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Evaluation of Thermal Performance of Agro-waste Material for Team SHUNYA Building

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Highlights

- Thermal performance of wall panels made up of bagasse was analyzed.
- Lower thermal conductivity compared with the traditional brick.
- 28 % decrease in the thermal cooling load of the house.
- A 16.4 % increase in the thermal comfort hours is obtained.

Abstract

Using brick-concrete for building envelope is a common practice in India. These envelopes have high heat gains and experience large embodied energy. Agro-waste panels made up of sugarcane waste can significantly reduce cooling load for new construction due to its better u-value and also reduce carbon emission since it is produced from sugarcane waste, i.e., bagasse. A double storey naturally ventilated building has been simulated for Mumbai climatic conditions to understand the performance of agro-waste materials. The total cooling load and temperature profile for a year have been simulated using EnergyPlus software. Thermal comfort hours are calculated using the India model for adaptive comfort (IMAC) band to show the potential of the agro-based panel. The thermal cooling load of the simulated building incorporated with an agro-waste panel decreased by 28 % as compared to the brick-concrete envelope. There is a 16.4 % increase in annual thermal comfort hours compared to brick-concrete envelope.

Keywords: IMAC band, Thermal cooling load, Agro-waste material, EnergyPlus

Introduction

The International Energy Agency's research indicates that the construction and operation of buildings were responsible for 35% of global final energy consumption and 38% of energy-related CO_2 emissions in 2019 [1]. This highlights the significance of addressing energy efficiency and decarbonization in the building sector to reduce greenhouse gas emissions and contribute to global efforts to mitigate climate change. The building envelope is one of the essential factors contributing to the energy efficiency of a building. Furthermore, the embodied energy of the material accounts for 20 % of the total life cycle carbon emissions of the building [2].

The building envelope consists of walls, roof, floor, windows and doors. Bricks and concrete are usually used for wall construction; concrete is used as the structure for roofs and floors. Walls contribute to 30% of the total heat gain of the building, which is second after roof.

The existing building material i.e., brick and concrete, have high embodied carbon emissions and operational carbon emissions [3-4]. Researchers have looked into alternate possible materials with low carbon footprints and better thermal performance. Agro-waste material is one of the found options having low/negligible embodied carbon [5-6]. Thus, some studies are performed to look at the possibility of using agro-waste as a building material. Straws are one of the most common agro-waste found in India. Around 2 billion tonnes of various straw varieties are generated globally [7].

Straws are burned in fields in many poor nations, releasing hundreds of greenhouse gases or air pollutants such as particulate matter, elemental carbon, organic carbon, and ions. [8]. Instead of burning, such waste straws can be used as building materials since they have strong thermal insulation, good sound insulation [9-10], and good shear performance

[11-12]. To substitute the single insulation layer, straws may be mixed with hollow bricks, a core wall material in the building component market [13]. Ahmadi et al. investigated the heat transmission coefficient of wheat straw-filled hollow bricks at various levels of compaction. The thermal transfer coefficient first increased and subsequently declined as the degree of compaction increased [14]. Hu et al. investigated how the filling location affected the thermal transmission coefficient of straw-filled hollow bricks at the same rate. The outcomes demonstrated that the straw stuffing performed admirably on both sides [15].

With the increase in the use of agro-waste panels, it becomes important to evaluate the thermal performance of the material. This paper aims to analyze the thermal performance of agro-waste wall panels and flooring. A specific case of products provided by Ecoboard Industries Limited is taken as an agro-waste material for the case study. The materials provided are made up of bagasse, which is a sugarcane waste, and used as wall panels and flooring for the building. A comparative analysis is also performed to inspect the performance of agro-waste panels against typical brick-concrete structures. This is a simulation-based study using EnergyPlus software. The validation of the conduction transfer function module used in EnergyPlus for evaluating conduction through components of the building has been performed by P. C. et al. [16]. Also, several researchers have performed simulation-based studies to evaluate the thermal performance or energy consumption of the material using EnergyPlus [17-19].

From the comparative analysis for the thermal performance, it has been concluded that the agro-waste material has higher numbers of hours within IMAC band compared to the brick-concrete envelope. Also, the thermal cooling load of the building is reduced by 28 % with the use of agro-waste material.

This paper starts with the description of the building taken for the simulation and the assumptions. The methodology section explains the background equation used by EnergyPlus to generate the temperature profile and thermal cooling load. Also, the Indian Model of Adaptive Comfort (IMAC) band is described in the same section. Then, the results and discussion section show the outcome of the simulation with proper reasoning. In the end, conclusions with some future work to further enhance the thermal performance of building envelope are mentioned.

