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Thermal Behaviour of Hybrid Composites Reinforced with Natural Fibers and Kevlar

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Abstract*: *There is a wide scope to develop suitable hybrid combination for making Fiber Reinforced Polymer (FRP) to utilize the properties of both natural and synthetic fibers. Economic and environmental reasons justify the use of natural fiber in place of synthetic fiber composite. Thermal stability is one of the important properties for the FRP panel in the applications such as structural panels/roof panels, cold storage and air conditioned ducts of building. The aim of this paper is to investigate thermal properties of hybrid FRP made of Jute, Flax, Sisal and Hemp in combination with kevlar-29. Composite wall conductivity measurement, DSC/TGA technique are used to study thermal conductivity, thermal stability, change in specific heat capacity, thermal degradation. All the panels showed lower thermal conductivity of less than 1 W/m ^{0}C; however the flax and hemp panels had lowest thermal conductivity of around 0.45 W/m^{0}C. DSC thermographs indicated broad exotherm and major changes in specific heat capacity at 200 ^{0}C for all panels. In addition, TGA technique showed main weight loss around 30%-51% of panels around 210 ^{0}C. Thus the thermal properties of all panels were stable till 200 ^{0}C. Thermogravimetric analysis of F- FRP shows thermal stability at lower range of temperature while in H- FRP thermal degradation occurs in two steps around 260 ^{0}C and 410 ^{0}C with the wt. loss of 53.72% and 26.79% respectively.

Index Terms*: *Hybrid composite, Natural fibers, Thermal conductivity, specific heat capacity, DSC, TGA

I. INTRODUCTION

Natural fiber from plant source to fabricate hybrid Fiber Reinforced Polymer (FRP) composite has significant potential over synthetic fiber FRP. Aerospace, automobile, marine industry, roof panels and air-conditioned duct in buildings need mechanical strength as well as thermal stability in their applications [1]. The suitable configuration of various natural and synthetic fibers to create hybrid FRP composite have many advantages such as light weight, low cost, specific strength, better thermal stability and biodegradable nature as compare to synthetic FRP composites[1]. FRP are frequently reinforced with different types of fibers to improve basic mechanical and thermal properties through various manufacturing methods. And therefore, it is important to study the thermal conductivity, specific heat, transition phase, thermal stability and thermal degradation of any hybrid composite. Researchers are still working on thermosetting hybrid composite to attain unique mechanical and thermal properties which will be less costly and ecofriendly [2]. Thermal conductivity of polymers is lower which means they are good heat insulators for architectural applications.

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Chemical treatment on natural fibers was necessary in fabrication of FRP composite. The purpose of chemical treatment on natural fibers is to improve the desired mechanical and thermal properties of FRP by the enhancement of interfacial bonding between fiber and matrix. Thermal property of jute fiber reinforced epoxy composite was studied and found higher due to stronger adhesion with the glass transition between 64 ^{0}C to 70 ^{0}C by using Differential Scanning Calorimeter (DSC) and Thermo Gravimetric Analysis (TGA) by M K Gupta et al. [3]. Increase of temperature from 20 ^{0}C to 150 ^{0}C causes increase of specific heat capacity from 1.083 J/g ^{0}C to 3.317 J/g ^{0}C was observed by L. Mohammed et al. [4] after chemical treatment on natural fiber composite of hemp and flax due to improvement in surface and thermal properties. Composite made of bamboo fiber and epoxy shown good thermal stability for engineering applications upto 374 ^{0}C [5].

M. Teja et al. [6] investigated the thermal properties of Sisal fiber reinforced composite and studied effect on thermal conductivity and specific heat capacity with addition of Sic filler. The thermal degradation temperature shifted to higher range upto 230 ^{0}C – 307 ^{0}C in four layered stacked jute epoxy composite was observed by G. Raghavendra et al. [2]. The emu feather based epoxy composite showed improvement in thermal stability at higher temperature ranges under nitrogen at 10 ^{0}C from 50 ^{0}C to 600 ^{0}C [7]. The work done by M. Narendra et al. [8] on borassus seed composite shown improvement in thermal conductivity in the range of 0.176 to 0.196. TGA analysis carried out on kenaf fiber/epoxy FRP by Z. N. Azwa et al. [9] showed more thermal stability with glass fibers from room temperature to 600 ^{0}C. The glass transition temperature (T_g) of hybrid composite made by coconut coir and bagasse showed increase upto 190 ^{0}C as compared to plain epoxy composite and put forward to use in applications like wall ceiling and packaging industry. The initial degradation was observed at 150 ^{0}C [10].

