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INVESTIGATION OF MECHANICAL AND THERMAL PROPERTIES OF DATE PALM FIBER BASED POLYMER COMPOSITES FOR THERMAL INSULATION APPLICATIONS

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Highlights:

- *Tensile tests (ASTM D3039), Brinell hardness tests, and Charpy impact tests (ASTM D256) were performed to evaluate the composites mechanical performance.*
- *Thermal conductivity measurements were carried out according to ASTM E1530 standards.*
- *The panels exhibited thermal conductivity values suitable for use in thermal insulation applications.*

Abstract: Date palm fibre-based polymer composite panels are fabricated for thermal insulation applications using fibres extracted from locally abundant date palms in Oman. These fibres, sourced from the abundant date palms in Oman, serve as a sustainable and cost-effective alternative to conventional insulation materials. The integration of date palm fibres into polymer matrices not only enhances thermal insulation properties but also contributes to the reduction of environmental impact associated with traditional building materials. Six specimens of date palm fibre-based composites were prepared using treated and untreated fibres in a variety of matrix types with a 50:50 weight ratio, including unidirectional, cross-directional, and multidirectional orientation. The fibres from leaf sheath of date palm tree were collected and were cleaned with water and soaked for 24 hrs, later the fibres were extracted by retting method to prepare the specimens. Initially, three specimens were prepared with above mentioned orientations such as 1A, 1B and 1C and the fibres were treated with 5 % NaOH solution to improve the characteristics of fibre. The fibres were soaked in NaOH solution for the 24 hrs at a steady temperature and dried, therefore another three specimens prepared with treated fibres i.e 2A, 2B and 2C, in total six specimens were prepared by the fibres with the mentioned proportion of polymer matrix. To analyse the behaviour of the composite and determine its appropriateness for thermal insulation applications, tensile test, hardness test, impact test, water absorption test and thermal conductivity test were conducted for all the specimens. The specimens were prepared according to the ASTM standards for each test. The study found that the specimens demonstrated promising results in terms of both tensile strength and impact strength. Additionally, the panels exhibited thermal conductivity values suitable for use in thermal insulation applications.

Keywords: date palm fibres; weight ratio; NaOH; fibre orientation

1. Introduction

Thermal insulation is a key worry and vital system in the construction sector that helps to produce a comfortable and hygienic atmosphere within structures by protecting from heat and cold which helps to reduce energy expenses (Ali *et al.*, 2024). The relevance of thermal insulation has grown dramatically in recent years because of changes in standards and legislation around the world, prompting us to consider better solutions and systems to satisfy our needs. While there are numerous insulating materials and methods in use for various applications, the insulation types utilized in these applications should have excellent thermal characteristics as well as improved mechanical capabilities to sustain the desired loads (Kumar *et al.*, 2020). The consumption of energy by structures has increased dramatically because of the usage of inefficient thermal insulating materials. In 2018, it was anticipated that the construction sector accounted for approximately 40% of global energy usage, with this figure slightly higher in Gulf Cooperation Council (GCC) nations where temperature is a key concern (Fatma *et al.*, 2023). According to the study from the literature (Ali *et al.*, 2024), the overall energy consumption in several GCC nations in building is around 70%, with 80% of it contributing to the beginning phase and the remainder going to the construction phase. As per capita energy use has increased, so have the pollutant emissions. Therefore, it is critical to use suitable insulation materials to reduce energy consumption and emissions during the manufacturing process (Fatma *et al.*, 2023). Thermal insulation is an important part of building construction, and several materials, such as expanded polystyrene, fiberglass, mineral wool, and polyurethane, are used for thermal insulation in buildings. These materials have low thermal conductivity ranging from 0.02 to 0.05 W/m^2K. At the same time, some materials, like fiberglass and glass wool, can cause serious health problems in humans, and there are some restrictions on their use during the construction phase due to poor mechanical qualities (Y¨ucel *et al.*, 2003). To overcome the high cost and toxicity of existing insulating materials, biodegradable, non-poisonous, and low-cost insulating materials are in high demand in today's world. There are numerous benefits to creating such materials from renewable resources (Rafiq *et al.*, 2020). Natural and eco-friendly materials are being investigated for many applications since they have numerous benefits such as being compostable, recyclable, replicable, and sustainable. These materials offer excellent service qualities, allowing them to replace traditional building materials (Marín Calvo *et al.*, 2023).

