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A Comparative Study to Assess the Thermal Behaviour of Sandwich Roof Panels with Coconut Fibre as an Alternative Core Material to Polyurethane

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Abstract

Sandwich panels (modular panels) promote optimal solutions to some major issues prevailing in the construction industry such as increased energy consumption by building elements, excessive disposal of constructional waste and unproductive time spent during construction. Hence, the inclination towards sandwich elements has been increased vastly deviating from conventional building construction materials and methods. However, the potentiality of using locally available natural materials for the development of sandwich panels is a salient sustainable approach that needs to be addressed. This study evaluates the current and potential materials used in modular panels and key properties of sandwich panels including mechanical, thermal insulation, and sound insulation properties. Moreover, various test methods followed, and standards specified to investigate the mechanical, thermal and acoustic insulation properties are also discussed. The possibility of using coconut fibre as a locally available natural alternative core material to polyurethane core of sandwich panels has been evaluated using simulations based on the material properties obtained from literature. The study identifies coconut fibre as a potential alternative core material for sandwich roof panels as it reflects nearly similar thermal behaviour to polyurethane.

Keywords

Modular Panels, Insulation, Coconut Fibre, Sustainability

1. Introduction

With rapid urbanisation, the energy consumption of buildings has become a vital problem worldwide. Since energy can be regarded as a prerequisite for the development process of a country, a drastically gearing-up demand for energy consumption is observed in developing countries (Jayasinghe, Attalage, & Jayawardena, 2003). This rise in per capita consumption of fossil fuels has given rise to critical environmental issues such as the "urban heat island effect" (Shashua-Bar & Hoffman,2000). Hence, minimisation of energy consumption is considered one of the major primary challenges in the construction industry from environmental and economic points of view. The energy consumption of buildings has become notable since buildings consume about 30% to 40% of all primary energy (Korol & Shushunova, 2016). Hence more concern towards sustainable development measures with building energy conservation practices has arisen. This building energy conservation can be achieved by using energy-efficient building design (Xing, Hao, Lin, Tan, & Yang, 2019), efficient energy supply facilities (Chen et al., 2019) and energy-efficient equipment (Zhou et al., 2019).

The roof is one of the major components in a building which is greatly responsible for the energy consumption of the building and for maintaining the internal thermal comfort. In warm, humid climatic conditions where a significant portion of the global population lives, the sun path generally goes through high altitudes during the daytime, which results in the buildings getting exposed to intense sunlight (Jayasinghe, Attalage, & Jayawardena, 2003). Hence, attention must be paid when selecting a roofing material in addition to other factors such as roof orientation and the surface colour. Over the years, the use of various types of roofing materials, such as clay tiles, timber, aluminium foil, polystyrene etc., can be observed and several roofing materials are shown in Fig. 1 below. Due to the previously discussed issue of higher energy consumption of these building materials and the shifting of people's concern towards sustainable construction practices, a new trend has been set for the use of modular/sandwich roof panels instead of conventional roofing materials and techniques.

Generally, these sandwich panels consist of two facing sheets sandwiching a core material. These two facings are relatively thin and of high strength, and the enclosed core is made up of a rigid, thick and lighter material. Furthermore, the core material has an adequate stiffness in the direction normal to the panel facings. Preliminarily sandwich roof panels made up of synthetic core materials were found in the market, and at present, the use of different natural materials for the core is significant in the view of sustainability. Hence the rise of concern about developing a sandwich roof panel with locally available sustainable materials is notable.

Fig. 1 Types of roofing materials; clay tiles, timber, aluminium sheets, expanded polystyrene sheets

This study was conducted to compare the thermal behaviour of sandwich roof panels with coconut fibre as an alternative core material to polyurethane (PU) by investigating available and innovative materials, manufacturing processes, properties of sandwich panels and testing procedures. This paper presents the history of the development of sandwich panels, the study's objective, the methodology adopted, materials used in sandwich panels, properties, test methods, and standards available to determine mechanical performance.

2. Methodology

This study aims to identify a potential natural raw material to replace the currently available synthetic polyurethane core of sandwich panels through a detailed analysis of available materials, properties and testing procedures and standards that can be followed. A detailed literature review was conducted to identify a range of materials used in sandwich panels, thermal and mechanical which includes the relevant test methods and standards available to conduct experimental analysis. Then, a numerical model was developed using a commercially available software (Dynamic Energy Response of Building-DEROB-LTH). After theoretically validating the thermal simulations, a detailed parametric study was conducted to identify a suitable sustainable core material for the sandwich panels.