Model description

For analyzing the thermal performance of a bagasse-based wall panel, we consider a G+1 unit with a carpet area of 1367 ft², as depicted in Figure 1. The drawings of the building are provided by Team SHUNYA, and they are using it for U.S. Solar Decathlon Build Challenge 2023 [20]. The building has 2 bedrooms, a double-height living room, a dining room, a kitchen, 2 toilets, a utility area, and a battery area. The building has a plinth height of 750 mm. To restrict the scope of the analysis to building envelope related thermal loading and performance, the building is considered in its unoccupied condition with no lighting, computers, or office equipment. The building is naturally ventilated with no heating and cooling air conditioning. The deep ground surface temperature has been assumed to be 2 °C below the monthly mean outdoor air temperature.

Figure 1: Floor plan of ground floor and first floor of the building

The envelope details and their thermal properties have been given in Table 1 for a typical construction case and Table 2 for new construction with the agro-waste material case. Therefore, two envelopes are simulated, i.e., typical construction (details in Table 1) and agro-waste construction (details in Table 2) made up of bagasse and provided by Ecoboard Industries Limited. The properties of the Ecoboard are provided by the supplier after conducting the experiment test using the ASTM C518 method for thermal conductivity and IS: 3087-2005 method for density. The insulation used in the wall and roof assembly is provided by Owens Corning Composite Material Company and is made up of fiberglass wool. The overall U-value is calculated on the basis of the parameters provided by the suppliers. The infiltration through the building envelope is assumed to be 0.7 ac/h. It is assumed that the occupants' metabolic rates are within the range of 1-1.3 met, and occupants are free to adapt their clothing value in the range of 0.5-1 clo.

Table 1: Material details of typical construction

Components	**Description**	**U-value** (W/m^2-K)
External wall	Plaster (12 mm) Brick (105 mm) Plaster (12 mm)	1.3
Roof	Concrete (200 mm)	2.4
Floor	Concrete (200 mm)	2.4
Partition wall	Plaster (12 mm) Brick (105 mm) Plaster (12 mm)	1.6
Window	Sgl Clr (6 mm)	4.2

Table 2: Material details of agro-waste construction

Components	**Description**	**U-value** (W/m^2-K)
External wall	Fibre cement board (8 mm) Ecoboard (9 mm) Insulation (100 mm) Ecoboard (9 mm)	0.2
Roof	Concrete (100 mm) Metal deck Insulation (100 mm)	0.3
Floor	Metal deck	1.6
	Ecoboard (38 mm)	
Partition wall	Ecoboard (9 mm) Insulation (50 mm) Ecoboard (9 mm)	0.2
Window	Dbl Clr/Air (6 mm)	2.6

Methodology

The building is modeled in Design Builder and simulated in EnergyPlus V22-2-0. The hourly simulation was performed in EnergyPlus with outputs such as indoor temperature profile and cooling load.

EnergyPlus model

To analyze the thermal properties of the dwelling unit, it has been simulated in EnergyPlus. EnergyPlus is a building energy simulation tool that works on the fundamental principle of energy balance. Each zone (volumetric space of each zone) is assumed as one node containing uniform properties of state variables, e.g., temperature, pressure, and density. For the one node temperature T_z of the air inside the zone, an energy balance can be given as

$$m_z c_z \frac{dT_z}{dt} = \sum_{i=1}^{N_s} Q_i + \sum_{i=1}^{N_{surface}} h_i A_i (T_{si} - T_z) + \sum_{i=1}^{N_{zones}} m_i c_p (T_{zi} - T_z) + m_{inf} c_p (T_\infty - T_z) + Q_{sys} \tag{1}$$

where the L.H.S. represents the energy stored in zone air. For the R.H.S., the first, second, third, fourth, and fifth term represents the sum of the convective internal loads, the sum of convective heat transfer from the envelope, heat transfer due to interzone air mixing, heat transfer due to infiltration of outside air and air system output, respectively. The above equation results in the calculation of the temperature T_z of the air inside each zone.

After the calculation of zone temperature, the system energy provided to the zone for meeting cooling or heating load is calculated from the difference between the supply air enthalpy and the enthalpy of the air leaving the zone, as shown in Equation (2)

$$Load = m_{sys}C_p(T_{sup} - T_z) \qquad (2)$$

where, T_{sup} is the supply air temperature, and T_z is the indoor air temperature.