Natural fibres found in nature have good and long-lasting characteristics such as improved efficiency, lightweight, high strength, and effective durability that boost their usage and application. Natural fibres are promising alternatives to high-cost synthetic fibres that harm the environment (Karimah *et al.*, 2021). Date palm is one of the most noteworthy and promising agricultural crops, abundant in the Sultanate of Oman and throughout the GCC. According to certain research (Ali *et al.*, 2022), a large amount of date palm leaves and trunks are gathered as waste. Many researchers such as Ali *et al.* have shown rapid interest in finding a solution for synthetic fibres, which are regarded as pollutant materials throughout their production phase, while natural fibres have advantages, superior qualities, and an eco-friendly nature (Ali *et al.*, 2022). By incorporating date palm fibres with polymers, the composites' characteristics can be improved (Al-Khanbashi *et al.*, 2005). Date palm fibres hygroscopic nature can be remedied by treating them with chemicals such as sodium hydroxide (NaOH). Previous study has demonstrated a considerable change in their characteristics as well as enhanced adhesion between the date palm fibre and the polymer matrix after being treated with NaOH solution (Wazzan, 2006). Date palm fibre is one of the most compatible natural fibres, with a superior chemical composition and mechanical strength when compared to other natural fibres (Faiad *et al.*, 2022).

2. Materials and Methods

2.1. Mold Box

Figure 1 shows the mold box, which is fabricated using mild steel square pipes. The dimensions of the mold box were set as 250 mm × 250 mm × 25 mm (Length × Width × Height). Also, a 5 mm thick plate with dimensions of 250 mm × 250 mm was used as bottom plate and 245 mm × 245 mm were used as top plate to cover the mold box. The specification of the mold box are presented in **Table 1**.

Figure 1. Mold box

Table 1. Specification of the mold box

Description	Specification
Material	MS Steel square pipe
Cover plate	MS Plate 5 mm thick
Length	250 mm
Width	250 mm
Height	25 mm

2.2. Date Palm Fibres

Date palm waste was collected from the surrounding date palm farms located in and around the muscat city of Oman and fibres were extracted from the leaf sheath of date palm tree. These leaf sheaths were soaked in water for 24 hours and dried for at least 2 to 3 hours. After that the fibres were extracted from retting method as shown in **Figure 2**. It is one of the traditional methods of extracting natural fibres where the fibres are separated from the wet strips by repetitive beating, scraping, and combing. This method is used from very long time in preparation of ropes from natural fibres.

(a) (b) (c)

Figure 2. Date palm fibres (a) Raw date palm waste, (b) Soaked DPF, and (c) Dry DPF

2.3. Compression Machine

In this work, a manually operated pneumatic compression machine was used to prepare the composites. This machine has a manual handle from which air can be pressurized and is used to press the mold. The capacity of the machine is 50 tons, and other specifications are shown in **Table 2**.

Table 2. Specification of compression machine

Description	Specification
Maximum load	50 ton
Method of operation	Manual
Type	Pneumatic

2.4. Epoxy with Hardener

Figure 3 shows the epoxy resin used as a matrix in the preparation of composites. A ratio of 2:1 was used to prepare the matrix, and the composite is prepared with specified weight ratio with date palm fibers. Epoxy resins provide a composite of its strength, toughness, and chemical resistance.

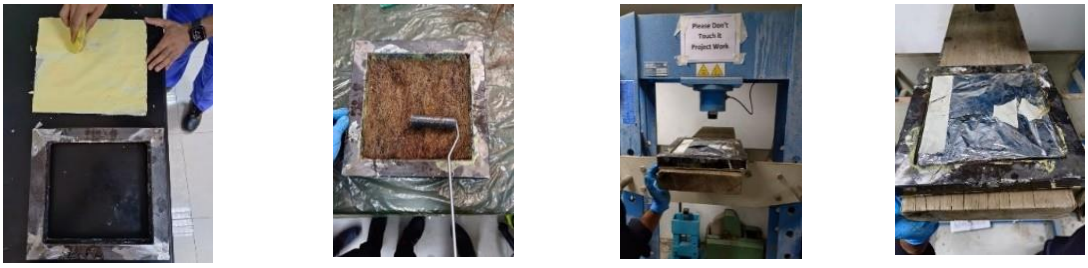
Figure 3. Epoxy resin with hardener

3. Preparation of Specimens

Figure 4a shows the extracted date palm fibres from retting process, where they were immersed in water to facilitate the separation of fibres from the plant material. This traditional method utilizes moisture and microorganisms to break down the pectin and other substances binding the fibres to their stems. After extraction, the fibres were thoroughly washed with water to remove impurities such as dirt and other contaminants. They were then soaked properly to ensure complete removal of residual substances. To enhance the properties of the date palm fibres, they were treated with an alkaline solution, typically sodium hydroxide (NaOH). This treatment improves fibre adhesion and compatibility with the polymer matrix shown in **Figure 4b**. The treated fibres were dried thoroughly at an atmospheric temperature of approximately 30°C. This drying process eliminates excess moisture, ensuring the fibres are in an optimal state for composite fabrication.