3. Literature Review

3.1 Materials

Basically, as depicted in Fig. 2, a sandwich panel is composed of three main components: two face sheets (skin), core material sandwiched between the two face sheets and the adhesive layer used to ensure proper bonding between the face sheets and the core.

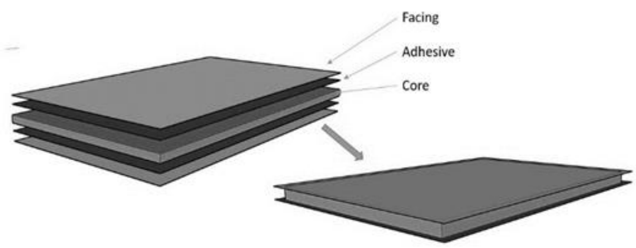

Fig. 2 Basic structure of a sandwich roof panel

The most widely used face sheet materials include Glass Fibre reinforced polymer (GFRP) composites, Carbon Fibre reinforced polymer (CFRP) composites, metal sheets, Ferro-cement panels, etc. When considering the core material of a sandwich panel, the core can be mainly categorised into three main types. They are synthetic, honeycomb and natural fibre core. Various studies have been carried out using different combinations of these materials for the face sheets and core to evaluate the mechanical properties of different sandwich panels, and some such combinations are summarized in Table 1.

Table 1. Summary of materials used in sandwich panels

Type of material		Reference
Core material	Face sheet material	
Phenolic coated aramid Nomex paper honeycomb	Bio-fibre reinforced polymer using Whatman filter paper	Du et al., (2012)
Wooden foam core using pine and beech	Glass fibre reinforced concrete sheets	Bunzel et al., (2020)
Honeycombed core using eucalyptus sawdust and cement particles	Piassava laminates	Dutra et al., (2020)
Cork agglomerates, Nomex Rohacell 71, WF rigid foam	Carbon/epoxy face sheets	Castro et al., (2020)
Coconut fibre	Ferro-cement panels	Alavez-Ramirez (2012)
Prismatic core of Veneer sheet	3-ply plywood beech	Smardzweski (2019)

3.2 Properties of sandwich panels

Modular/ sandwich panels have become a trend in the present construction industry due to their mechanical properties, lightweight, high thermal and sound insulation, higher strength, low cost and durability. The face sheets carry the tensile and compressive loads under flexural loading conditions while the shear stress is transmitted through the core of the sandwich panel. In addition, the core material's high thermal and sound insulation properties are significant. Hence these properties have been evaluated in the studies conducted using sandwich panels prepared using different skin and core materials. Table 2 summarizes the thermal conductivity of materials found in previous studies.

Table 2. Thermal properties of materials

Material	Thermal conductivity (W/m K)	Reference
Wooden foam	0.045	Bunzel et al., (2020)
Polystyrene	0.03	Bunzel et al., (2020)
Wooden veneer	0.19	Lakreb et al., (2015)
Rocacell WF 71	0.03	Castro et al., (2010)
Cork agglomerates	0.045-0.047	Castro et al., (2010)
Ferro-cement	0.696	Alavez-Ramirez (2012)
Coconut fibre filled ferro-cement panel	0.221	Alavez-Ramirez (2012)
Air filled ferro-cement panel	0.506	Alavez-Ramirez (2012)
Lightweight concrete brick	0.536	Alavez-Ramirez (2012)
Hollow concrete brick	0.683	Alavez-Ramirez (2012)
Saw dust biomass-based material	0.087-0.27	Zou et al., (2020)
Wheat straw biomass-based material	0.092-0.186	Liu et al., (2017)
Hemp biomass	0.117	Walker & Pavia (2014)
Coconut fibre	0.048	Jayasinghe,Attalage & Jayawardana (2003)
PUR foam core	0.025	Jayasinghe,Attalage & Jayawardana (2003)
PVC foam core	0.022-0.048	Jayasinghe,Attalage & Jayawardana (2003)

3.3 Test methods and standards

In a sandwich or modular panel, the two faces covering the core provide bending and in-plane stiffness. The core embedded between the two faces carries the shear loads transmitted through the thickness. Literature provides evidence on several tests, including experimental and numerical test methods, which have been carried out to determine the flexural and shear capacities of different face materials and core materials. Apart from these tests, several tests have been carried out to investigate the properties of core materials such as heat and sound insulation, the effect of density, resistance to hygro-thermal environment etc. The test methods followed and specified standards related to the thermal insulation are briefed in Table 3, and other measured properties and the test methods and standards adopted are listed in Table 4.