The thermal stability in eucalyptus fiber composites was recorded using TGA analysis by M. VF. Ferreira et al. [11] upto 300 ^{0}C for practical applications. The influence of thermal degradation on mechanical properties of flax fiber composite was studied by Gassan and Bledzki [12]. The thermal conductivity, specific heat and diffusivity reduced with increase in the flax fiber content upto 170 ^{0}C[4]. The detailed review article on thermo gravimetric stability analysis of various natural fiber FRP showed that very less work was done in thermal behavior investigation in spite of large potential in all types of industrial applications [13].

In this paper, four different types of FRP panels made of Jute, Flax, Sisal and Hemp with kevlar as outer facesheet, were studied for thermal behavior to find suitability in structural applications.

II. EXPERIMENTAL DETAILS

A. Materials and Fabrication

Hybrid composite were fabricated by reinforcing the kevlar-29 fibers in combination with natural fibers. Natural fibers like jute, flax, sisal and hemp were used to get four varieties and represented as J-FRP, F-FRP, S-FRP and H-FRP. In all the panels, outer facesheet were made of kevlar fabric. The chemical treatment on natural fibers was carried out with the help of 0.1% concentrated NaOH alkaline solution before reinforcement in composite. The configuration was as follows:

i) Kevlar/Jute/ Jute / Jute /Jute/ Kevlar – J-FRP
ii) Kevlar /Flax/ Flax / Flax /Flax/ Kevlar – F-FRP
iii) Kevlar /Sisal/ Sisal / Sisal /Sisal/ Kevlar – S-FRP
iv) Kevlar /Hemp/ Hemp / Hemp /Hemp/ Kevlar – H-FRP

Vacuum bagging technique was used for fabrication of panels. The volume fraction of fibers in FRP composite was around 0.37 and thickness of all panels was around 4 mm.

B. Thermal Conductivity Test

Thermal conductivity is the heat conduction property which is nothing but the extent of heat transmitted through a unit thickness in the direction normal to unit surface area due to unit temperature rise under steady state condition. Thermal conductivity (k) of all specimens of hybrid FRP composite were determined using composite wall apparatus as per ASTM E1530 standard [8] as shown in the figure 1(a).The aluminium plate heat source was placed close to FRP specimens with four k-type thermocouples placed centrally to measure the temperatures of the specimens. Heat source was connected to electrical supply as an energy input with varying current and voltage. Specimens were tested to find out the thermal conductivity (W/m^{0}C) by varying heat flux, q (W/m^2). Two FRP samples were placed between upper and lower support plates with heat source at the center to ensure heat flow in upward and downward direction through specimens. The arrangement of specimens and thermocouples is shown in Figure 1(b). For each reading of heat flux, temperatures were measured and average values were recorded.

The heat flux (q) was calculated using heat supplied per unit area using (1).

$$Q = 0.8VI \qquad (1)$$

Where Q- heat supplied, W
V- Voltage (Volt) and I- current (Amp)

Size of circular specimen was 150 mm and average temperature were calculated by taking mean of T_1, T_2 and T_3 T_4 temperatures respectively. The thermal conductivity (k) of a specimen is defined as heat transfer per unit distance per unit temperature difference which can be mathematically written as in (2).

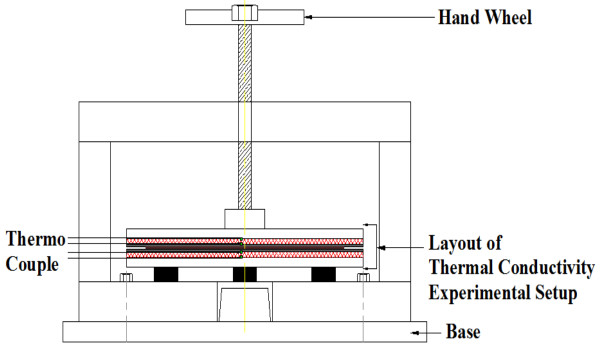

Fig. 1(a): Schematic layout of set up.

