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ENERGY-SAVING POTENTIAL OF PREFABRICATED STRAW BALE CONSTRUCTION (PSBC) FOR BUILDINGS IN INDIAN CONTEXT

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ABSTRACT

In India, straw is a very common building material. It is still in use in traditional buildings mostly found in rural part of India. Structural straw bale buildings are yet to gain any visibility in India. Straw-bale building is a method of construction that uses bales of straw as structural elements. Straw bales are environment friendly and low cost due to the availability in abundance as agricultural residues. In rural areas, availability of building materials is always an issue. Under the Pradhan Mantri Awas Yojana – Gramin (PMAY-G, or Housing for All), the world's largest housing programming for the rural poor, India aims to build 30 million houses for the rural poor for 2022–which means building five million houses every year in rural areas. Strawbales can be a viable option and can be very effectively used in building construction in rural areas due to its easy availability. The cost of conventional construction is generally quite high and thus ensuring a sizeable, habitable housing unit for the beneficiaries often becomes a challenge towards designers/policy makers. Further, a typical construction method involves lot of energy intensive materials which is neither beneficial to the environment nor acceptable to the occupants living in rural context. Thus a search for an appropriate material and techniques is always there to satisfy the local needs. In this study, a comparative analysis w.r.t cost and energy aspects is done for a model ICDS centre between conventional and strawbale structures so as to understand the effectiveness of strawbale construction.

With the increase in population and technological advancement, the energy consumption and demand of resources has gradually increased. The construction industry, by direct or indirect actions, consumes over 50% of the energy produced, is responsible for 30% of the carbon emissions, and consumes more raw material than any other industrial activity. Architecture alone cannot solve global environmental problems, but it can contribute significantly. A high recyclability rate can be achieved through the management of renewable natural materials or waste. The application of prefabricated building system can be an economical solution, saving energy and reducing waste. This paper discusses prefabricated compressed straw panels (PSBC) as part of a paradigm shift towards sustainable architecture, which offers the opportunity to use new materials and construction systems taking local and specific circumstances into account.

This paper aims to explore the possibilities of designing, estimating a typical habitable unit with strawbale and thus comparing the same with a conventional unit design in Indian context. The study will explore whether the use of straw bales in the construction in rural India is possible in order to provide low cost alternative option, environment- friendly and help in achieving sustainable development. This paper is based on the idea of a low-energy building design, this study provides an optimal combination of renewable energy sources and energy efficiency measures into the building design.

KEYWORDS: *Strawbale Buildings, PSBC, Energy Efficiency, Low-Energy Building, Cost Analysis*

INTRODUCTION

Census report says that the urban population of India has seen a rise from 11.4% to 29.2% between 1901 and 2015. According to a survey by the UN, 40.76% of the country's population is expected to reside in urban areas by 2030. Meanwhile, though the rural population declined from 82.9 percent in 1915 to 2015's 67.2 percent still two-thirds of the population live in rural areas. To accommodate more and more population cities across India are increasingly experiencing peri-urban growth due to uncontrollable rapid urbanization. On the other hand, rural areas experience noticeable changes in their physical, social, and economic characteristics as well as deterioration in living conditions due to the impact of urbanization. Ministry of Rural Development, Government of India estimated shortage of houses to the tune of 47.3 million in rural areas during 2007-12. Out of which 90% are for BPL families, which leaves a challenging task to provide shelter to all in the most economical way. The urban shortage has increased fast in recent times and continues to worsen as migration and natural population growth have intensified, but the biggest shortage is still in rural areas. The construction sector in rural areas of India, in general, is in great distress today because of continued apathy and neglect from policymakers and scholars. Some of the reasons for this shortage are the non-availability of efficient design, low-cost building material, and speedier technology in delivering the stock. In rural areas, construction systems need an innovative approach. Sustainable rural building technology is a method of construction that involves the use of cheap, environment-friendly, and locally sourced materials such as bamboo, bagasse boards, fly ash-based bricks, mud, and lime for building cost effective, comfortable, and calamity resistant houses which provide adequate standards of living. It integrates the use of local construction techniques suitable for the climatic and geographical conditions of a region with the elements of modern architecture and technology, as, easy-to-use construction machinery, pre-fabricated components, use of agricultural and industrial by product-based construction materials, and advanced architectural features that enhance the quality and sustainability of the buildings.

