteria and thus, its peak is observed at an early stress value than the CFA-based concrete.

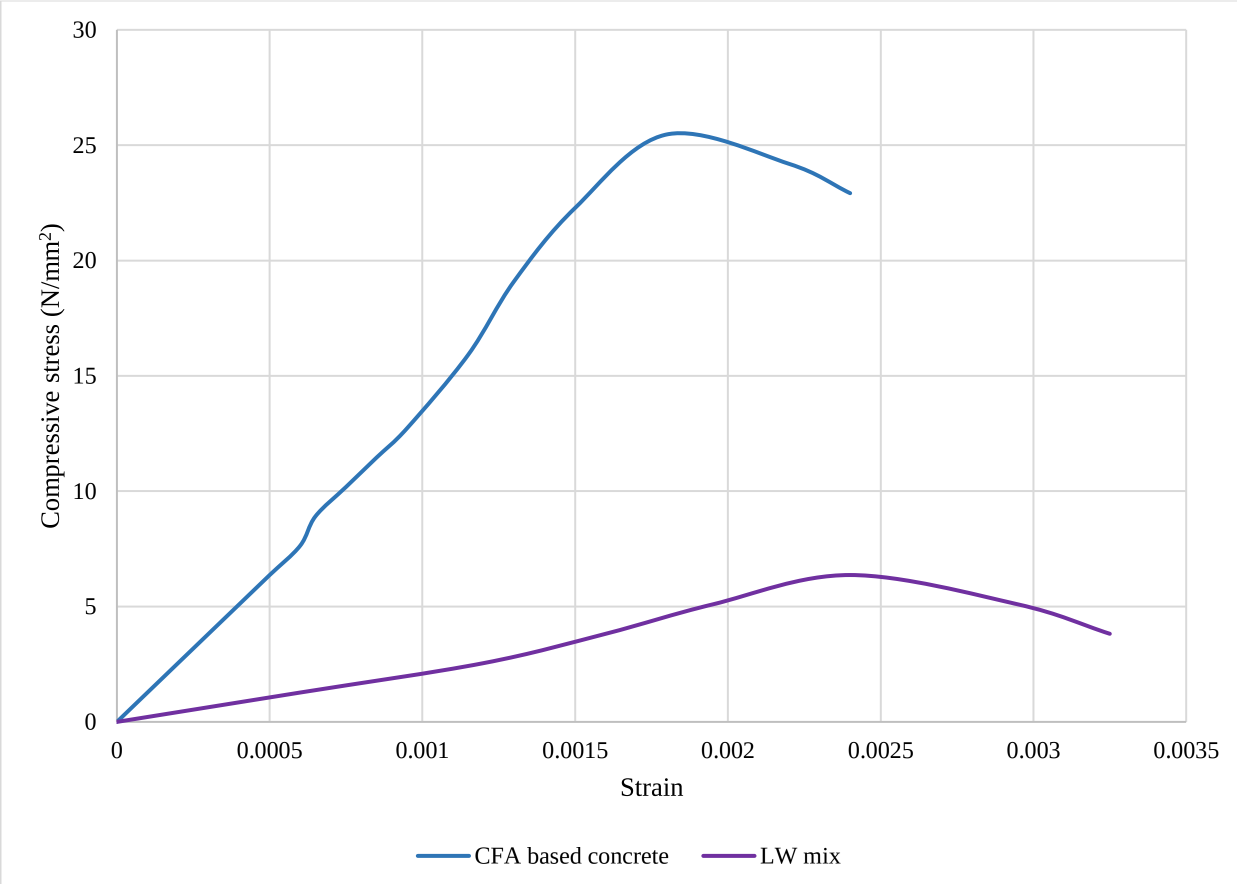


Figure 13. Stress-strain curve of both the developed end-products

Table 8. Thermal and durability properties of developed end-products

S. No.	Property	Name of test	Concrete	LW mix	Remarks
1	Thermal	Thermal conductivity (W/mK)	0.806	0.40	-
2	Durability	Chloride permeability (Coulombs)	619.29	329.04	Chloride permeability lies in very low range

A comparative analysis is studied between the developed end-product and commercially available walling materials such as burnt clay bricks and fly ash bricks. The details of the properties were referred from earlier research (Sakhare and Ralegaonkar, 2016b) and compared with the developed end-product. The proposed lightweight prefab panel is found to have better properties in four categories as mentioned in Table 9.