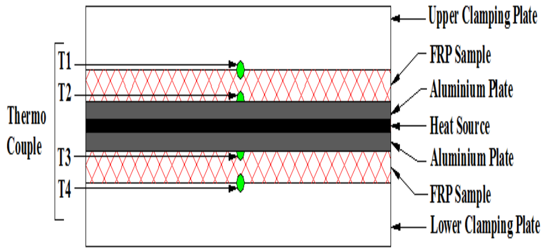

Fig. 1(b): Arrangement of specimen and thermocouples.

$$k = q \times dx / (T_A - T_B) \qquad (2)$$

Where q- heat flux (W/m^2);
dx- specimen thickness (m);
T_A and T_B - Average temperature values represented as
$T_A = T_2 + T_3 / 2$ And $T_B = T_1 + T_4 / 2$ (^{0}C)

Numerical Simulation

Steady state thermal analysis of the hybrid composite panels was carried out by using ‘ANSYS Workbench’. The effective thermal conductivity of the panels was determined through numerical simulation. The layered model was created as shown in Figure 2. The material was assigned to the individual layer of panel. The thermal conductivity of each layer was supplied to material model. The bonded contact afterwards was defined between the adjacent layers. Each layer of panel was meshed by solid brick element.

The edge length of the element was 10 mm; and single element was taken along the thickness of each layer as shown in Figure 3.

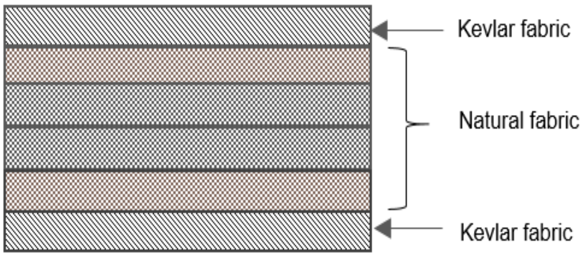

Fig. 2: Layer stack of hybrid FRP panel.

The heat flux was applied to the bottom surface of the panel. Also conductive losses were considered by supplying the film coefficient. The maximum temperature difference was determined through simulation. Furthermore, the effective thermal conductivity of composite panel was calculated by using (2).

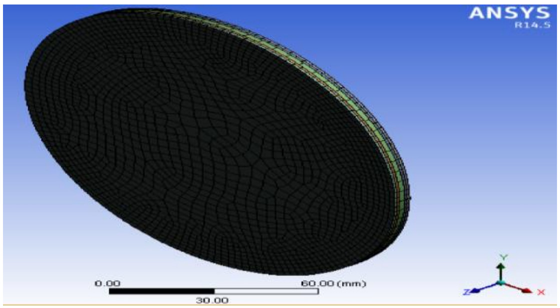

Fig. 3: Mesh FRP panel

C. Differential Scanning Calorimeter (DSC)

DSC is a thermo analytical technique used to measured thermal properties like glass transition (Tg), thermal stability and change in specific heat capacity (ΔCp). The analysis is carried out using DSC 821- METTLER TOTEDO instrument in the temperature range of room temperature to 400 ^{0}C at scanning rate of 10 ^{0}C /min. under nitrogen atmosphere with closed lid aluminium pan. Nitrogen atmosphere is selected for better heat transfer and removal of volatiles from sample. A plot is drawn between heat flow (mW) and temperature (^{0}C) with time (min.) using Star SW 9.01 evaluation software.

D. Thermo-Gravimetric Analysis (TGA)

TGA is a method in which thermal degradation of materials is measured as a function of increments in temperature with constant heating rate. These are evaluated using TGA/SDTA 851- METTER TOLDO instrument. The experiment was carried out in the temperature range from room temperature to 800 ^{0}C at a scanning rate of 10 ^{0}C under nitrogen atmosphere to avoid oxidization. In TGA run, a plot of weight of sample Vs temperature (^{0}C) and time (min.) using Star SW 9.01 evaluation software was determined to find % weight loss over a given period of time.

III. RESULTS AND DISCUSSION

A. Thermal Conductivity

The four readings were taken for each FRP specimen by varying heat flux and average values of thermal conductivity were estimated as shown in the Table 1. The comparison of thermal conductivity and heat flux of J-FRP, F-FRP, S-FRP and H-FRP are as shown in Table 1 and Figure 4.