Table 3. Test methods and standards to determine the thermal properties of sandwich panels

Thermal property	Test method/ Standard	Reference
Thermal conductivity of wooden foam	TBH instrument	Bunzel et al., (2020)
Heat transmission coefficient	DIE EN 12667	Bunzel et al., (2020)
Thermal conductivity	ISO 2582 EN 12664	Castro et al., (2010)
Thermal conductivity	ASTM C1777	Alavez-Ramirez (2012)
Heat conductivity	Heat conductivity tester (DRE-III)	Zou et al., (2020)
Amount of heat absorbed	Graphical integration of function of compression or bending force and deflection	Smardzweski (2019)

Table 4. Test methods to determine other properties

Property	Test method	Reference
Water absorption	DIE EN 1609	Bunzel et al., (2020)
Fire behaviour (foam)	EN ISO 9239-1	Bunzel et al., (2020)
Sound absorption	A Kundt's tube with perpendicular sound incidence	Bunzel et al., (2020)
Airflow resistivity	ASTM C522-3	Silva et al., (2019)
Sound absorption coefficient	ASTM D638-10	Silva et al., (2019)
Impact tests	ASTM D7136/D7136M-05	Castro et al., (2010)

4. Numerical Simulations

After conducting a detailed literature analysis to identify the properties of materials used in sandwich panels, a thermal analysis was conducted to evaluate the possibilities of using natural materials to replace synthetic core materials. A comparative analysis was conducted to check the possibility of using a natural raw material to replace synthetic core materials. Hence, average values were used for solar radiation intensities considering the average sunshine hours (Jayasinghe, Attalage, & Jayawardena, 2003).

For the simulations, the behaviour of the roof was prioritised. Hence, the effects from other building elements were maintained at a minimum adverse level to the indoor temperature by adopting the passive features suggested in Jayasinghe et al. (2003).

A case study of single-storey house with two volumes was used for simulations. The plan view and the three-dimensional view of the model house used are depicted in Fig.s 3 and 4, respectively. Table 05 states the sizes of the doors and windows used in the model.

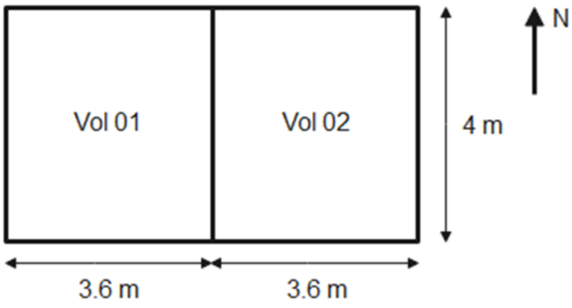

Fig. 3. Floor plan

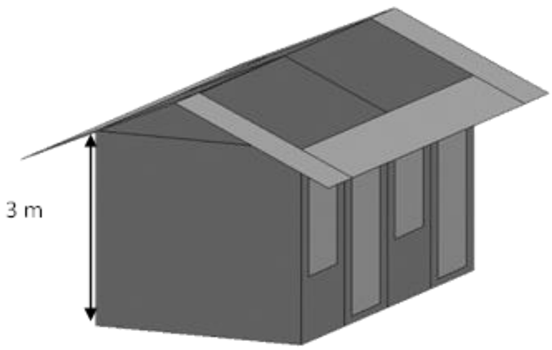

Fig. 4. Three-dimensional model of the building used for the analysis

Table 5. Sizes of doors and windows of the model

Element	Size (width × height) (m)
Doors	1.2 × 2.0
Windows	1.2 × 1.5

Initially, the model was analysed based on the material properties obtained from the literature review to compare the behaviour of existing foam core sandwich panels and the behaviour of sandwich panels with coconut fibre as core material. Coconut fibre core material can be produced by compressing sun dried coconut fibre material at 115.54 MPa (Rodriguez et al., 2011). Mild steel was used as the face material in both cases. The properties of the materials and configurations of sandwich panels used for the analysis are mentioned in Tables 6 and 7, respectively.