India is an agro-economic country with a 13.7% (GoI, 2013) share of agriculture in the gross domestic product (GDP). Around 45% of the land area in India is agricultural. Rice is the primary crop in the country. Straw is a natural fiber that is available as a co-product of agriculture. In the majority of states of India, farmers grow three crops in a year and the mode of harvesting is changing from manual to mechanical, which leaves the straw standing in the fields. The burning of the straw results to the formation of black cloud causing serious chronic chest diseases and carbon evolved from it affect the quality of the environment a lot. One ton of rice straw on burning in the field is estimated to produce, on average (kg) of 1168 CO^2, 1.0 CH4, 0.06 N2O, 27.8 CO, 3.2 non methane hydrocarbons (NMHC), 2.9 NOx, 1.6 SO2, and 10.4 total particulate matter (TPM) emissions (Gadde et al., 2009b; Silalertruksa and Gheewala, 2013; Venkataraman et al., 2006). India and other agro-based countries have not been able to utilize it for productive work up till now. Thus, straw bale construction can be considered as an appropriate option to cater the economic environmental building alternative in India.

CLIMATIC FEATURES AND ENERGY CONSUMPTION PATTERNS IN BUILDINGS

The climate in India encompasses a wide range of air temperatures and humidity. Bureau of Energy Efficiency published the ECBC for thermal design of buildings, which identifies five different climatic regions which are 1) Hot and dry 2) Warm and Humid, 3) Composite 4) Cold and 5) Temperate. The design and construction of buildings in India are guided by these climatic regions which are differentiated by the climatic characteristics of the regions. The climatic features of each of the climatic zones represent typical climatic characteristics. Predominantly two critical climatic zones cover the majority part of the country which are 1) warm and humid and 2) Composite. A warm and humid climate is characterized by high relative humidity, around 70-90 %, and high precipitation levels, about 1200 mm per year. The temperatures usually vary between 25–35 ºC in summers; while in winters, temperatures vary between 20–30 ºC. Most characteristics of the composite zone are similar to that of the hot and dry climate zone, except that composite regions experience higher humidity levels during monsoons. The building design in warm and humid climates should aim at reducing heat gain by providing shading, and promoting heat loss by maximizing cross ventilation. Dissipation of humidity is also required to reduce discomfort whereas the building design criteria are more or less the same as for hot and dry climate (appropriate shading, reduced exposed area, and increased thermal capacity), except that maximizing cross ventilation is desirable in the monsoon period. The need for improved building energy efficiency is most critical in this region due to the presence of high humidity.