Table 1: Average thermal conductivity of FRP panels

Specimen	q (W/m^2)	K (W/m^{0}c)
J - FRP	1232.18	0.454
	2022.04	0.474
	3633.35	0.534
	5307.86	0.576
F - FRP	1137.39	0.427
	2148.42	0.471
	3633.35	0.539
	5307.86	0.579
S – FRP	1137.39	0.481
	2198.97	0.510
	3633.38	0.564
	5304.86	0.622
H - FRP	1232.18	0.379
	2148.42	0.424
	3633.38	0.498
	5304.86	0.595

By using ANSYS workbench, the thermal conductivity of all the FRP panels are determined. The values are compared with experimental results and found maximum 5% of variation which validates the results. The numerical results of H-FRP are shown with dashed line in Figure 4. The F-FRP and H-FRP composite showed the lower thermal conductivity of 0.427 and 0.379 W/m^{0}C at 1232.18 W/m^2 respectively. The thermal conductivity of H-FRP increased linearly with the increase in heat flux while thermal conductivity of F-FRP found linear upto 3633.35 W/m^2 heat flux and increased slowly towards the higher heat flux. The J-FRP and S-FRP showed higher thermal conductivity of 0.454 W/m^{0}C and 0.481 W/m^{0}C respectively at 1137.39 W/m^2. S-FRP sample showed linear variation with higher thermal conductivity as compare to all FRP samples with the variation in heat flux.

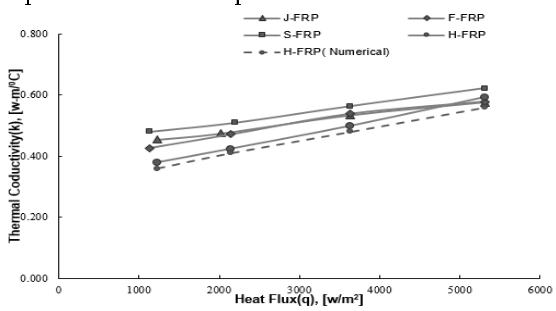

Fig. 4: Thermal conductivity Vs heat flux for various FRP Composite.

The highest thermal conductivity 0.622 W/m^{0}C was observed in S-FRP. While thermal conductivity of J-FRP increased upto 3633.35W/m^2 heat flux and was almost constant towards higher heat flux. The thermal conductivity of F-FRP and H-FRP specimen was found lower at lower values of heat flux as compared to J-FRP and S-FRP. J-FRP and F-FRP exhibited almost same thermal conductivity at higher heat flux as compared to H-FRP which showed promising lower thermal conductivity. This showed suitability of F-FRP and H-FRP with lower thermal conductivity for structural elements applications such as roof panels, doors, furniture, duct insulation etc. as compared to S-FRP and J-FRP specimens having higher thermal conductivity [6]. Lower thermal conductivity indicate higher resistance to heat conduction through the material. Lower the thermal conductivity, superior will be the thermal insulation property. In other research papers, many authors reported that FRP made of natural fibers can be used as a viable alternative material instead of FRP made of synthetic fibers [2], [8], [12].

B. Differential Scanning Calorimeter Thermograph

The samples of J-FRP, F-FRP, S-FRP and H-FRP were analysed in detail using DSC. J- FRP showed thermal stability from room temperature to 210 ^{0}C and melting occurred at 380 ^{0}C. The sample displayed less purity in composition from change in temperature values as shown in Figure 5. F-FRP is thermally stable upto 220 ^{0}C with a strong exotherm which does not recover to base line from 220 ^{0}C – 330 ^{0}C. The exotherm was broad but the energy associated seemed very small as indicated by the plot and also the observed ΔT values.

Sisal FRP displayed thermal stability upto 200 ^{0}C with initial endotherm lie between 90 ^{0}C -105 ^{0}C and exotherm around 220 ^{0}C with the area lesser than F-FRP, while H-FRP showed thermal stability upto 200 ^{0}C with melting point at around 400 ^{0}C. Above thermographs from DSC for F-FRP and H-FRP showed slightly higher thermal stability as compared to J-FRP and S-FRP as shown in Figure 5 and 6.

