DEVELOPMENT OF COMPOSITE PANELS BASED ON FIBROUS MATERIALS FOR THE MANUFACTURING OF MODULAR HOUSING

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Abstract

The present work describes the development of sandwich composite panels for application in modular housing in developing countries. Sandwich panels were developed with hybrid fibrous skins combined with polyurethane core. Different fibrous materials and structures were studied in order to achieve a sustainable solution. The analyzed fibers were jute, sisal, flax and glass fiber. In order to select the most suitable fibrous materials, mechanical performance as well as acoustic and thermal insulation behaviors were investigated. The selection of materials was based on a decision matrix that took in to account all analyzed parameters. After defining the final solution a prototype, which was a sandwiched panel with skins made of glass and jute fibres and having 2.50 m length, was produced and characterized for flexural strength and stiffness, in-plane and out-of-plane compressive strength as well as thermal and acoustic insulation performances. It was observed that glass fiber was mainly responsible for the strength and stiffness of the panel, while jute fiber contributed to the good thermal and acoustic insulation behaviors.

1. Introduction

In current times, Fibre Reinforced Plastics (FRPs) have allowed the development of alternative solutions for construction industries with several advantages such as light weight, durability, high strength / weight ratio and corrosion resistance, among others. These advantages made it possible to apply these materials extensively in construction in various situations including strengthening and rehabilitation of structures, construction of bridges and other precast elements such as profiles and panels for construction [1]. Due to these features and industrialized process, FRP materials can also be applied in more efficient building systems such as modular housing. As an alternative to the traditional construction, this industrialized construction process can provide the production of construction elements in series, increasing the quality parameters and lowering the generated wastes due to a more efficient construction process [2]. In order to find suitable materials for modular house construction, the present research is focused on the investigation of performance of various types of synthetic and natural fibres and selection of the most suitable fibre system for development of sandwich composites to be applied in modular housing.

2. Materials

In this study, 8 different fibrous reinforcements were analyzed and characterized. 4 of these reinforcements were based on natural fibers (T1, T2, T3, T4 samples) and other 4 were based on synthetic fibers (glass). Details of these fibrous raw materials are presented in Table 1.

Code	T1	T2	T3	T4	T5	T6	T7	T8
Type	Sisal Fabric	Jute Fabric	Jute fabric	Linen Fabric	Glass fiber Fabric	Glass fiber Fabric	Glass fiber Fabric	Glass fiber mat
GSM (g/m^2)	1098.4	398.3	254.9	255.2	296.7	287.0	304.3	469.2
Thickness (mm)	3.18	1.20	1.13	0.85	0.42	0.55	0.57	1.66

Table 1 Fibrous reinforcements used in this study

To produce different composite samples, fibrous reinforcements were impregnated with isopthalic polyester resin, which was mixed with 2% of hardener and 0.2% of accelerator. The characteristics of the resin used are detailed in Table 2.

Characteristics	Units	Testing Standards	Values
Distortional Temperature	[ºC]	ASTM D-648	90-100
Water Absorption	[%]	ASTM D-570	0.15
Tensile Strength	[MPa]	ASTM D-638	50-70
Flexural Strength	[MPa]	ASTM D-790	90-120
Extension at rupture	[%]	ASTM D-638	3.5

Table 2 Physical and mechanical properties of the polymeric resin used in the present study

The impregnation of fibrous reinforcements was carried out using a vacuum infusion process (Figure 1).This process consists of placing the fibrous reinforcements over a glass plate which was hermetically sealed with a vacuum bag containing two output tubes. One of these outlet tubes was connected to a vacuum pump that put negative pressure in the vacuum bag resulting in filling of the resin in the vacuum bag through the second tube.

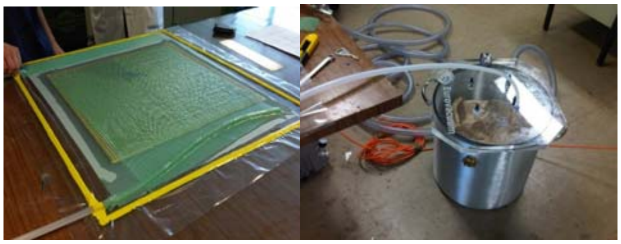

Figure 1 Production of samples using vacuum infusion impregnation process

3. Testing methods

3.1 Tensile properties characterization

To characterize the mechanical behavior of different composites uni-axial tensile testing has been performed according to ASTM 597-4 standard. . For this purpose, the samples were cut in order to obtain the specific dimensions as presented in Figure 2. The tests were performed at constant extension rate of 20 mm/min and the deformation was measured using a 25mm gauge extensometer.

Figure 2 Dimensions of composite speciments used for tensile testing

3.2 Thermal characterization

Thermal performance of the composite samples was evaluated based on their thermal conductivity. To determinate this property Alambeta instrument was used as shown in Figure 3.