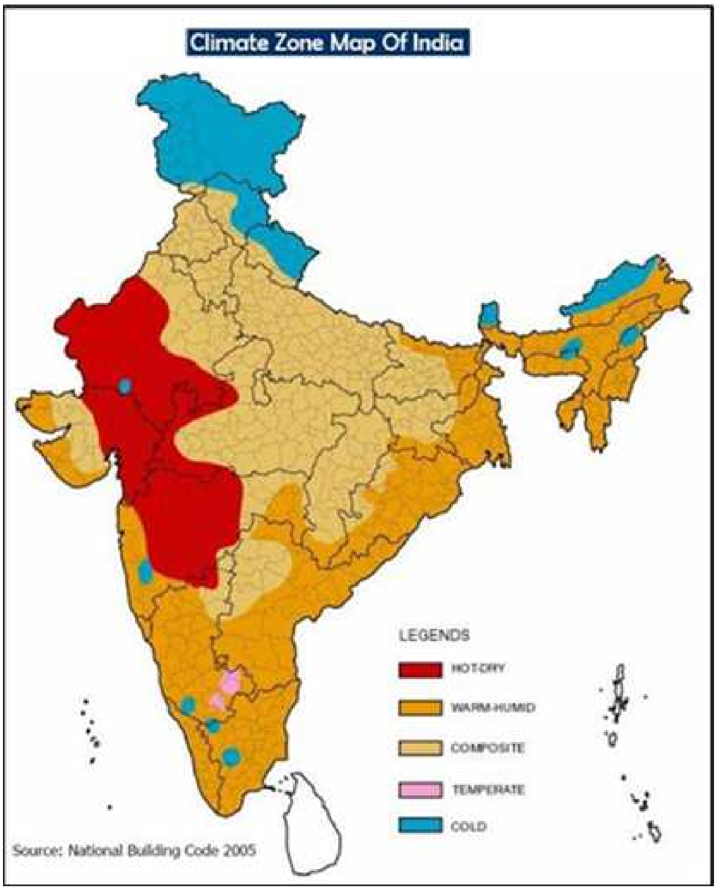

Figure 1

According to the predictions for 2021, in comparison with the 1996 energy consumption levels, energy use increased at its most rapid rate in India in 2008. The latest versions of Model Building Bylaws drafted by MoHUA as well as ECBC commit to a substantial reduction in the energy consumption of buildings against the present levels in India. The regulations specify the thermal conductivity of the building envelope, with U-values ranging from 0.25 to 0.7 W/m2K, depending on the locations of buildings in India.

RATIONALE FOR STRAW BALE CONSTRUCTION IN INDIA

Straw bale construction uses agricultural co-products. The concept was originally developed due to a shortage of building materials in Nebraska in the late 19th century. Strawbale buildings are characterized by a combination of the low-cost, quick construction process with high thermal insulation. India has the largest area under rice cultivation, as it is one of the principal food crops. Rice is a tropical plant that flourishes comfortably in a hot and humid climate. Thus as per climatic zones in India, two zones i.e. warm and humid and composite zones majorly cover the rice-producing areas which means the possibility of strawbale construction in these two climatic zones are quite high.

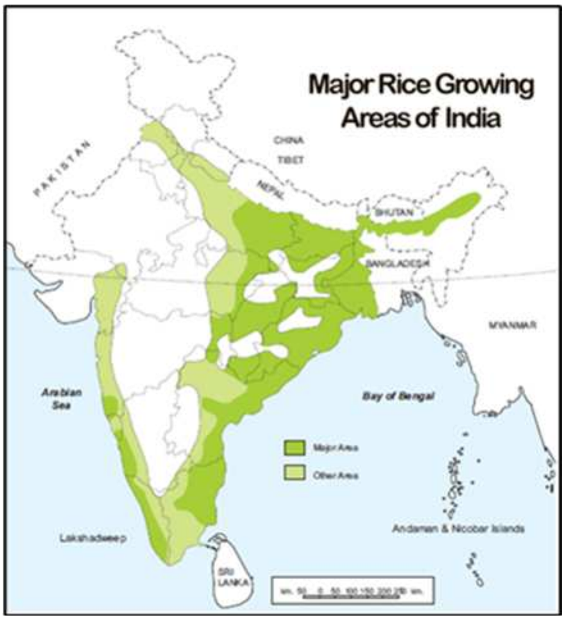

Figure 2

There are three main advantages in using straw bale in construction sector in Indian context. First of all, straw bales are a carbon-sink building material with low embodied energy and embodied carbon. The atmospheric CO^2 is sequestered in the plant body through the process of photosynthesis. A calculation through stoichiometry shows that 1 kg of carbon sequestered in the straw stems requires the removal of 3.67 kg of CO2 from the atmosphere. This amount of adsorbed carbon cannot be released into the atmosphere until the straw bale buildings are demolished.

Secondly, due to the high thermal insulation properties of straw bale walls, straw bale buildings have low heating energy demand. The U-value of typical prefabricated straw bale walls can be as low as from 0.11 to 0.19 Wm2K-1 for 450 mm thick wall panels. In comparison with the thermal performance stipulated in current Indian standards for walls, the thermal resistances of these panels are 50–300% better than those of standard wall constructions. The high thermal insulation properties of straw bale buildings notably decrease both heating and cooling demand; therefore, less energy is required for winter heating or summer cooling.

Thirdly, the use of straw in the building industry will benefit the agricultural economy of India. Straw is considered a waste material in the farming process for rice and wheat in India. The total annual rice production in India is approximately 117.94 million tonnes in 2019-2020. Due to the associated large amount of waste straw, disposal of the material has been a concern in India for decades. Currently, the most common approach for disposal of the straw is burning of it in fields. This issue demands more environmentally friendly disposal solutions for straw as an alternative to burning.