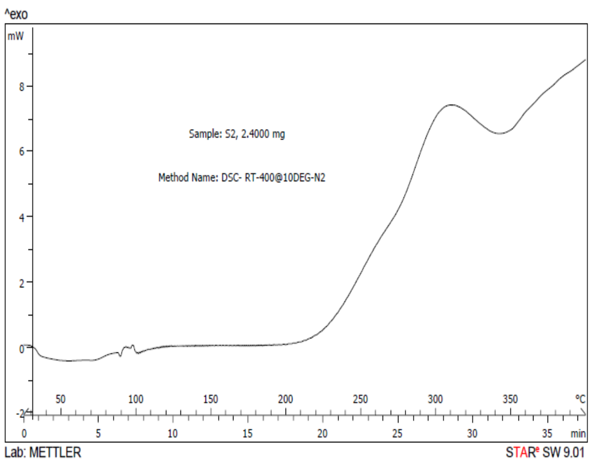

Fig. 5: DSC plot for J-FRP composite.

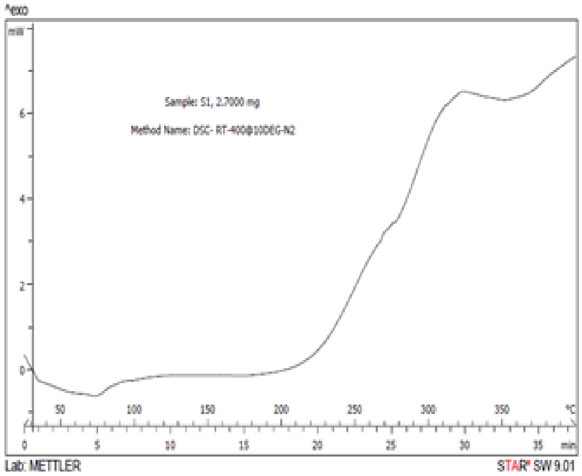

Fig. 6: DSC plot for F-FRP composite.

The melting point recorded for J-FRP, F-FRP, S-FRP and H-FRP are 370 ^{0}C, 400 ^{0}C, 350 ^{0}C and 410 ^{0}C respectively. There was no significant change observed in glass transition temperature ranges for all varieties of FRP composite. The exothermic non-sharp peaks in all FRPs plots were commonly observed, as composite fall under the category of semi crystalline material. The change in the specific heat capacity (ΔCp) can be determined (ASTM E1269) from the shift in the baseline of the thermograph. According to definition of specific heat capacity, we have [14]:

$$C_P = (dH / dT)_P \quad (3)$$

Where dH and dT are change in enthalpy and change in temperature under constant pressure.
By rearranging (3).

$$\Delta C_P = \Delta dH / dt \times dt / dT \quad (4)$$

Where, dH / dt is heat supplied per unit time and dt / dT is scanning rate. Equation (4) can be written for unit mass as:

$$\Delta C_P = \Delta dH / dt \times dt / dT \times (1/m) \quad (5)$$

Where, m is the mass of the sample. The unit of heat flow was mJ/s and min/s was expressed as inverse of scanning rate. The change in specific heat capacity (J/Kg^{0}C) was calculated using (5). The five reading were taken for each type of FRP and average values of change in specific heat capacity are shown in Table 2 and represented in Figure 7.

Table 2: Average Change in Specific heat capacity

Specimen	Avg. change in specific heat capacity(ΔCp), J/Kg^{0}C
J-FRP	1.2
F-FRP	0.21
S-FRP	2
H-FRP	0.77

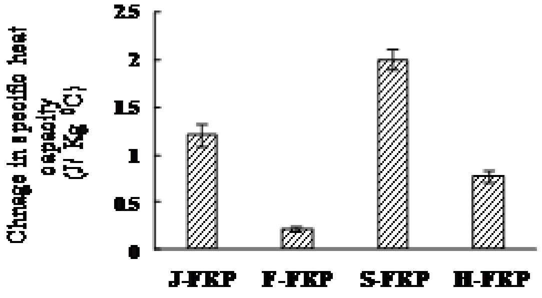

Fig. 7: Change in Specific heat capacity for various FRP Composite.