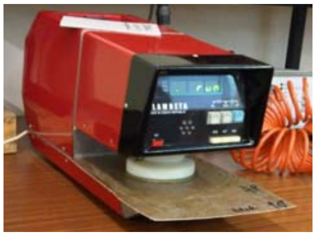

Figure 3 Alambeta Instrument for measuring thermal properties

Thermal conductivity was measured according to the procedure followed by Lubos et al. [3]. The composite samples were placed on the steel block which was heated or cooled down to achieve a constant temperature (20ºC). , Then the temperature sensor came down and made contact with the sample to determine its temperature. Based on this measurement, thermal conductivity of the samples was determined.

3.3 Acoustic insulation characterization

The characterization of acoustic insulation was performed on specimens having dimension of 220x220mm in a box made of composite material, which is acoustically isolated and built (Figure 4) in accordance with the specifications followed in the references [4] and [5]. This box consists of:

- Sound Source: responsible for creating the noise;
- Holes for placement of sound level meters: available at different distances from the sound source;
- Slots for placement of specimens to ensure the fixation of samples and their positioning to known distances from the source.

The sound insulation was measured in terms of reducing audible noise by each sample, keeping the distance between the sample and the source of noise emission constant. Noise reduction was calculated by subtracting the reduction of the noise level obtained with and without the sample. Measurements were made using two sound level meters which measured the sound intensity before and after the samples (Figure 5).The sound was originated in a computer using an audio track with pink noise and the noise reduction was determined at 500 and 1000 Hz frequency.

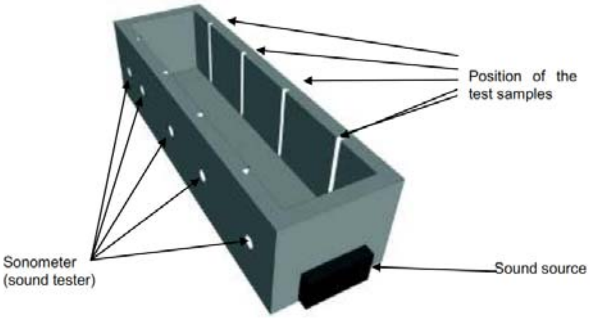

Figure 4 Acoustic insulated chamber [7]

Figure 5 Interior of acoustic insulation testing box (left) and assembly used (right)

The evaluation of noise reduction was performed in the 1st and 2nd positions of the box, having a distance of 12.5cm between both sound level meters. The sample was placed in the middle of the sound meters.

4. Results obtained

4.1 Tensile testing

The results obtained in the mechanical testing are presented in Table 3. To obtain the fiber volume fraction of each composite, the absolute density was determined according to ASTM 597-4. As expected, the results show that the tensile strength of natural fibre composites (T1, T2, t3 and T4) are much lower than that of glass fiber composites (T7, T8, T9 and M1). The same observation is also made in case of Young's modulus. Beside this, higher variability of results in case of natural fiber composites is reflected from the higher C.V. % of obtained results.

4.2 Thermal testing

The results obtained in the thermal conductivity characterization are listed in Table 4. Since the principal design consideration for these composite panels is the weight limit, besides considering the listed thermal conductivity values the weight of the samples should also be taken in to account in order to evaluate the thermal performance of these composites.

Composite	Density (g/cm^3)	Fiber Volume Fraction (%)	Orientation (º)	Tensile Strength (Mpa)	c.v. (%)	Elastic Modulus (Mpa)	c.v. (%)
T1 Sisal Fabric	1.210	24.5	0º	17.2	6.3%	3227	41.9%
			90º	14.4	15.2%	2433	16.3%
T2 Jute Fabric	1.240	27.2	0º	39.2	4.6%	1502	2.8%
			90º	44.7	4.3%	1607	4.2%
T3 Jute Fabric	1.242	21.1	0º	23.2	10.0%	1582	19.6%
			90º	34.5	12.0%	1953	8.2%
T4 Linen Fabric	1.294	35.1	0º	74.8	6.6%	3844	6.8%
			90º	52.7	2.6%	2470	9.9%
T7 Glass Fabric	1.781	40.9	0º	294.6	7.1%	7816	6.5%
			90º	264.3	8.4%	8351	8.7%
T8 Glass Fabric	1.841	46.0	0º	344.4	6.6%	16887	6.6%
			90º	255.2	6.8%	10976	7.2%
T9 Glass Fabric	1.875	47.4	0º	352.9	6.7%	16785	8.9%
			90º	324.6	2.6%	14312	1.7%
M1 Glass Mat	1.600	33.0	N.A	84.8	7.3%	5150	8.4%

Table 3 Density, fiber volume fraction, tensile strength and elastic modulus of composite samples