PREFABRICATED STRAW BALE CONSTRUCTION (PSBC)

Prefabricated Straw Bale Construction (PSBC) is a prefabricated construction technique for utilizing straw bales in buildings. This building technique combines conventional straw bales with the superior characteristics of controlled prefabricated construction processes. In comparison with conventional straw bale construction, the main benefit of PSBC is that this construction technique minimizes the risks associated with wet weather on construction sites. It also offers better quality control than the onsite construction of straw bale walls. Additional benefits of PSBC include a reduction in onsite construction time, no site waste removal, and lower risks of fire on the construction site due to the elimination of loose straw.

ModCell is one of the premier companies to produce PSBC. This PSBC is in the form of PSBC panels. The panels typically consist of engineered timber frames, in-fill straw bales, and lime renders. The dimensions of the engineered frames are typically 100 x 480 mm to accommodate the dimensions of the in-fill straw bales. The sizes of the panels vary according to different building projects but are typically 3.0 (width) × 3.2 m (height). The in-fill straw bales are stacked to form walls of densities of around 110 kg/m3, and these are pre-compressed during the process to increase stability and reduce thermal bridging arising from gaps between the bales and the frames.

The Advantage and Application of PSBC in Indian Context

PSBC panels are load bearing up to 3.5 floor as evident from the Mod cell experience. Low storied medium density housing complexes in semi-urban and rural areas are best context where PSBC can be utilised. The national housing scheme, Pradhan Mantry Awas Yojona (PMAY)-Gramin envisages a basic housing unit for all villagers. Such schemes can get maximum benefit from PSBC constructions. Besides, the buildings made by the government for other schemes like education, small scale industry etc. will also get benefit of such constructions. The main advantage from the PSBC driven rural housing will be

- Availability of straw and wood as local and vernacular materials will ensure timely completion and sustainable supply chain in the manufacturing
- Zero or near-zero energy consumption leads to no-pollution scenario
- Better workmanship compared to other factories since villagers are acquainted with the materials.
- Cost efficiency per unit for the end users and also for the providers (in this case government)
- Local employment generations and local entrepreneurship possibility
- Transportation of bale panels also can be made with the local transports even with the rural roads.
- Significantly lower labour costs by eliminating skilled plastering. Horizontal pour in one coat, not vertical towelling in three coats.
- Straight and square walls guaranteed

The primary benefit of prefabricated construction is reduction in time of construction. Waste management and cost efficient construction. Precast construction provides stability, flexibility, sound durable and adaptability with cost efficiency. Cost minimization on labour policies, skills, development of employ, providing training to them is main factors.

Repairs cost also reduces in precast concrete construction. The following table shows the comparison of precast conventional construction and prefabricated straw bale construction on basis of duration.

PSBC Research Scope and Objectives

With a relatively long history of straw bale buildings, Prefabricated Straw Bale Construction (PSBC) has developed in recent years. Current research verifies the rationale for applying straw bale buildings by the policies and climatic features prevailing in India. However, the discussion of feasibility and the potential benefits of this,relatively innovative construction method has been limited. This research discusses the feasibility of using prefabricated straw bale construction in buildings to reduce energy consumption in India. To establish the efficiency of using straw bale into construction, this research discusses:

- Comparative estimates of both prefabricated straw bale construction and standard construction;
- The operational energy load (heating and cooling) of reference buildings in the climatic conditions for two zones in India. This is followed by a comparison of the operational heating and cooling energy demand of buildings with proposed model and with standard wall construction.

A Comparative Cost Analysis of a Standard Building with Respect to Prefabricated Strawbale Building

For any construction project cost is an important factor. Total cost of a project can be determined by calculating the individual cost of materials used in the construction process. This research specifically deals with the cost of the materials for the construction of a 630 sq.ft. standard building, by conventional method as well as construction through prefab straw bale construction.