Table 9. Comparative analysis between various walling materials

Walling Material	Density (kg/m^3)	Compressive strength (MPa)	Water absorption (%)	Thermal conductivity (W/mK)
Burnt clay brick	1600	7.0	15	1.25
Fly ash brick	1800	6.5	10	1.05
Lightweight prefab panel	1312	7.05	7.64	0.40

From the comparison, the prefab walling panel is found to be 18% lighter, 0.7% stronger, 49% less water absorbent, and 68% thermally efficient when compared with the burnt clay brick. Similarly, the designed end product results as 27% less dense, 8% stronger, 24% less water absorbent, and 62% less conductive than the fly ash brick.

The energy generated from the installed solar PV panel on the top of model house is analysed. Based on its specifications mentioned earlier, the panel is capable of generating 2.56 kW-h of energy when 8 hours of daylight is considered as per Energy Conservation Building Code standards (ECBC, 2017). This can sufficiently accommodate a 75W ceiling fan and a 40W tube light assuming the working hours as 18 hours and 12 hours respectively which is around 71% of the generated energy.

4 Small scale modelling

The test results indicate their suitability in the construction industry resulting to execute a model house as discussed earlier with these end products. Thus, the total construction of this model house can be classified into 3 types which include works from raw material consumption to the final erection of the model house.

4.1 Prior casting work

As per the given plan of the structure, 6 columns and 7 beams are identified as structural elements. A structural plan is presented in Figure 14 showing the column and beam placements. Along with this, 40 prefab panels of varying dimensions are identified as walling and roofing members. The concrete beams have male and female-type joints where each beam rests on another beam and are jointed accordingly with the polymer-based epoxy grout. Similarly, roofing elements of south elevation have grooves for the PV panel to fit in the panels as an integrated solar PV panel roof.

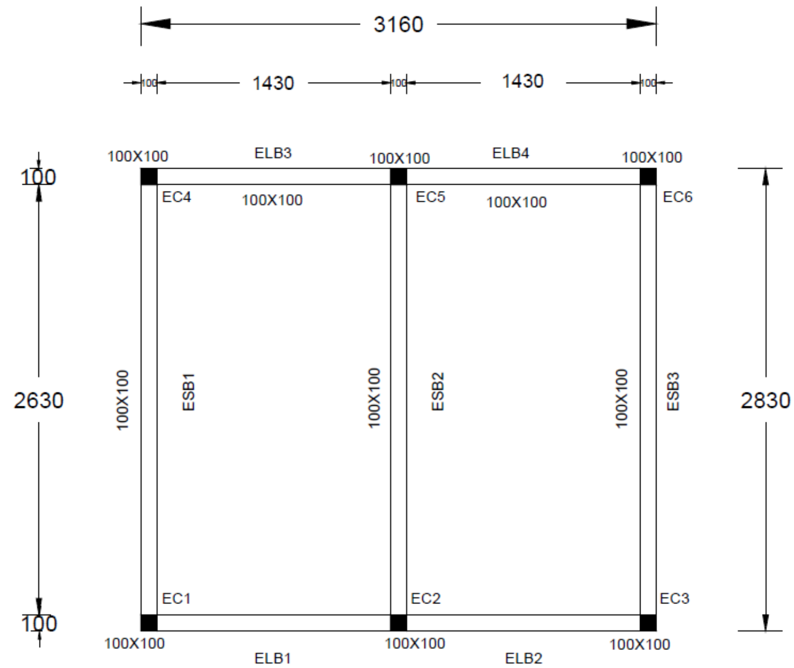


Figure 14. Structural plan of the proposed model house (Note: All dimensions are in mm)

Individual mould method (BIS, 2016) is opted for the casting process of elements. Wooden moulds are prepared as per the requirement such that each mould can be re-used multiple times for casting, intending to make the casting process time and resource saving. These moulds are shown in the Figures 15 and 16. They are oiled before casting and are repaired and cleaned after demoulding for casting the next set of panels.