IMAC MODEL

India Model for Adaptive Comfort (IMAC) model is the standard for adaptive thermal comfort, based on Indian specific climatic conditions. It is applicable for naturally ventilated, mix-mode and air-conditioned buildings and remains valid for the wide range of outdoor temperatures of Indian climatic zones. The indoor operative temperature is calculated using the equations given below.

For Naturally ventilated building:

$$\textit{Indoor operative temperature} = (0.54 \times \textit{outdoor temperature}) + 12.83 \qquad (3)$$

For Mixed-mode building:

$$\textit{Indoor operative temperature} = (0.28 \times \textit{outdoor temperature}) + 17.87 \qquad (4)$$

For Air-Conditioned building:

$$\textit{Indoor operative temperature} = (0.078 \times \textit{outdoor temperature}) + 23.25 \qquad (5)$$

The indoor operative temperature obtained from the above equation is comfortable for most people. 90 % acceptability range is derived as ± 2.83 °C, ± 3.46 °C, and ± 1.5 °C in naturally ventilated, mix-mode and air-conditioned buildings, respectively. Similarly, for the 80 % acceptability band, the comfort band is ± 4.1 °C, ± 5.9 °C and ± 3.6 °C for naturally ventilated, mix-mode and air-conditioned buildings, respectively. The acceptability band’s narrowness increases when we move from a naturally ventilated building to an air-conditioned building.

Results and Discussion

For the thermal performance analysis, a simulation has been performed for a warm and humid climatic condition. The simulation is performed by turning off the air conditioner and using only natural and mechanical ventilation. The Indian model of adaptive comfort (IMAC) band for mixed mode building with a 90% acceptability range is calculated for each day of the year.

Figure 2 shows the hourly simulation of the maximum outdoor temperature day in Mumbai, i.e., 16 March. Agro-waste construction has only 4 hours out of the band, whereas typical construction has 13 hours out of the IMAC band. To quantify the discomfort hours further, the area under the curve, i.e., outside the IMAC band for both cases, has been calculated using the trapezoidal rule. It is found that for typical construction and agro-waste construction, the area outside the IMAC band is 32 and 1.55, respectively. This shows that agro-waste construction is marginally out of the comfort band as compared to typical construction. The diurnal temperature range of maximum temperature day is 16.7 °C. The temperature swing of agro-waste construction is 4 °C approximately, while the temperature swing of typical construction is around 10 °C.

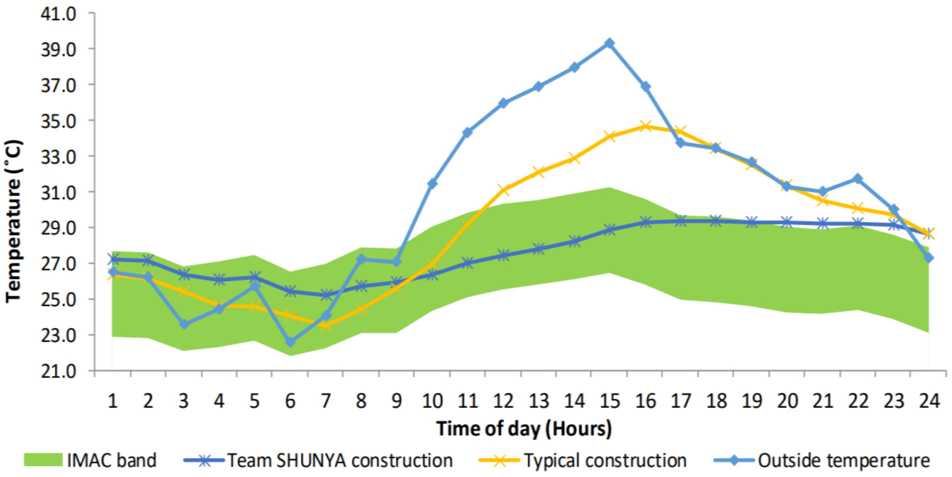

Figure 2: IMAC comfort band for Mixed Mode building (90% acceptability range)

Figure 3 shows the diurnal temperature of the peak temperature day of each month for outdoor temperature and indoor temperature of agro-waste construction and typical construction. It can be seen from the graph that the maximum temperature swing for outdoor temperature is 16.7 °C in the month of March, and the maximum temperature swing for typical construction and agro waste construction is 11.16 °C and 4.15 °C, respectively, in the same month. It can also be concluded that for agro waste construction, the diurnal temperature ranges between 1.0 °C to 4.15 °C, whereas the temperature swing of typical construction ranges between 2.63 °C to 11.16 °C. The reason for the lower diurnal temperature of agro-waste construction is the lower thermal conductivity and lower u-value of agro-waste materials used. Even the thickness of both construction types is equivalent for most of the building components, but lower diurnal temperature swings show that the agro-waste construction has better thermal mass and performs better in all the seasons for warm and humid climatic conditions.