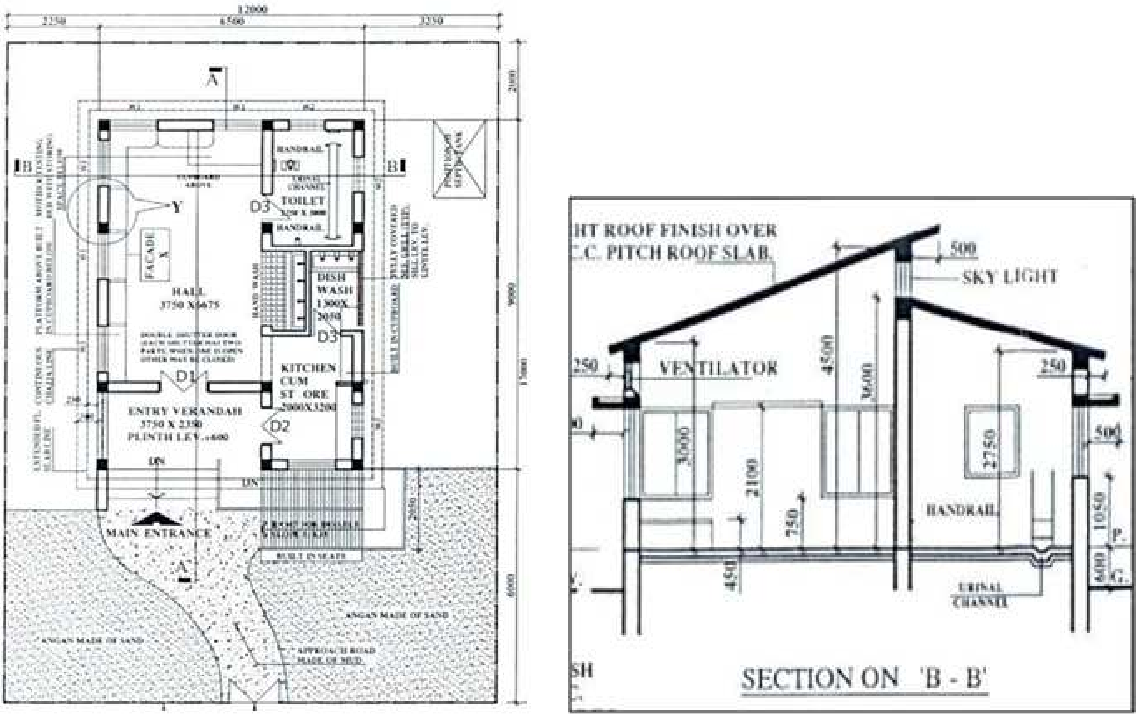

Figure 3: Typical Floor Plan and Section of the Reference Anganwadi Structure.

Anganwadi centres were started by Government of India in the year 1975 as part of the Integrated Child Development Services (ICDS) program to combat child hunger and malnutrition. The department of Child Development & Women Development & Social Welfare of each state constructs child friendly Anganwadi centres throughout the states. Model plans and detailed estimates are prepared by PWDs. Single storey structures (Fig. 3) with a rectangular /square shape plans are designed to fit into different geographical locations and land conditions. The estimated value of such a sample design is around Rs. 12,61,500/ i.e. Rupees Twelve Lakhs, sixty- one thousand and five hundred only. In majority cases, frame structures are designed using reinforced cement concrete and bricks as primary building materials (Section Fig. 3). For the purpose of this research, one such Anganwadi structure has been designed using prefab straw bale construction (Fig. 6). Considering the overall context, this research aims to undertake the design of one of such Anganwadi centre as a model for the possible straw bale construction. To achieve wider acceptance, a rectangular shaped building keeping the same area as of the existing ones has been designed. Since most of these buildings are constructed on low lying virgin land without any infrastructure, a raised concrete slab is designed as the base for the structure in order to arrest the moisture percolation into the structure. The foundation has been designed with post-column (Fig.4). This design may act as a prototype. The estimated cost would be around Rs. 8,70,000/