Figure 15. Wooden moulds

Figure 16. Oiling of moulds

4.2 Casting, handling, curing and stacking

Eight batches of concrete and 30 batches of LW mix are prepared in their respective mixers and by placing them in the wooden moulds with required reinforcements (Fig. 17 and 18). Workability was inspected during the castings and the concrete and LW mixes have resulted in a medium and low degree of workability through the slump cone test. Each casting from the mixer was placed into the moulds within 30 minutes from addition of water into the mix.

As per the structural calculations, a minimum reinforcement criterion was satisfied by placing one reinforcement bar of 8mm diameter in the centre of concrete columns and beams, whereas a layer of steel grid mesh was inserted in between LW prefab panels.

The door, window, and ventilator openings are provided while casting as per the drawings mentioned in Figure 19. Sample pipe fittings for electrical and plumbing requirements are also incorporated as shown in Figure 20.

Figure 17. Casting of structural elements

Figure 18. Casting of prefab panels

Figure 19. Provision for window opening

Figure 20. Provision of pipe fitting

Figure 21. Curing of concrete elements

Figure 22. Curing and stacking of prefab panels

Concrete beams and columns are placed into the water bath for curing (Fig. 21). Whereas, prefab panels are stacked one against each other vertically and are cured with the help of soaked gunny bags (Fig. 22). Age of curing for all the elements is 28 days after which elements are ready for application on site.

4.3 Transport, plotting, erection and jointing

The concrete elements and prefab panels are loaded into the trucks for their transport to the site. The area is plotted as per the plan and the ground is cleared and levelled. As the model is a framed structure, columns and beams are first erected followed by wall panels (Fig. 23). For placing columns, small grooves are made on the surface such that columns are fit into them. Beams have slots at the ends. The adjacent beams are placed into them and grouted. Jointing of both the concrete and prefab elements is done through application of polymer-based epoxy grout (Fig. 24). Small finishing works such as filling up of gaps between the elements are done by application of cement mortar.

Figure 23. Erection of structural elements and wall panels

Figure 24. Application of Epoxy grout

Figure 25. Erection of roof supporting elements

Figure 26. Erection of slab panels

Figure 27. PV panel embedded into roof

Roofing members are erected after a day of erection of roof supporting elements (TRP 1-6) such that the grout is properly set and hardened (Fig. 25 and 26). As this model is small-scale, the elements and panels were handled and erected manually. By scaling up the model to real-scale, handling can be mechanized in view of its increased size and weight for which handling stress can be evaluated further.

Roofing members of south elevation have the provision for the PV panel to be integrated into the roof. A day after the roofing members are erected, the proposed PV panel is fixed into the groove provided with the help of polyurethane foam (Fig. 27). The electrical cables are arranged such that they are inserted through the roof into the model house without getting effected by any kind of climatic and environmental conditions. The openings are furnished with wooden doors, and wooden framed glass windows. Figures 28 and 29 indicate the constructed prefabricated housing model.

Figure 28. Front (North) elevation of model house

Figure 29. Backside (South) of model house

A time-duration study is conducted through analytical tools by considering activities starting from material acquisition to the erection of the model house. Labour output was included in this study based on an Indian standard code (IS:7272-1(1974), 1974). Results depict that erection of the designed prefabricated model house is 20% faster than the conventional construction that involves cast in-situ concreting and brickwork.

