Polish Society of Composite Materials
Polskie Towarzystwo Materiałów Kompozytowych

22: 1 (2022) 44-49

COMPOSITES THEORY AND PRACTICE
ISSN: 2084-6096
ISSN (online): 2299-128X

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Received (Otrzymano) 2.12.2021

DESIGN STUDY OF NATURAL FIBER REINFORCED HONEYCOMB PANEL FOR LIGHTWEIGHT AND PORTABLE SHELTER MATERIALS FOR TYPICAL MALAYSIAN CLIMATE

An evacuation shelter provides simple living facilities made of lightweight materials for repeated use and ensures that the shelters provide a safe and suitable long-term environment. Improving the shelter material in terms of thermal quality in the Malaysian climate is one requirement when evacuating victims to emergency shelters in open areas. The article aims to investigate the effect of using local natural fibers for composite honeycomb skin on the thermal and mechanical performance. The composite skin is a natural fiber processed in a concrete panel to make a honeycomb sandwich. This work introduces a model of natural fiber distribution embedded in a concrete panel, which is subjected to thermal analysis and three-point bending (TPB) to optimize the honeycomb structure. In order to understand the thermal interaction of the panel sheet for an insulating system, the model provides a six-level range of the number of fibers (100, 200, 300, 400, 500 and 600) to analyze the fiber network. The simulation demonstrated that improvement in the insulating panel of about 2.58% could be achieved by using the number of 600 coconut fibers, which is much lower compared to plain concrete. The morphology study successfully demonstrates the understanding of the fiber distribution and thermal absorption by the concrete. Moreover, the mechanical performance is also positively affected by using fiber in the panel, especially sugar cane, which achieved a 47% improvement. This successfully simulated model provides a promising solution to promote local products for shelter material applications.

Keywords: **fiber distribution, thermal conductivity, insulating, finite element analysis, honeycomb sandwich**

INTRODUCTION

Floods frequently occur in the yearly cycle as a natural disaster, directly impacting society and the environment. Floods have increased in recent years as climate changes continue to impact the world. On 2nd January 2021, Malaysia reported five flood-affected states, including Johor, Pahang, Kelantan, Selangor, and Perak, in the Malaysian Peninsula. The National Disaster Management Administration (NADMA) recorded that 23,776 people were affected and evacuated to 303 shelters [1]. Previous research stated that enforcing the evacuation of a certain percentage of the population may cause heat extremes as a result of overcrowding in small spaces [2]. An evacuation shelter provides simple living facilities made of lightweight materials for repeated use and ensures that the shelters provide a safe and suitable long-term environment. A further study found that the thermal conditions in shelters can be uncomfortable as the internal temperatures reach 39 and 46°C as detected by internal surface temperatures [3]. Unfortunately, this temperature causes increased morbidity and mortality during long time exposure [4]. Therefore, it was suggested to propose a shelter that provides comfortable thermal conditions for people during prolonged use.

Regarding the Malaysian climate, the challenges of simple shelters depend on the changing climate, including extensive exposure to rain and sun. A previous report showed that high temperatures leading to heatstroke excessively affected the mortality rate [5]. Moreover, the findings of engineering studies on thermal issues point to a number of ways to improve shelter performance. Re-designing of the shelter using architecture knowledge to improve air circulation and performance is required [6-7]. Architectural improvement has been proposed for refugee shelter design in the extreme climates of Jordan, Afghanistan and South Sudan [7]. The study was conducted using thermal performance determiners of each shelter type under the stated climate locations. Another method that can be employed is to improve the lightweight material that provides insulation for repeated use over long periods [8]. Here, local materials are promising and have a high potential for a low environmental impact and costs. Therefore, the authors proposed a combination of some local materials such as bamboo, wood, concrete, and steel to construct the shelter.

Although materials and local construction systems can promise the best compromise between environmental impacts and cost, their structural design requires more effort. The aim of this paper is to examine the potential of such an approach. It aims to examine the use of locally based materials by performing simulations. The study investigates the effect of using a composite containing local natural fibers as honeycomb skin to predict the thermal and mechanical performance. In this work, an efficient fiber distribution model embedded in the concrete panel sheet is proposed, while thermal analysis and the three-point flexural test were conducted to optimize the honeycomb structure.