Composite	T1	T2	T3	T4	T5	T6	T7	M1
thickness (mm)	3,9	2,35	1,9	2,21	1,49	1,49	2,13	0,78
λ (W/mK)	121	71	70	80	103	123	50	55

Table 4 Thermal conductivity (λ) of different composites samples

The presented results show that the lowest thermal conductivity is obtained in glass fiber composites, T7 and M1 having conductivity of 50 and 55 W/mK, respectively. Better than these samples are T2 and T3 which have thermal conductivity of 71 and 70 W/mk, respectively. The results also show a big variability in the thermal conductivity of glass fiber composites, T6 and T7 which exhibited the highest and lowest thermal conductivity respectively (123 and 50 W/mk).

4.3 Acoustic insulation testing

Acoustic insulation of the developed composites was evaluated at 500 and 1000 Hz, since these 2 frequencies are the most determinant to quantify the acoustic insulation at air sounds. In order to obtain an equivalent sound reduction a mean value was calculated based on the noise reduction at 500 and 1000 Hz. The obtained results are showed in the table 5. These results showed that the glass fiber composite T7 had the highest acoustic insulation property with an equivalent noise reduction of 11.64 dB, followed by the composite M1 with 10.42 dB and jute fiber composite (T2) with 10.06 dB. However, in terms of acoustic insulation, it is necessary to correlate the equivalent sound reduction with the weight of the composites, since the acoustic insulation is directly related to the weight of the insulators. The ratio of sound reduction to the weight of samples is presented in Table 5.Using this ratio it's possible to identify the composites with higher sound reduction performance at similar weights. . In the present study, composites with better sound reduction performance are M1, T7 and T2 with 8.35, 5.17 and 3.12 dB.m^2/kg respectively.

Composite		**T1**	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**M1**
thickness (mm)		5.5	2.44	1.85	1.95	1.49	1.49	1.2	0.78
Noise reduction [dB]	**500 Hz**	10.68	8.8	6.9	6.98	9.32	7.68	10.8	10.48
	1000 Hz	5.72	10.06	6.16	7.88	7.08	7.74	12.46	10.36
Equivalent Sound reduction [dB]		8.2	9.43	6.53	7.43	8.2	7.71	11.63	10.42
Superficial weigth (kg/m^2)		6.66	3.03	2.30	2.52	2.65	2.74	2.25	1.25
Sound reduction by weight (dB.m^2/kg)		1.23	3.12	2.84	2.94	3.09	2.81	5.17	8.35

Table 5 Acoustic insulation properties of developed composites

5. Results analysis and solution design

5.1 Decision matrix

In order to design the sandwich panel it is necessary to choose the best materials taking into account all performance properties important for this application such as weight, strength, stiffness, thermal insulation, acoustic insulation and also the price. Therefore, from the experimental data obtained in this work a decision matrix was developed taking into account these 6 parameters. For each parameter a classification grade was assigned based on the rule that the best performance had a classification of 5 and the worst had 0 classification. In order to analyze the performance of composites from the cost perspective, a research on the market price was carried out. The research showed that the prices are subject to market fluctuations and therefore, a range was chosen for the price of these materials. As a result, a lower and a higher bound of the material´s price was used and therefore, the final classification also had a lower and higher limit. The results of this analysis are presented in Table 6.

Property		**T1**	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**M1**
Weight		5.0	4.8	4.8	4.4	0.7	0.3	0.0	2.1
Mechanical	**Strength**	0.0	0.4	0.3	0.9	4.1	4.9	5.0	1.0
	Stiffness	0.5	0.0	0.1	0.7	2.2	5.0	5.0	1.2
Thermal Insulation		0.1	3.6	3.6	2.9	1.4	0.0	5.0	4.7
Acoustic Insulation		0.0	1.3	1.1	1.2	1.3	1.1	2.8	5.0
Price	**lower bound**	3.7	5.0	4.8	1.4	0.3	0.2	0.0	4.7
	higher bound	4.4	4.3	4.0	0.0	2.8	2.8	2.7	5.0
Final Classification	**Lower bound**	1.56	2.51	2.44	1.92	1.67	1.91	2.96	3.09
	Higher bound	1.69	2.40	2.32	1.68	2.09	2.34	3.40	3.15