5. Conclusion and recommendations

This study proposes a novel, sustainable, and lightweight product to be used as a walling member. An agro-industrial by-product namely CFA was used as a sustainable alternative to the naturally available resource. This alternate material has potential application to be mixed in design of both concrete and lightweight prefab elements. This study mainly focusses on development of lightweight prefabricated walling elements and analysing its suitability over the commercially available products. Accordingly, tests related to physico-mechanical properties (density, water absorption, compressive strength, split tensile strength, and flexural strength), durability (chloride permeability), thermal conductivity, and workability were performed as per the standards. Based on compliance criteria, it is concluded that the proposed end-products are sustainable alternatives to commercially available construction products, and suitable for real-time construction. The comparative study resulted the proposed end-product as 18% and 27% lighter than burnt clay and fly ash bricks respectively. The lightweight prefab panel resulted in 0.7% and 8.5% higher compressive strength over burnt clay brick and fly ash brick respectively. Similarly, the comparison of thermal property for lightweight prefab panel resulted in 68% and 62% less conductivity than burnt clay and fly ash bricks respectively. However, the connections during the model house erection were made with epoxy-based grout that can be replaced with mechanical connections for the scaled-up model houses. Furthermore, an energy calculation regarding solar PV panel embedded into the roof indicates that a ceiling fan and a tube-light can be accommodated by considering 71% of its energy generation under provided assumptions. Prefab construction is found effective in reducing the total duration of the project by around 20% in comparison to the conventional construction. Overall, the lightweight end-product proposed as a prefab walling member was successfully cast and erected as a small-scale experimental model house.

Funding: This research was supported by funding under the grant LJMU GCRF fund—271002/ S0001/954FET/GCRFFET04.

Acknowledgments: This research is supported by funding under the grant LJMU Global Challenge Research Fund 2018–2020. The experimentation and castings were conducted with the support of M/s. Apple Chemie India Pvt Ltd.

Conflicts of Interest: The authors declare no conflict of interest.

References

Amran, Y. H. M. *et al.* (2016) 'Response of precast foamed concrete sandwich panels to flexural loading', *Journal of Building Engineering*, 7, pp. 143–158. doi: 10.1016/j.jobe.2016.06.006.

BIS (2016) 'National Building Code of India, 2016 Volume 1', *National Building Code of India*, 80, p. 1 v. (various pagings).

Bras, A. *et al.* (2020) 'Sustainable and affordable prefab housing systems with minimal whole life energy use', *Energy and Buildings*, 220, p. 110030. doi: 10.1016/J.ENBUILD.2020.110030.

Chippagiri, R. *et al.* (2021) 'Application of Sustainable Prefabricated Wall Technology for Energy Efficient Social Housing', *Sustainability*, 13(1195). doi: https://doi.org/10.3390/su13031195.

Correia, J. R., Ferreira, J. and Branco, F. A. (2006) 'A rehabilitation study of sandwich GRC facade panels', *Construction and Building Materials*, 20(8), pp. 554–561. doi: 10.1016/j.conbuildmat.2005.01.066.

Dakwale, V. A. and Ralegaonkar, R. V. (2014) 'Development of sustainable construction material using construction and demolition waste', *Indian Journal of Engineering and Materials Sciences*, 21(4), pp. 451–457.

Daniel Ronald Joseph, J., Prabakar, J. and Alagusundaramoorthy, P. (2018) ‘Flexural behavior of precast concrete sandwich panels under different loading conditions such as punching and bending’, *Alexandria Engineering Journal*, 57(1), pp. 309–320. doi: 10.1016/j.aej.2016.11.016.

Dave, M., Watson, B. and Prasad, D. (2017) ‘Performance and perception in prefab housing: An exploratory industry survey on sustainability and affordability’, *Procedia Engineering*, 180, pp. 676–686. doi: 10.1016/j.proeng.2017.04.227.

Department of Economic and Social Affairs, U. N. (no date) *India Population (2020) [Internet]*. Available at: https://www.worldometers.info/world-population/india-population/ (Accessed: 12 March 2020).

ECBC (2017) ‘Energy Conservation Building Code’, *Bureau of Energy Efficiency*.

Einea, A. *et al.* (1991) ‘State-of-the-art of Precast Concrete Sandwich Panels’, *PCI Journal*, 36(6), pp. 78–92. doi: 10.15554/pcij.11011991.78.98.

Ferdous, W. *et al.* (2019a) ‘New advancements, challenges and opportunities of multi-storey modular buildings – A state-of-the-art review’, *Engineering Structures*, 183, pp. 883–893. doi: 10.1016/J.ENGSTRUCT.2019.01.061.