METHODS

In the simulation, the honeycomb structure was designed to construct a sandwich with three parts. The honeycomb sandwich was constructed with a panel sheet as the skin (top and bottom), honeycomb as the core, and fibers to reinforce the panel. The paramount part contributing to this research concerns the fiber development model. The simulation was processed in MATLAB then exported to Ansys Workbench for further analysis, namely thermal and mechanical testing. The details of the process are explained below.

Geometry

The honeycomb sandwich design was subject to three-point bending (TPB), which satisfies the ASTM C-393 standard [9]. The dimensions of the panel sheet were 76 mm × 221 mm × 3 mm followed by the honeycomb core, which was 76 mm × 221 mm × 20 mm as shown in Figure 1. This TPB size followed the procedure of the C-393 standard, which represents the condition of the ratio of width/total thickness ≥ 2, length/width ≥ (1.5+50 mm) and t_{panel}/t_{core} ratio < 0.1. Thus, the bending impactor represented by a semi-cylinder shape is located at the center of the specimen. At the same time, two other semi-cylinders supported the end of the sample to accommodate the bending process. The thermal conductivity was investigated on a panel sheet size of 76 mm × 221 mm × 3 mm with varied fiber reinforcement contents. Before varying the fiber loading embedded in the panel sheet, the validation analysis was studied. Due to the initial bending absorber being on the top of the sandwich, the panel sheet on the topside was chosen to embed various fiber loadings. This study focused on predicting the early effect of natural fibers subjected to thermal analysis and mechanical performance.

Fiber generation

The developed fiber size was 0.1 mm in diameter, while the adopted length was the position of the fiber in the panel sheet along the longitudinal direction. The principle of fiber development was formed by two points passing the line from the starting point to the endpoint. The random points were launched through the thickness of both plate sides at the longitudinal ends where these points were then positioned as benchmarks to pass the line. The details of the fiber development are described in the flowchart shown in Figure 2. The simplified steps are the following:

1. Recognize the domain size
2. Launch the points
3. Avoid similar selected points
4. Create the line through the points
5. Export the fibers into Ansys

Six different quantities of fiber reinforcement content were evaluated: 100 (1.4 vol.%), 200 (2.8 vol.%), 300 (4.2 vol.%), 400 (5.6 vol.%), 500 (7 vol.%), and 600 (8.4 vol.%) number of fibers.

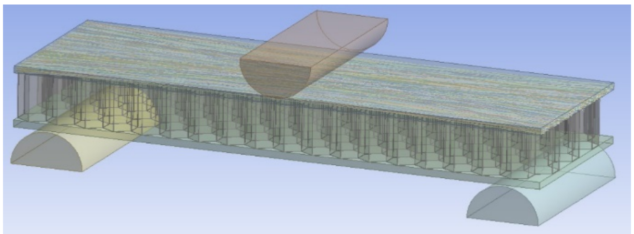

Fig. 1. Three-point bending sample

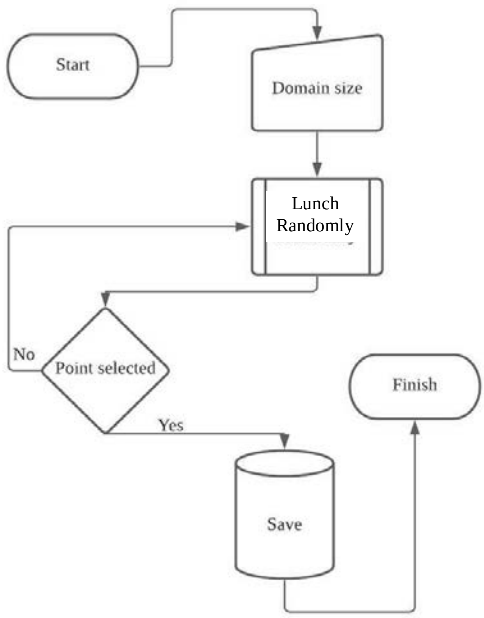

Fig. 2. Flow chart of fiber development using MATLAB software for unidirectional fibers

Simulation on ANSYS Workbench

The fibers were imported to Ansys Workbench during geometry construction. The coordinate points were embedded in the top of the panel sheet, while further steps were required for reinforcement parts and others were solid objects. In order to study the effect of thermal performance, the simulation method for thermal conductivity was obtained from previous research [10, 11], as given below:

$$k = \frac{Q \cdot l}{A \cdot \Delta T}, \quad (1)$$

where Q denotes thermal energy in [W], l is the length of the sample in meter, A is the area and ΔT is the temperature difference. The boundary conditions were 100 and 22°C without any resistance on the surface. To calculate the TPB failure, the core shear stress of a single-point midspan load was calculated as follows [9]:

$$\boldsymbol{\tau} = \frac{\boldsymbol{P}}{(\boldsymbol{d}+\boldsymbol{c})\boldsymbol{b}} \quad (2)$$