C. Thermo-Gravimetric Analysis (TGA)

The FRP samples were then tested for thermal degradation on TGA under ASTM E1131 standard. J-FRP composite sample showed no thermal stability over observed range of temperature. The weight loss occurred in 2 steps, one at 180 ^{0}C with 30.06% wt. loss may be from jute and second at 210 ^{0}C with wt. loss of 69.93% as shown in Figure 8.

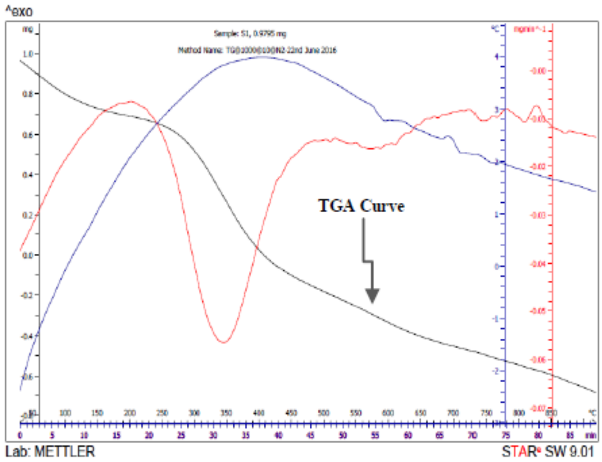

Fig. 8: TGA for J-FRP composite.

The maximum wt. loss was observed at 340 ^{0}C representing the volatile nature. F-FRP sample showed better stability at lower range of temperature with one stage thermal degradation at temperature of 40 ^{0}C. TG was carried out on S-FRP sample from room temperature to 800 ^{0}C. The total weight loss was 84.25% in three steps, showing safely useful till 270 ^{0}C. The decomposition rate slower down from 400 ^{0}C.

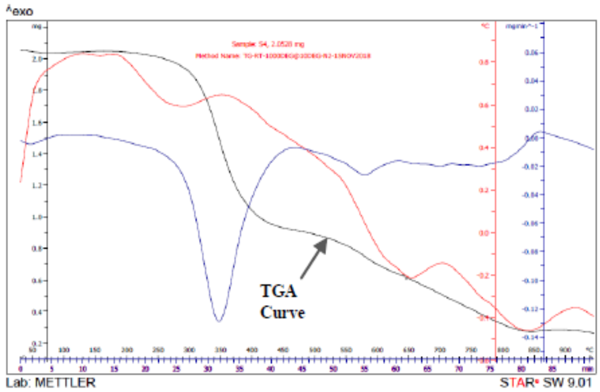

Fig. 9: TGA for H-FRP composite.

TG observed for H-FRP sample showed thermal degradation in 2 steps around 260 ^{0}C with 53.72% wt. loss and at 410 ^{0}C with 26.79% wt. loss. The total % wt. loss observed was around 80.51%. The TGA plots for H-FRP were around 80.51%. The TGA plot for H-FRP was shown in Figure 9.

IV. CONCLUSION

1. Four varieties of FRP panels: J-FRP, F-FRP, S-FRP and H-FRP were fabricated using vacuum bagging technique with volume fraction of composite around 0.37. The thermal analysis was carried out for FRP panels using composite wall measurement, DSC/TGA methods. Also the panels were numerically simulated using ANSYS workbench.
2. All the FRP panels showed lower thermal conductivity of less than 1 W/m^{0}C; however, F-FRP and H-FRP exhibited lowest thermal conductivity of 0.427 W/m^{0}C and 0.379 W/m^{0}C at 1232.18 W/m^{2} respectively. Lower the thermal conductivity superior will be the thermal insulation property.
3. DSC thermographs indicated major exotherm and large change in specific heat capacity above 200 ^{0}C, thus these panels were stable till 200 ^{0}C. Higher thermal stability for F-FRP and H-FRP was found.
4. The change in specific heat capacity for all above samples was found in the range of 0.21- 0.8 J/Kg^{0}C.
5. Themogravimetric analysis indicated major weight loss of 30% - 51% for all FRP panels at 200 ^{0}C, indicating their thermal stability upto 200 ^{0}C.

It was witnessed that combination of Kevlar-29 fabric with natural fiber provide better thermal stability to FRP panels. In addition, better thermal results were found when kevlar was used in combination with either hemp or flax fibers. The panels could be investigated further for the flexural, impact, damping and acoustic properties.

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