Ferdous, W. *et al.* (2019b) ‘New advancements, challenges and opportunities of multi-storey modular buildings – A state-of-the-art review’, *Engineering Structures*, 183(October 2018), pp. 883–893. doi: 10.1016/j.engstruct.2019.01.061.

Flansbjer, M. *et al.* (2018) ‘Composite Behaviour of Textile Reinforced Reactive Powder Concrete

Sandwich Façade Elements', *International Journal of Concrete Structures and Materials*, 12(1). doi: 10.1186/s40069-018-0301-4.

Gavali, H. R. *et al.* (2019) 'Development of sustainable alkali-activated bricks using industrial wastes', *Construction and Building Materials*, 215, pp. 180–191. doi: 10.1016/j.conbuildmat.2019.04.152.

Gavali, H. R. and Ralegaonkar, R. V. (2020) 'Design of eco-efficient housing with sustainable alkali-activated bricks', *Journal of Cleaner Production*, 254, p. 120061. doi: 10.1016/j.jclepro.2020.120061.

Grandoliniede, G. M. and Ijjasz-Vasquez, E. (2016) *3 reasons why 'Housing for All' can happen by 2030*. Available at: https://blogs.worldbank.org/voices/3-reasons-why-housing-all-can-happen-2030 (Accessed: 5 August 2021).

I. Goh, W. *et al.* (2016) 'Finite Element Analysis of Precast Lightweight Foamed Concrete Sandwich Panel Subjected to Axial Compression', *Journal of Computer Science & Computational Mathematics*, (February), pp. 1–9. doi: 10.20967/jcscm.2016.01.001.

IS:2185 (2005) 'Concrete masonry units, Part 1: Hollow and solid concrete blocks', *Bureau of Indian Standards, New Delhi*, p. 17.

IS:7272-1(1974) (1974) 'Recommendation for Labour Output Constants for Building Work, Part I: North Zone', *Bureau of Indian Standards, New Delhi*.

IS 456: 2000 (no date) 'Plain and Reinforced Concrete - Code of Practice', *Bureau of Indian Standards, New Delhi*, pp. 1–114.

Krishnanunny, M. and K, A. K. (2018) ‘Prefab technology a solution to existing challenges in construction sector of India - A Kerala perspective’, *International Journal of Pure and Applied Mathematics*, 119(15), pp. 1339–1347. Available at: http://www.acadpubl.eu/hub/.

Kulshreshtha, Y. *et al.* (2020) ‘The potential and current status of earthen material for low-cost housing in rural India’, *Construction and Building Materials*, 247, p. 118615. doi: 10.1016/j.conbuildmat.2020.118615.

Kumar Gangaram Singh, M. and Kizhakkumodom Venkatanarayanan, H. (2020) ‘Performance of Self-Consolidating High-Strength Mortars Developed from Portland Pozzolana Cement for Precast Applications’, *Journal of Materials in Civil Engineering*, 32(3), p. 04019375. doi: 10.1061/(asce)mt.1943-5533.0003041.

Kumar, K. R. *et al.* (2021) ‘Cleaner production of self-compacting concrete with selected industrial rejects-an overview’, *Silicon*, 13(8), pp. 2809–2820. doi: 10.1007/s12633-020-00636-6.

Li, Z., Shen, G. Q. and Xue, X. (2014) ‘Critical review of the research on the management of prefabricated construction’, *Habitat International*, 43, pp. 240–249. doi: 10.1016/j.habitatint.2014.04.001.

Liu, M., Jia, S. and Liu, X. (2019) ‘Evaluation of mitigation potential of GHG emissions from the construction of prefabricated subway station’, *Journal of Cleaner Production*, 236, p. 117700. doi: 10.1016/j.jclepro.2019.117700.

Lopez, D. and Froese, T. M. (2016) ‘Analysis of costs and benefits of panelized and modular prefabricated homes’, *Procedia Engineering*, 145, pp. 1291–1297. doi: 10.1016/j.proeng.2016.04.166.

Madurwar, M. V., Mandavgane, S. A. and Ralegaonkar, R. V. (2015) 'Development and feasibility analysis of bagasse ash bricks', *Journal of Energy Engineering*, 141(3), pp. 1–9. doi: 10.1061/(ASCE)EY.1943-7897.0000200.