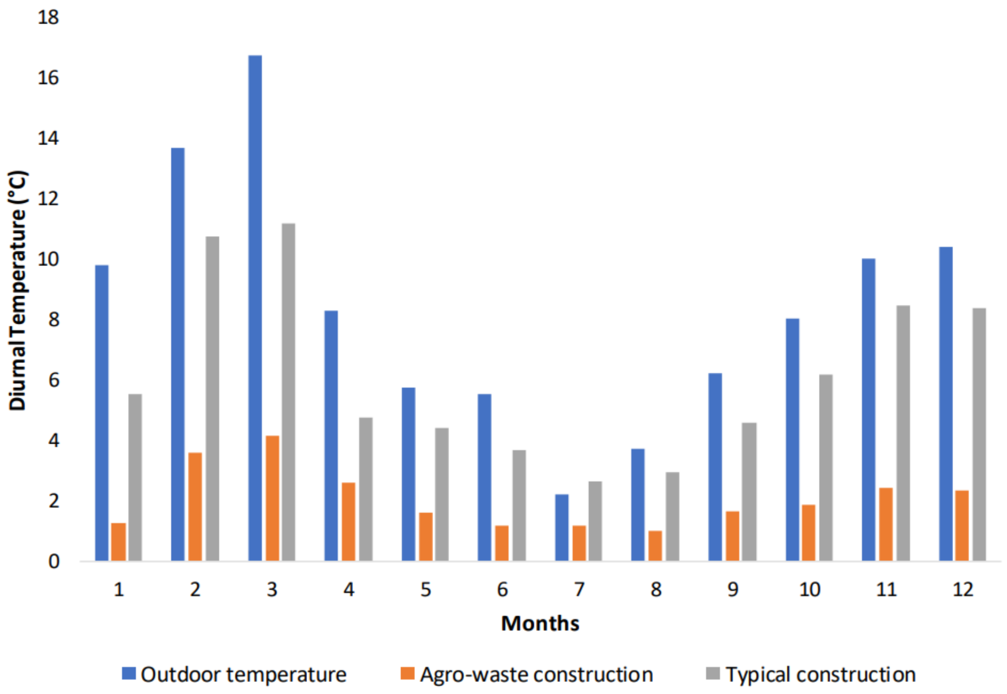

Figure 3: Diurnal temperature for all the months of Mumbai

After looking at the temperature profile of the maximum temperature day, the indoor temperature for the whole year is analysed, and the number of hours within the comfort band is calculated. Figure 4 shows the number of hours within the comfort band for each month for both construction types. The comfort hours for agro-waste construction are greater than the typical construction every month. The number of comfort hours is maximum for the month of May and minimum comfort hours are observed in February. The reason for less comfort hours in February is the low outdoor temperature, due to which the lower temperature of the IMAC band is above the indoor temperature. In the case of May, 96 % of the indoor temperature is within the thermal comfort band. Quantitatively, it is observed that 8154 hours and 7000 hours are within the IMAC band for agro-waste construction and typical construction, respectively. This indicates that when the construction material is changed from typical construction to agro-waste construction, a 16.4 % increase in comfort hours is obtained.