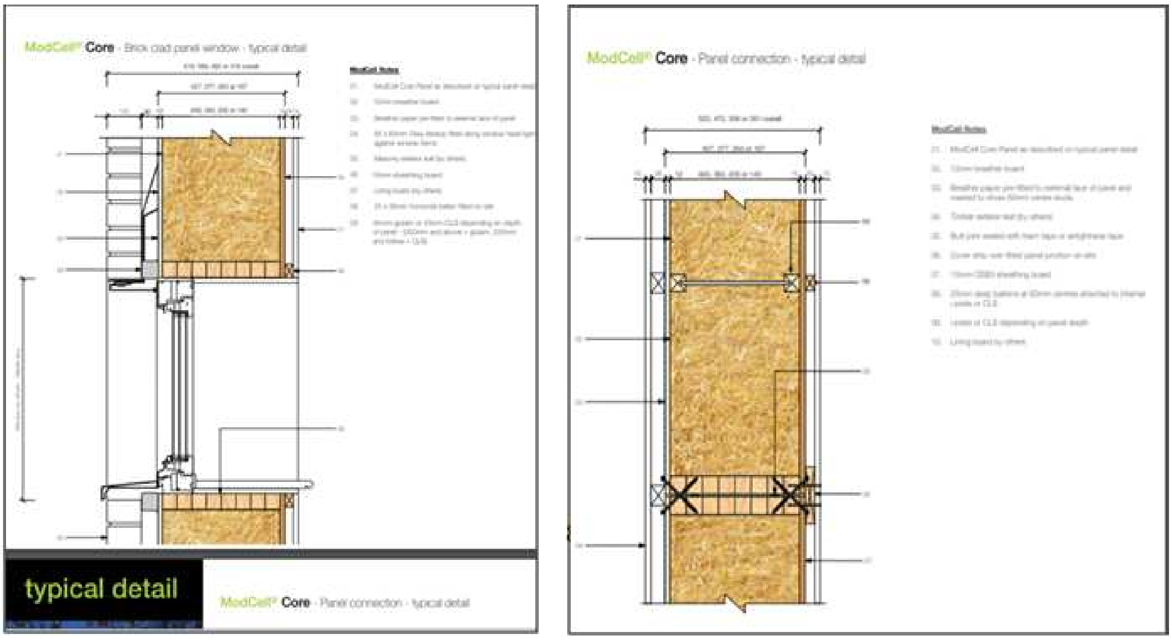

Figure 4: Typical Detail of Wall and Window Fixing Detail.

For the cost comparison, three options with different construction techniques and specifications are considered to get an idea about which combination will be the most effective cost-wise. For all options walls are considered with PSBC (Fig. 4). The flooring, wall finish, roofing materials are proposed differently. For option I conventional materials are chosen like concrete for foundation and flooring, asphalt shingles for roofing, cement stucco for wall finish on bale with steel bar. For option II all conventional materials are chosen like brick wall is taken for foundation, timber for flooring, clay tile for roofing, lime plaster for wall finish on bale with wooden frame. For Option III mostly locally available materials are chosen with rammed earth foundation, bamboo reinforced mud floor, thatch roof, wall having straw with bamboo stakes coated with earthen plaster.

Figure 5: Conceptual Sketch of Unit using PSBC.

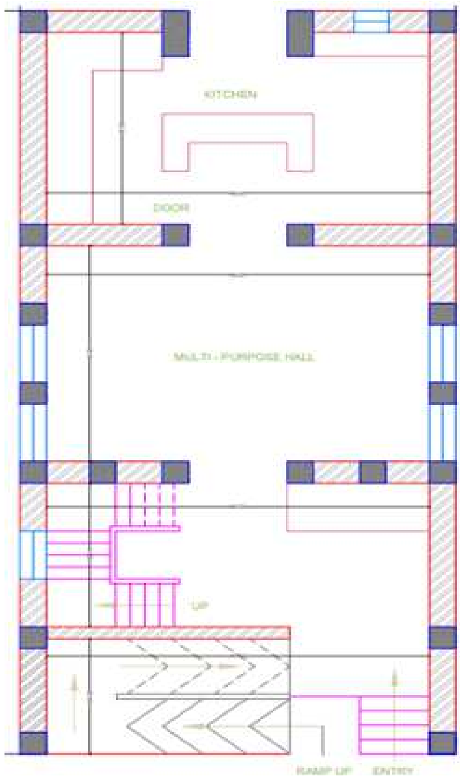

Figure 6: Prototype Plan of Unit using PSBC.