Parameter τ denotes the core shear stress [MPa], P is the load [N], while d, c, and b are the sandwich thickness, core thickness, and width of the sandwich, respectively. Eq. (2) also determines the ultimate shear strength with P as the maximum load. The shear yield strength determined by P equals the yield load of the core materials, which yields more than 2% strain using the 2% offset method for the yield strength. Then, the facing bending stress (midspan load) was determined as follows [9]:

$$\boldsymbol{\sigma} = \frac{\boldsymbol{PL}}{\boldsymbol{2t}(\boldsymbol{d}+\boldsymbol{c})\boldsymbol{b}}. \quad (3)$$

Testing of the honeycomb was conducted under axial loads since the face sheet wrinkled due to skin buckling with a wavelength greater than the honeycomb cell width [9]. Therefore, the critical stress that occurs on the wrinkling face sheet can be calculated based on Eq. (4):

$$\sigma_w = \sqrt{\frac{2t_f E_c \sqrt{E_{fx} E_{fy}}}{3t_c \sqrt{1 - v_{xy} v_{yx}}}}. \quad (4)$$

Parameter Ec denotes the core modulus, E_{fx} stands for the face sheet modulus in the axial direction, E_{fy} is the face sheet modulus in the transverse direction, while v_{xy} and v_{yx} are the face sheet Poisson's ratios.

Equation (5) shows the core failure predicted using shear failure:

$$S \le \frac{2\sigma_{fmax} t}{kF_s}. \quad (5)$$

Here, S is the distance support span, σ_{fmax} is the estimated facing sheet ultimate strength, k is the core shear strength factor to ensure face sheet failure (0.75 is recommended by the previous researcher [12]), and F_s is the core shear strength.

This research also concerns a grid independence study. It was carried out on plain concrete to determine the suitable element numbers for thermal analysis, similar to previous studies [10, 11]. Hexahedron meshing was chosen to represent both the thermal and TPB analysis.

Validation

Concrete samples 50 mm × 50 mm × 50 mm were used for thermal validation, and 0.836 W/m·C was the thermal conductivity, while the temperature boundaries were 200 and 22°C. The Ansys Workbench recorded the results of Q = 7.4404 W in stable conditions, implying that the maximum energy which may penetrate the wall and the wall conductivity, k, were calculated as follows:

$$k = \frac{\mathrm{Q \cdot l}}{\mathrm{A \cdot \Delta T}} = \frac{7.4404\mathrm{W} \cdot 0.05\mathrm{m}}{(0.05\mathrm{m} \cdot 0.05\mathrm{m})(200^\circ\mathrm{C} - 22^\circ\mathrm{C})} = 0.836\,\mathrm{W/m \cdot C}$$

The comparison between the numerical and experimental methods shows almost no difference and thus is suitable for further analysis by adding reinforcement fibers.

In the mechanical performance validation, the concrete sample was 100 mm × 100 mm × 500 mm in size, whose flexural strength was 6.75 MPa. The numerical and experimental results were 6.80 and 6.75 MPa, respectively. There is a 0.7936% difference in the standard flexural strength equation or a 4.1595% error calculated using $f_C^{0.5}$. The flexural strength proposed by $f_C^{0.5}$ should be around 7 MPa [13].

Material properties

The mechanical and thermal properties of steel, cement and aluminum panel sheets are summarized in Table 1, while the natural fiber is presented in Table 2.