Table 6. Material properties

Material	Thermal conductivity (W/m K)	Density (kg/m^3)	Specific heat capacity (J/kg K)	Reference
PU	0.025	30	1400	Zenhert et al., (1997)
Mild steel	50	7800	480	Zenhert et al., (1997)
Coconut fibre	0.048	174	2600	Rodriguez et al., (2011)

Table 7. Configuration of sandwich panels

Sample identity	Thickness and configuration of sandwich panel core		
	Configuration	Facing thickness (mm)	Core thickness (mm)
SP01		0.6	100
SP02		0.6	100
Key	PU	Coconut fibre	Mild steel

Table 8. Thickness and configuration of composite core layers

Sample identity	Configuration	Thickness of Pu layer/s (mm)	Thickness of coconut fibre layer/s (mm)
SP03		50	50
SP04		40	30
SP05		30	40
Key	PU	Coconut fibre	

Secondly, the behaviour of sandwich panels was analysed based on the composite behaviour of polyurethane foam (PU) and coconut fibre as core materials. Several combinations of polyurethane and coconut fibre with varying thicknesses, maintaining the overall thickness of sandwich panels at 100 mm, were evaluated and the details are mentioned in the Table 8 above. Mild steel was used as the facing material.

Finally, the indoor temperature variation was evaluated for varying core thicknesses (60 mm, 80 mm, 100 mm, 120 mm, and 140 mm) of coconut fibre layers. Face material remained unchanged from mild steel.

5. Results And Discussion

Detailed thermal simulations were conducted to assess the possibility of replacing the polyurethane core material with coconut fibre as a potential natural raw material. It has been shown that coconut fibre reflects similar thermal behaviour to polyurethane. Fig. 5 below elaborates on the variation of indoor temperature with two different core materials with the material properties and panel configurations stated in Tables 6 and 7 above. The indoor air temperature for both the materials varies much like each other.

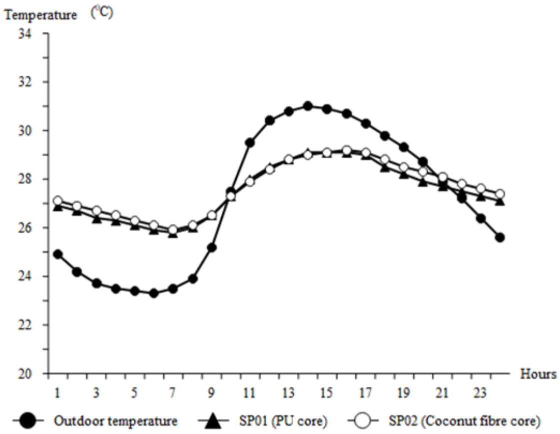

Fig. 5. Variation of indoor temperature with two different core materials

Fig. 6 below illustrates the variation of indoor temperature with the composite behaviour of PU and coconut fibre according to the configurations mentioned in Table 8. When considering the results obtained for the composite behaviour of cores with polyurethane and coconut fibre, it was observed that the change in indoor temperature is independent of the configuration of core layers.

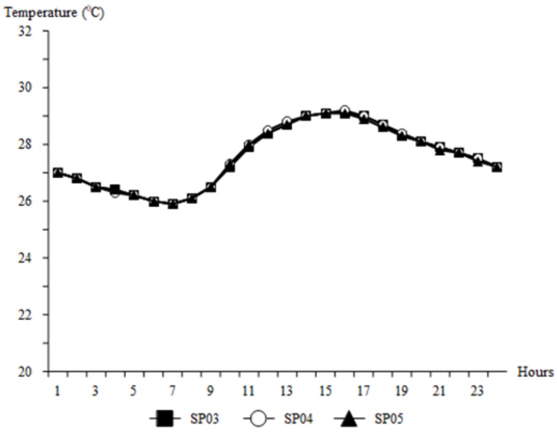

Fig. 6. Variation of indoor temperature with composite behaviour of PU and coconut fibre

Additionally, the effect of the thickness of the coconut fibre core on the indoor temperature is depicted in Fig. 7. The coconut fibre core thickness has been changed from 60 mm to 140 mm. It is noticeable that increasing the thickness of the coconut fibre core resulted in reducing the indoor temperature during daytime and vice versa. However, the optimum thickness must be selected considering the optimum weight of the sandwich panel for a given stiffness. To achieve this, an experimental procedure can be followed to determine the mechanical properties of sandwich panels.