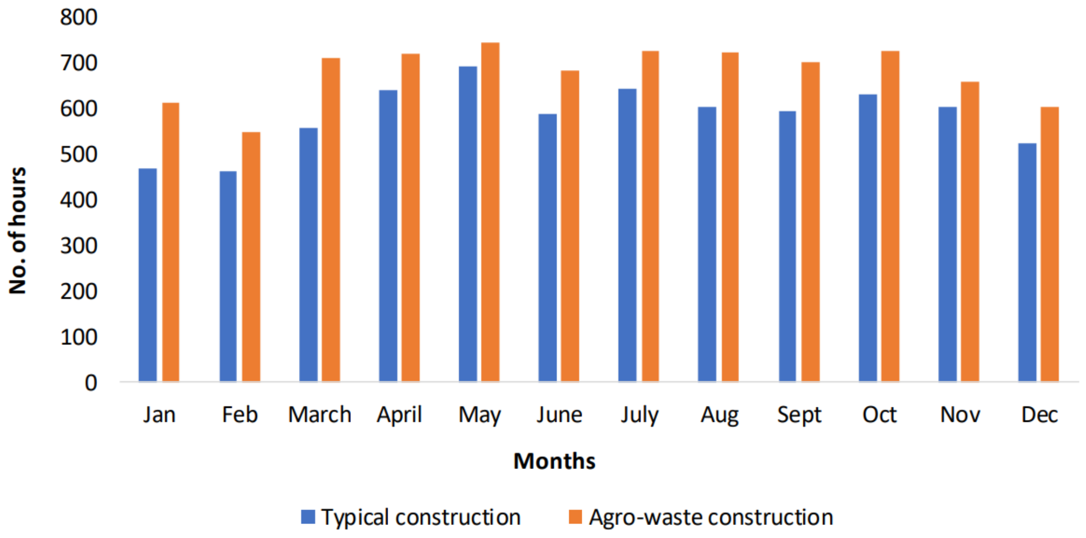

Figure 4: IMAC comfort hours of Mumbai

Figure 5 shows the comparison of cooling load for agro-waste and typical construction. The total cooling load of agro-waste construction is 28 % less than that of typical construction. The highest cooling load of typical construction and agro-waste construction is 2247 kWh and 1182 kWh, respectively. For the peak month, the cooling load is reduced by 45 % using agro-waste construction. The low cooling load of agro-waste construction is due to the low u-value of material used in the building.

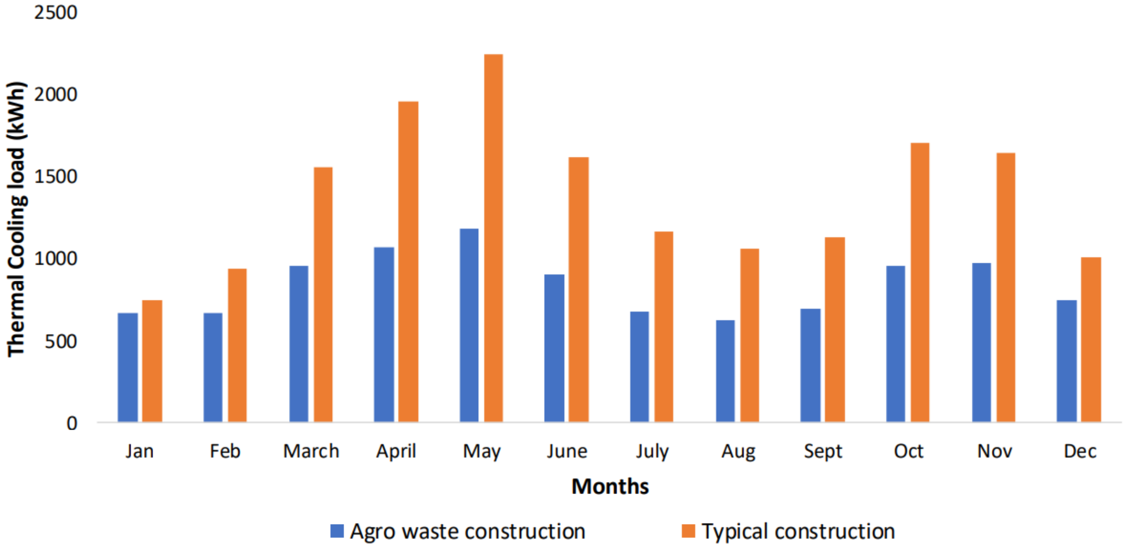

Figure 5: Monthly thermal cooling load of Mumbai

Conclusion

This study compared the thermal performance of the G+1 dwelling unit using agro-waste construction and typical construction. It has been concluded that the agro-waste construction performed better in terms of thermal comfort and thermal cooling load of the building as compared to the typical construction. Then, the monthly cooling load of the building is calculated, which shows a 28% reduction in yearly consumption.

The use of agro-waste panels for wall assembly and floor has minimal carbon emission as the product is in its second life. As the panel is pre-fabricated, this could fasten the construction as compared to the brick-concerte structure. However, strength and waterproof tests should be performed to further implement it in the future.

In the future, the wall gain and cooling load can be decreased with the use of advanced materials such as phase change material (PCM), green roof, and skin green façade. The agro-waste panels would behave differently in different climatic condition, so it becomes important to simulate the performance of agro-waste panel before using it for any climatic zone. A simulation of the agro-waste panel with advanced materials such as phase change materials becomes important as it would reduce the u-value of the assembly, and a very low u-valued material could restrict the internal heat load to decapitate outside, resulting in a rise of indoor temperature. Also, a techno-economic analysis of the product should be performed according to different income groups of India.

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