TABLE 1. **Material properties of steel, cement and aluminum panel sheets**

Properties	Aluminum	Steel	Cement
Density [kg/m³]	2770	7850	2520
Young's modulus [GPa]	71	200	41000
Poisson's ratio	0.33	0.3	0.21
Ultimate strength [MPa]	310	420	2520
Thermal conductivity [W/m·C]	237.5	50.2	0.836

TABLE 2. **Material properties of natural fibers [14]**

Properties	Palm	Sugar cane	Coconut
Density [kg/m³]	1.55	1.2	1.2
Young's modulus [GPa]	2.7-3.2	18-27	4-6
Tensile strength [MPa]	227.5-278.4	20-290	105-175
Thermal conductivity [W/m·C]	0.057	0.05314	0.05

RESULTS AND DISCUSSION

The concrete panel sheet composite simulation showed different thermal conductivity performances with varied fiber reinforcement loading in Figure 3. Then the graph was plotted with the number of fibers against the thermal conductivity of the concrete panel sheet, revealinga decreasing trend. This observation also analyzes the variation in the characteristics of the natural fibers, in which coconut fibers were slightly lower than other fibers regarding thermal conductivity. This was in good agreement for shelter applications compared to the thermal conductivity of plain concrete. Here, the thermal insulation improved by approximately 2.5, 2.11, and 2.58% for palm, sugar cane, and coconut, respectively. This prediction was useful in proving that natural fibers are better thermal insulators than local products for shelter construction. Previous researchers also reported the same results, which reveal that fiber reinforcement helps the composite reduce energy waste in, e.g. the air condition system in a spacecraft [11].

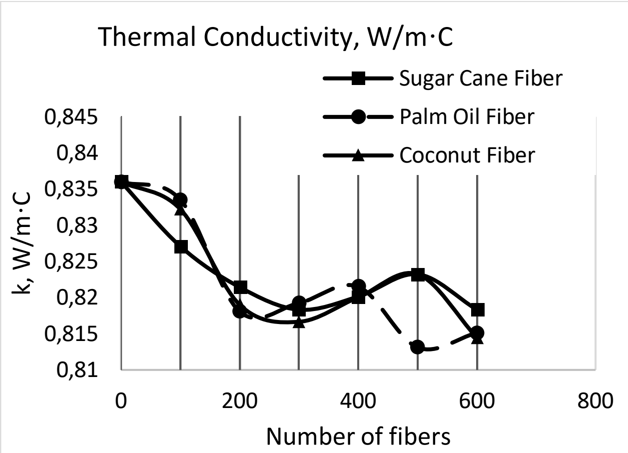

Fig. 3. Thermal conductivity vs number of fibers

The study further focuses on the morphology characteristics influencing thermal conductivity. This implies that the fiber reinforcement successfully blocked the heat owing to their low thermal conductivity, which was similar to previous work, due to the greater alveolar structure in the fiber distribution [15]. Figure 4 shows the distribution of temperature around the fibers that was absorbed and blocked before passing to the other side of the concrete. As the thermal resistance of the concrete sheet wasincreased, it is clear that the character of fiber distribution synergizes with the temperature absorption.

It also blocks the thermal pathway from the thermal network chain by decreasing the thermal energy passing through a specific area per unit of time.

In the TPB analysis, the simulation process was observed in the step range of 1×10^{-5} to 1.92×10^{-4}s. The early bending resistance was captured via the stress mode with varied fiber contents and natural fiber types, as presented in Figure 5. It described the normal stress in the z-axis condition, in varying fiber contents of palm, coconut and sugar cane, respectively. In this part, the stress on the honeycomb core was investigated to analyze the interaction load between the panel sheet and core. Permanent deflection of the honeycomb increased with the passage of time, during which the damage of the face sheet gradually increased, reaching the failure stage at the end of the process. It can be seen that the normal stress (z-axis) was successfully reduced by increasing the fiber content for all thenatural types. It has a positive effect on blocking normal stress while penetrating the plate sheet, reducing the stress through the honeycomb core. The fiber content consistently absorbed the stress by reducing early penetration in the range of 10-47% compared to the plain concrete, as shown in Figure 6. The fibers significantly help absorb the stress, giving an advantage in mechanical performance due to the tensile strength inthe numbers of fibers as reinforcement. In addition, the sugar cane fiber dominated in terms of stress absorption, which reached 47% at the 600 fiber content. Similar results were also reported by previous researchers, whose composite was very effective in avoiding preliminary failure, and at the same time, in increasing the mechanical properties of the sandwich structure [16]. Furthermore, buckling waveforms were not found in the panel sheet due to the brittle material characteristics revealed during bending. Finally, the panel sheet results showed that local crushing in the middle of the sample induces debonding between the panel sheet and the core. The absence of buckling waveforms in the top sheet illustrates that the fibers greatly help to bond the panel and the core.