Ministry of Housing & Urban Poverty Alleviation Government of India (2017) 'Pradhan Mantri Awas Yojana - Housing for All (Urban) - Credit Linked Subsidy Scheme', 2017, pp. 1–62. Available at: http://mhupa.gov.in/pmay/repository/01_PMAY_Guidelines_English.pdf.

Naito, C. *et al.* (2012) 'Performance and characterization of shear ties for use in insulated precast concrete sandwich wall panels', *Journal of Structural Engineering (United States)*, 138(1), pp. 52–61. doi: 10.1061/(ASCE)ST.1943-541X.0000430.

Nath, A. J., Lal, R. and Das, A. K. (2018) 'Fired Bricks: CO_2 Emission and Food Insecurity', *Global Challenges*, 2(4), p. 1700115. doi: 10.1002/gch2.201700115.

Ram, S., Ralegaonkar, R. V. and Pradhan, K. (2017) 'Use of co-fired blended ash in the development of sustainable construction materials', *Proceedings of the Institution of Civil Engineers: Engineering Sustainability*, 171(8), pp. 425–432. doi: 10.1680/jensu.17.00008.

Rathod, N. *et al.* (2020) 'Development of Sustainable Masonry Blocks Using Industrial Rejects and Alkali Activation', in *International Conference on Innovative Technologies for Clean and Sustainable Development*. Chandigarh, India: Springer, pp. 357–368. doi: https://doi.org/10.1007/978-3-030-51485-3_24.

Raut, S. P. *et al.* (2012) 'Reuse of recycle paper mill waste in energy absorbing light weight bricks', *Construction and Building Materials*, 27(1), pp. 247–251. doi: 10.1016/j.conbuildmat.2011.07.053.

Van Ruijven, B. J. *et al.* (2016) ‘Long-term model-based projections of energy use and CO2 emissions from the global steel and cement industries’, *Resources, Conservation and Recycling*, 112, pp. 15–36. doi: 10.1016/j.resconrec.2016.04.016.

Sakhare, V. V. and Ralegaonkar, R. V. (2016a) ‘Use of bio-briquette ash for the development of bricks’, *Journal of Cleaner Production*, 112, pp. 684–689. doi: 10.1016/J.JCLEPRO.2015.07.088.

Sakhare, V. V. and Ralegaonkar, R. V. (2016b) ‘Use of bio-briquette ash for the development of bricks’, *Journal of Cleaner Production*, 112, pp. 684–689. doi: 10.1016/j.jclepro.2015.07.088.

Sakhare, V. V. and Ralegaonkar, R. V. (2018) ‘Strategy to control indoor temperature for redevelopment of slum dwellings’, *Indoor and Built Environment*, 27(9), pp. 1203–1215. doi: 10.1177/1420326X17712107.

Shams, A. *et al.* (2015) ‘Innovative sandwich structures made of high performance concrete and foamed polyurethane’, *Composite Structures*, 121, pp. 271–279. doi: 10.1016/j.compstruct.2014.11.026.

Shelote, K. M. *et al.* (2021) ‘Utilization of co-fired blended ash and chopped basalt fiber in the development of sustainable mortar’, *Sustainability (Switzerland)*, 13(3), pp. 1–19. doi: 10.3390/su13031247.

Singla, R., Kumar, S. and Alex, T. C. (2020) ‘Reactivity Alteration of Granulated Blast Furnace Slag by Mechanical Activation for High Volume Usage in Portland Slag Cement’, *Waste and Biomass Valorization*, 11(6), pp. 2983–2993. doi: 10.1007/s12649-019-00580-6.

Steinhardt, D. A. and Manley, K. (2016) ‘Adoption of prefabricated housing–the role of country context', *Sustainable Cities and Society*, 22, pp. 126–135. doi: 10.1016/J.SCS.2016.02.008.

United Nations (2019) *UN Climate Action Summit 2019 [Internet]*, *un.org*. Available at: https://www.un.org/en/climatechange/un-climate-summit-2019.shtml.