Table 1: Estimation of the Building with Three Optional Specifications

Building Components	OPTION #I (in Rupees)		OPTION #II (in Rupees)		OPTION #III (in Rupees)	
Foundation	Concrete	185621.76	Brick Wall	74648.00	Rammed earth	41822.00
Floor	Concrete	110839.00	Wooden	323191.00	Mud with bamboo reinforcement	29400.00
Roof	Asphalt Shingles	454447.00	Clay Tile	17612.00	Thatch	415477.00
Walls	Bale with Steel-bar	113272.00	Bale with wooden frame	397434.00	Straw with bamboo stakes	103488.00
Wall Finishes	Cement stucco	75401.59	Lime Plaster	90805.01	Earthen plaster	38720.00
Doors & Windows	Wooden & CPVC	67237.95	Wooden & CPVC	62271.95	Wooden & CPVC	54968.95
Plumbing & Sanitary		63670.00		63670.00		63670.00
Total Amount (With 12% GST+1% Cess+Contigency3 %)		1246906		1199315		870741

From the values mentioned in the Table- 1 above for the three options, it is observed that cost-wise the best option is the third one with majority material as straw and strawbale. The first option though using PSBC is almost equivalent to the cost of the conventional building as designed by PWD.

A Comparative Energy Consumption Analysis of a Standard Building with Respect to Prefabricated Strawbale Building

Single story community building with three different specifications has been selected (See Figure 3) for the study. The total building area is 630 sq.ft. Table -2 shows the quantities of each material used in building.

Table 2: Quantities of Materials for Three Options

Material	OPTION # 1	OPTION # 2	OPTION # 3
Cement (kg)	14000	4250	0.00
Stone chips (Cu.m)	42050	5452	0.00
Sand (kg)	39600	24696	0.00
Bricks (kg)	7392	12254	0.00
Steel (Kg)	4090	100	0.00
Lime (Cu.m)	0.00	4175	0.00
Prefab Straw bale (Sq.m)	176	176	176
Mud (Cu.m)	0.00	0.00	114
Wood (Cu.m)	0.958	16.221	9.96
Bamboo (Sq.m)	0.00	0.00	295

Table 3: Table for Comparison of EI, EE, and Carbon Emission of all the Materials in Option I, II and III

Type of Material	Unit	Energy Intensity /unit	Embodied Energy (GJ)	Density (kg/m3)	CO2 Emission (Kg CO2/Kg)
Cement	kg	3.32	4.5 MJ/kg	2800	0.730
Stonechips	cum	0.16	0.119 MJ/kg	1450	0.010
Sand	cum	0.081	0.042 MJ	1760-2000	0.0048
Brick	kg	3.00		1400	0.220
Steel	kg	20.1	37210	7800	1.37
Lime	cum	5.3		3340	0.760
Prefab Straw bale (Sq.m)		0.91	0.9	100–110	0.010
Mud	cum	0.45	2007.8 MJ/m2	1906	0.023
wood	cum	8.5	1.0MJ/kg	900	0.46
Bamboo	kg			310-400	

From the values mentioned in Table - 3, PSBC has the least carbon emission which proves that it is a carbon-sink building material with significantly low embodied energy and embodied carbon. Straw additionally soak up and store carbon dioxide during photosynthesis consequently it acts as a carbon sink. 15 kg of carbon dioxide is being absorbed by means of each 10 kg of straw and seals it inside the walls for the lifetime of the constructing. So this is an advantage that amount of adsorbed carbon will not be released into the atmosphere until the straw bale buildings are demolished.

When we compare energy requirements of the standard construction and the PSBC although strawbales do not have enough thermal mass to provide an interim heat sink that helps to keep temperatures stable and prevents them from rising to discomfort levels, its higher thermal insulation overcomes this drawback.

As shown in Table-3 the comparative analysis of conventional constructing materials with PSBC which shows it has very low embodied energy that is the entire power required for generating it; for extracting, processing, transporting and many others. As the production and transport to the building site of straw bales consumes little or no strength consequently this production technique has minimal effect on the environment. Straw absolutely has lower embodied energy than wood on the grounds that wood calls for a lot greater energy for the manufacturing and processing and it also produces an awful lot more carbon dioxide in the production and processing in comparison with straw bales.