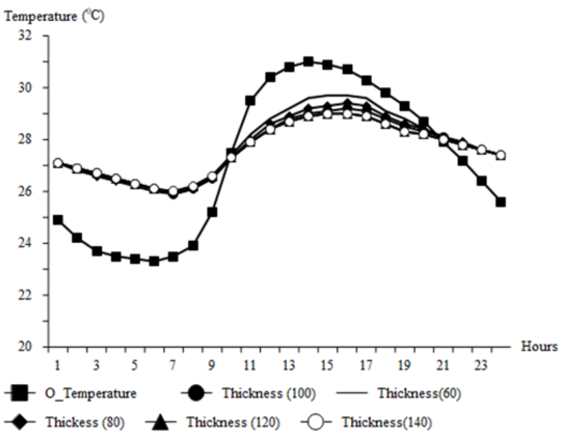

Fig. 7. Variation of indoor temperature with the thickness of sandwich panels with coconut fibre as core material

March was selected as the critical month for the simulations, as the number of sunshine hours is maximum in March (Jayasinghe, Attalage, & Jayawardena, 2003).

The thickness of the face material was used as 1mm for the simulations because 1mm is the minimum thickness that can be input into the simulations. The actual thickness of the face material is lower than 1mm. However, since a comparative study has been conducted maintaining the same thickness and face material for all the cases, the effect of using a higher thickness for the face material can be assumed to be insignificant.

Finally, it can be stated that, by using the experimental procedures mentioned in the chapter on test methods and standards, these results must be verified to develop a potential sandwich panel capable of providing thermal insulation as a primary function of a roofing panel while achieving the minimum weight condition for a given stiffness.

6. Conclusions

Modular roof panels have some prominent advantages over conventional roofing materials as modular panels are light in weight, durable, have low operational cost, have high thermal and sound insulation properties, etc. Numerous tests have been carried out to investigate the properties of sandwich panels so that those properties can be enhanced to obtain optimum results.

The study evaluated the different types of materials used in sandwich panels, their properties, including thermal and mechanical properties and various types of test methods used to determine the respective properties of sandwich panels. Different types of materials are currently used in producing modular panels, whereas more focus has been developed on sustainable organic materials such as coconut fibre, sisal, paddy husks, etc. Compared with honeycomb cores, foam cores are efficient in thermal insulation. Thermal conductivity values of foam core materials have varied in the range of 0.03 Wm-1K-1 to 0.036 Wm-1K-1. The natural materials tested in previous studies as core materials also have shown closely similar thermal insulation properties. The natural core materials' thermal conductivity values vary between 0.027 Wm-1K-1 to 0.045 Wm-1K-1. Hence, the values obtained for the sandwich panels with natural core materials highlight the suitability of using those materials to develop a sustainable modular roofing panel. Moreover, it was justified from the thermal simulations based on the properties obtained from the literature that coconut fibre displays potential behaviour of using as an alternative to polyurethane cores in sandwich panels.

Following key conclusions can be made regarding the composite roof panels with natural core materials concerning the details obtained from published sources:

Coconut fibres can be used as a potential alternative core material to the currently used polyurethane core material.

Increasing the thickness of the coconut fibre core results in further reduction of indoor temperature. The percentage reduction of outdoor temperature has varied from 3.26% to 5.54% with the varying thickness of coconut fibre.

The variation of indoor temperature is independent of the layer configuration when a composite core material of polyurethane and coconut fibre is used.

Hence from the study, it is salient to mention the potentiality of developing an innovative sandwich panel using coconut fibre as a locally available natural material. However, an appropriate thickness for the core can be optimised by considering the structural stability of the sandwich panel in future studies. To execute the structural optimisation of the panel, appropriate mechanical test methods can be performed.

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