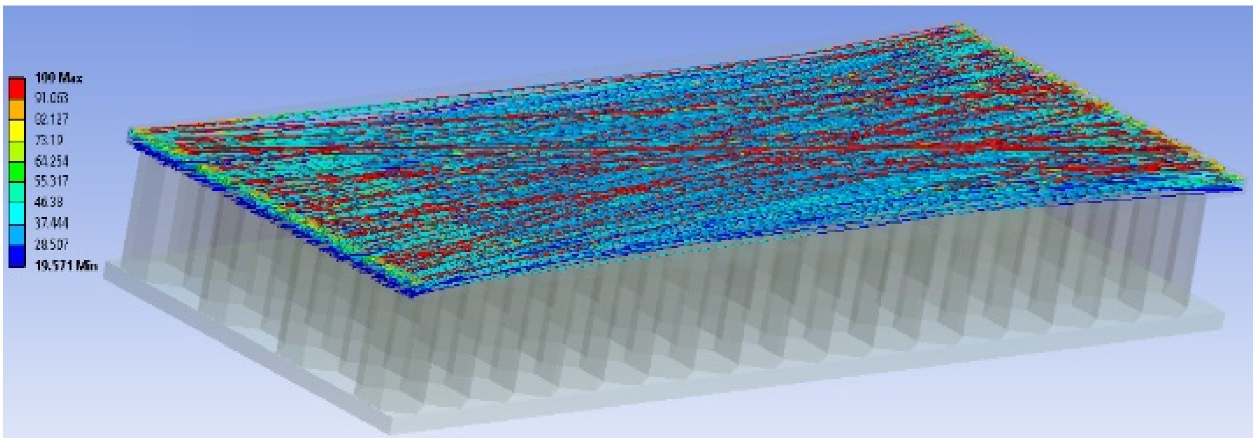

Fig. 4. Temperature distribution on 100 number of fibers of sugar cane

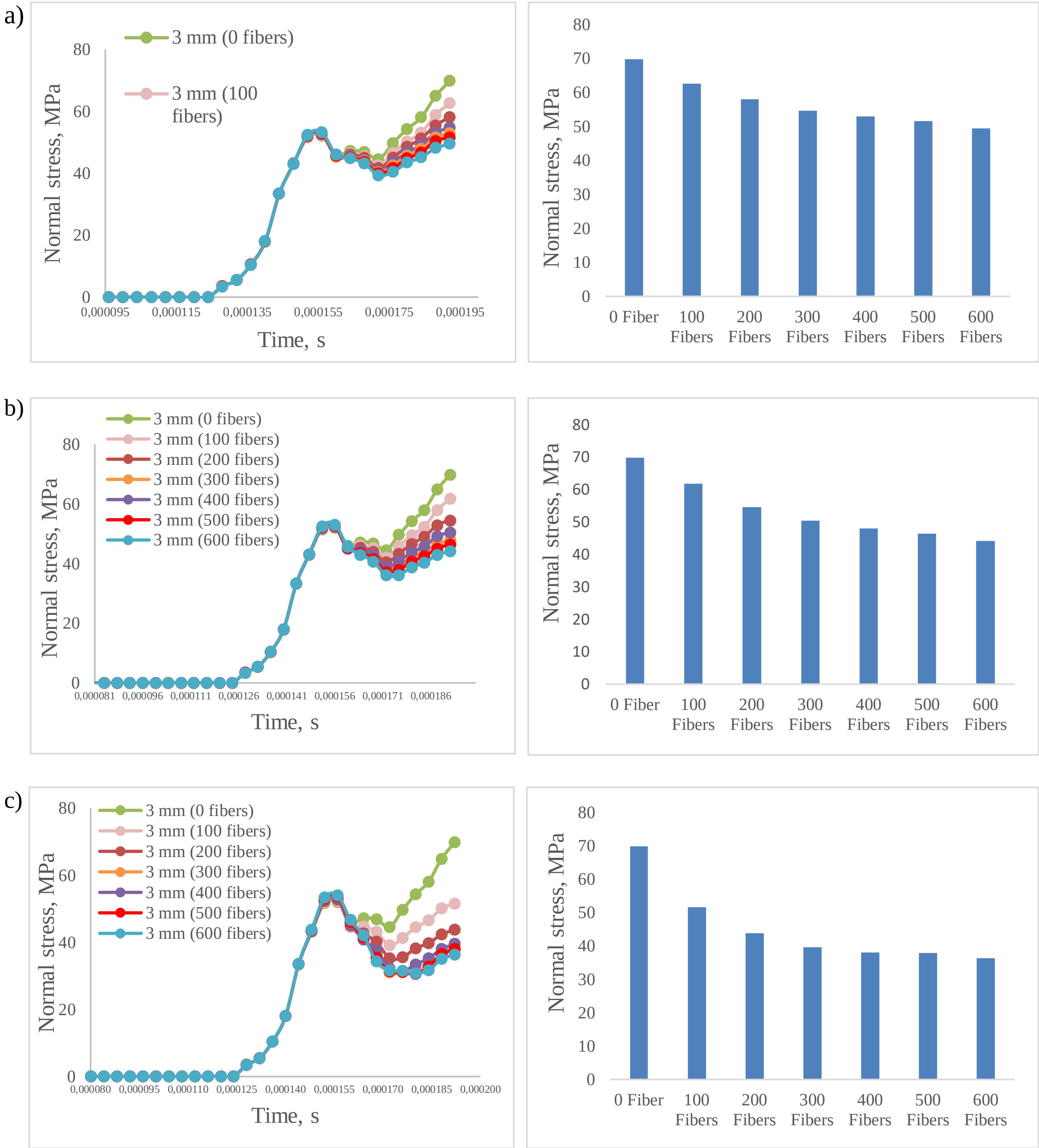

Fig. 5. Comparison of deformation in unidirectional orientation for: a) palm fiber, b) coconut fiber, and c) sugar cane fiber

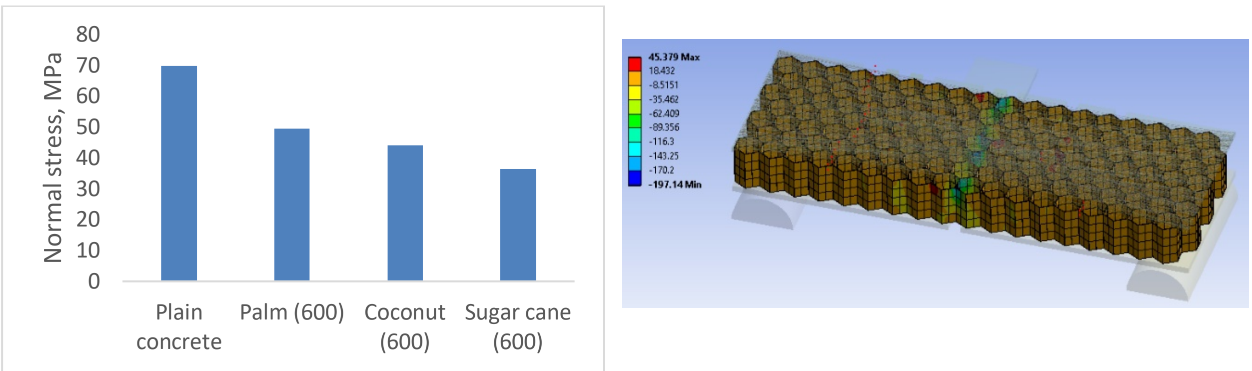

Fig. 6. Normal stress (z-axis) comparison of 600 fiber content

CONCLUSIONS

The honeycomb sandwich model was successfully investigated for both thermal and three-point bending (TPB) analysis. The fiber distribution technique was introduced by MATLAB coding and simulation software to describe the honeycomb composite panel sheet characteristics. According to the thermal analysis results, the fiber content primarily reduced the quantity of heat for all the natural fiber types, especially coconut fiber. In the morphology observation, the analysis found that the fiber helps to block the thermal networks in the concrete material owing to their insulating properties. The mechanical performance was also positively affected by adding fiber to the panel sheet, which increases the bending resistance due to an increase in stress absorption. The increment in stress absorption in early TPB indicates that preliminary failure in the honeycomb sandwich is prevented. The sugar cane fiber reinforcement achieved a high TPB due to its good tensile strength. This investigation successfully introduced local natural waste products to improve both the thermal and mechanical properties of concrete panels for a composite honeycomb skin.

Acknowledgements

On behalf of all the authors, the corresponding author expresses their appreciation to Universiti Teknikal Malaysia Melaka (UTeM) for financial support in the form of short-term grant no. PJP/2020/FTKMP/PP/S01765 and the equipment made available to conduct the research.

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