Table 4: Table for Comparison of Thermal Energy of the Materials used in all the Three Options

Material	OPTION # 1	Thermal Energy (MJ/kg)	CO2 Emission (kg/kg)	OPTION # 2	Thermal Energy (MJ/kg)	CO2 Emission (kg/kg)	OPTION # 3	Thermal Energy (MJ/kg)	CO2 Emission (kg/kg)
Cement (kg)	14000	464806	10220	4250	14110	3102	-		
Stone chips (Cu.m)	42050	6728000	420500	5452	872320	54520	-		
Sand (Cu.m)	39600	3207600	190080	24696	2000340	118440	-		
Bricks (Nos)	7392	44352	3252	12254	73524	5390	-		
Steel (Kg)	4090	82209	5603	100	30000	137	-		
Lime (Cu.m)	-	-	-	4175	22127500	3173000	-		
Prefab Straw bale (Sq.m), Weight of Panel 750kg (size of panel 2.7mx3.0M and depth of 0.45 m)	176	15840	93020	176	15840	93020	176	15840	93020
Mud (Cu.m)	0.00	-	-	-	-	-	114	51300	2622
Wood (Cu.m)	0.958	8143	441	16.221	137870	7461	9.96	84660	4581
Bamboo (Sq.m)	0.00	-	-	-	-	-	295		
TOTAL		10550950	723116		25271504	3455070		151800	100223

Prefabricated construction has an effective strategy for improving the productivity of the construction industry (Table -4) which is well known worldwide. This study also found that apart from reusability, energy savings obtained from waste reduction and high quality control recycling process could achieve 16%–24% energy reduction, saving 4%–14% of the total life-cycle energy consumption. So the precast construction can be regarded as important environment friendly strategies provider which is the most important advantage.

Prefabricated straw bale wall panels combine the performance and low environmental impact of traditional straw bale with reduced labour and more consistent results.

RESULTS AND DISCUSSIONS

The critical evaluation of the recent research confirms that straw bales can provide satisfactory results as thermal insulation material compared to conventional materials, while in parallel reflects a high potential for constructions with low embodied emissions. The potential of straw bale is tackled by the lack of consistent representation of material properties, which is controversial to the significant amount of the relevant scientific results that have been reported during the last years. This review provides a systematic framework that can function as basis for future research on straw bales as building material. Computer simulation and experimental testing suggest that the overall heat transfer coefficient (*U*-value) for the complete prefabricated panel is approximately 0.178 $W/m^2 \cdot K$.

Strawbales are 100% biodegradable – when the time comes the lifetime of the building ends and maintenance is impossible strawbale can be plowed back into the earth so it causes no harm to the environment whereas concrete makes up the largest proportion of construction and demolition waste, and represents about a third of all landfill waste. After water, concrete is the most widely used substance on Earth. If the cement industry were a country, it would be the third largest carbon dioxide emitter in the world with up to 2.8bn tonnes, surpassed only by China and the US. But other environmental impacts are far less well understood. Concrete is a thirsty behemoth, sucking up almost a 10th of the world's industrial water use. This often strains supplies for drinking and irrigation, because 75% of this consumption is in drought and water-stressed regions. In cities, concrete also adds to the heat island effect by absorbing the warmth of the sun and trapping gases from car exhausts and air-conditioner units – though it is, at least, better than darker asphalt.

CONCLUSION

Two structural systems have been compared between conventional and eco-friendly building materials in order to evaluate the sustainability of each type. A prototype of two storeys was constructed using eco- friendly building materials (Rammed earth foundation, Bamboo reinforced mud floor, thatch roof, Wall having straw with bamboo stakes coated with earthen plaster). A similar building with the same area and architectural layout was virtually estimated using conventional skeleton structural system (reinforced concrete and bricks). Results showed that the eco-friendly system had better overall sustainability rank than the conventional system by about 11% (67% for eco-friendly system and 56% for conventional system). Recyclability and resource/waste sustainable factors had the bigger difference in the sustainability scores between the two compared systems. As the population continuously growing rapidly, so the need of rapid or fast construction is requirement of future generation. Overall, this research has extended the understanding of the feasibility of using PSBC and their energy performanceThe Prefabricated Straw Bale Construction (PSBC) has been proven as one of the most efficient construction methods to achieve low-energy buildings with low carbon emission. As a result of comparative analysis of conventional construction method with Precast facade and form, they are found better energy-intensive components. Attention should be given on improving the maturity of the precast market to avoid additional energy consumption during prophase investigation.

The future opportunities of straw bale building are impressive, as people's interest in building with straw is noticeably increasing. The building industry in India is growing at high speed; consumers and builders start looking for more efficient and economic forms of construction. Straw bale building reduces greenhouse gas emissions so should be widely promoted and supported by researchers' and governments' attention. Exchanging of information and experience all over the world could speed up the development of straw bale building industries and contribute to sustainability of building.

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