Table 6 Decision matrix for composites

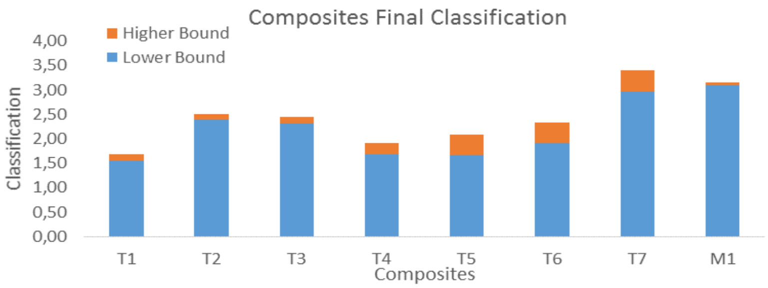

Figure 6 Classification of composites based on the analyzed parameters

In order to obtain the final classification for each composite, the 6 analyzed parameters were considered in equal weights. So the final classification was the average of the obtained classifications. Figure 6 shows the final classifications of various composite samples. The final classification showed that the best composite was T7, followed by M1, T2, T3, T6, T5, T4 and T1. The higher rating of T7 composite was mainly due to their superior mechanical properties as compared to natural composites (T1, T2, T3 and T4). However, in terms of weight, acoustic as well as thermal insulation natural fiber composites showed interesting results.

5.2 Solution design

The design of the final solution was made considering different requirements, among which the most important one was the sufficient resistance of the panel to flexural forces. The other requirements were: panel dimension of 1.00 x 2.30 m with 0.72 mm maximum thickness and a self-weight below 10 kg/m^2. Regarding the panel´s mechanical response, two types of limits states were considered: (1) Ultimate Limit state that is related to the ultimate resistance of the panel in flexural mode and (2) Service Limit State that is related to the deformation of the panel in service. For the Ultimate Limit State condition, two load conditions were considered such as Case 1: a load of 1kN/m^2 distributed along the span and Case 2: a load of 1kN concentrated at the midspan. The Service Limit State was based on a maximum mid-span deformation divided by 250 at a distributed load of 0.40 kN/m^2. Taking care of the above requirements, the solution was designed based on theoretical and finite element models. In order to fulfill the deflection limitations with a self-weight under 10 kg/m^2, glass fibre composites were used in the final panel design. However, it was also necessary to take into account the environmental sustainability of the solution, and in this sense, glass fibre composites are highly disadvantageous as compared to natural fiber composites. Based on the above fact, the designed solution used just the minimum quantity of glass fiber composite necessary to satisfy the Ultimate and Service Limit States. In order to avoid the application of high pollution paintings, gel-coats and other type of finishes, a layer of natural composite was used in the external side of the designed sandwich composites. This natural composite layer can also contribute to thermal and acoustic insulation, besides reducing the ecological impact of the solution. The designed solution is presented in the Figure 7. The material used in the core was extruded polyurethane (XPS) with a density of 40 kg/m^3. The sheath panel was composed of a hybrid laminate consisting of 4 plies of T9 composite and 1 layer of T2 composite. These laminated composites were glued to the core using a 350 g/m^2 epoxy based adhesive.

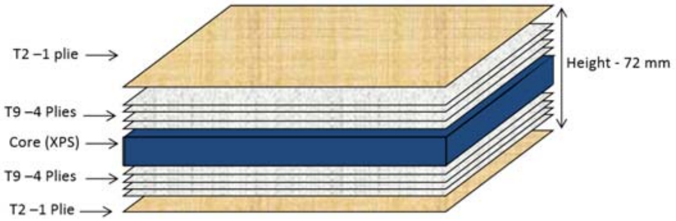

Figure 7 Schematic diagram of the developed sandwiched panel

The panel was characterized in flexural mode, in plane-compression and in out-of-plane compression. Thermal and acoustic insulation behaviors were also characterized. The obtained results are listed in Table 7.

Property	Standard Method	Units	Value
Out-of-Plane compression	ASTM C365	$\sigma_{máx}$ (kPa)	373
		$\sigma_{5\%\ def.}$ (Kpa)	300
In-Plane compression	ASTM C364	$\sigma_{máx}$ (KPa)	3579
		E (MPa)	323
Deflection in service	ASTM C393	(mm)	8,24 < 9
Moment resistance		(KN.m)	2.58
Noise reduction	ASTM E413	R_w (dB)	9
Thermal transmission coefficient	n.a.	U_i (m^{2o} K/W)	0.47

Table 7 Mechanical, thermal and acoustic insulation properties of the hybrid composite panel

6. Conclusions

In this study, an effort was made to incorporate natural fibers in a sandwich panel instead of using 100% glass fiber composite for modular construction applications, as natural fiber composites show good thermal and acoustic insulation properties combined with low-weight. However, in order to ensure sufficient flexural performance of the panel within the imposed limits of thickness, weight and resistance, it was necessary to incorporate glass fiber composites in the sheath of the designed sandwiched panel. Therefore, the designed solution incorporated natural fiber composites in order to avoid pollutant surface finishes such as paintings, gel-coats and others as well as to improve the thermal and acoustic insulation behaviors. As a result, a hybrid sandwich composite panel was successfully developed in order to have targeted flexural performance as well as good thermal and acoustic insulation behaviors.

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