Figure 4e shows the mold box with dimensions of 250 mm × 250 mm × 25 mm for the composite fabrication. Two cover plates were used to enclose the mold box from the top and bottom, ensuring uniform pressure application during the moulding process. An epoxy resin is mixed with a hardener in a 2:1 ratio by weight. This mixture serves as the matrix in the preparation of the composite, providing structural integrity and bonding the fibres together as shown in **Figure 4c**. To prevent the epoxy from sticking to the mold, a layer of wax was applied to the mold box, including the bottom plate and cover plates. This ensures easy removal of the composite panel after curing (**Figure 4e**). The extracted date palm fibres were placed in the mold box according to specified orientations, such as unidirectional, bidirectional, and cross orientation. This strategic layering enhances the mechanical properties of the composite panel as shown in **Figure 4f**. The epoxy and hardener mixture were applied thoroughly over the laid fibres using a paintbrush. This ensures complete impregnation of the fibres, facilitating optimal bonding and composite formation as shown in **Figure 4f**. The mold box was closed with cover plates and placed in a manual pneumatic compression machine. A load of 50 tons was applied to the mold box and was allowed to remain under pressure for at least 24 hours. This process ensures the composite panel achieves the desired thickness and uniformity as shown in **Figure 4g**.

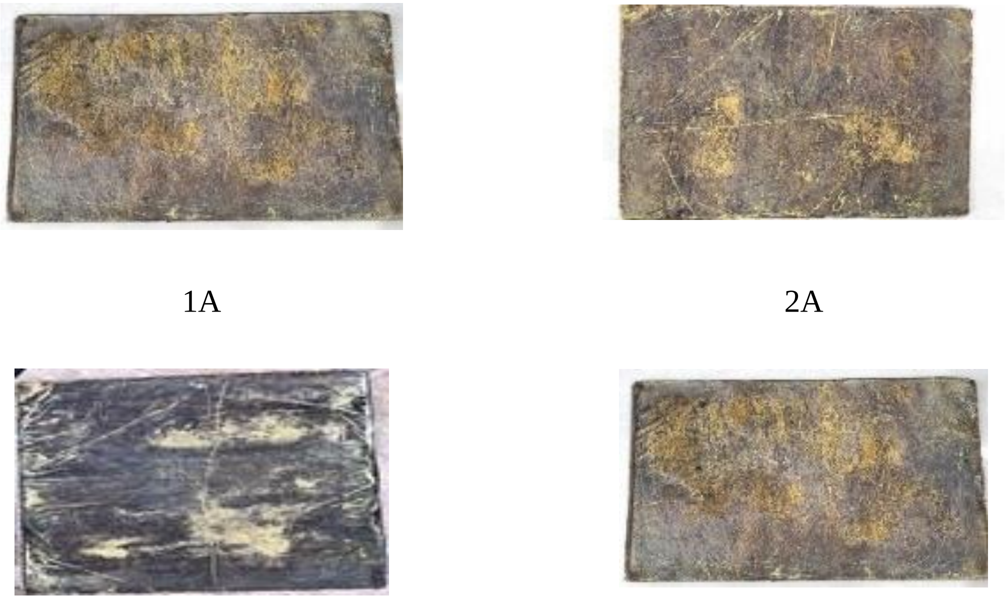
(a) (b) (c) (d)



(e) (f) (g) (h)

Figure 4. Specimen preparation (a) DPF, (b) Treated DPF, (c) Epoxy resin, (d) Weight ratio, (e) Mold box & cover plate, (f) DPF laying, (g) Mold box in compression machine, (h) Ready panel in mold box after compression

Figure 5 illustrates date palm fiber (DPF) polymer composite panels fabricated according to specified proportions and DPF combinations. Panels were prepared using different fiber orientations, including unidirectional, bidirectional, and cross-directional configurations. Both treated and untreated DPF variants were incorporated in the fabrication process. Following panel fabrication, each specimen underwent basic machining operations such as cutting and surface grinding to achieve the required dimensional accuracy and surface finish in compliance with standardized testing protocols.



1A 2A

1B 2B

1C 2C

Figure 5. Specimen of the date palm fibre polymer composites

Table 3 shows the different orientations and combinations of DPF used in the specimen preparation. There are six specimens were prepared, and they were identified as 1A, 1B, 1C, 2A, 2B and 2C, as 1 is used to identify the untreated DPF and the 2 is used to identify treated fibers with NaoH solution.

Table 3. Details of the specimen

Specimen No.	Description
1 A	Untreated unidirectional orientation
1 B	Untreated bidirectional orientation
1 C	Untreated cross directional orientation
2 A	Treated with 5 % NaOH unidirectional orientation
2 B	Treated with 5 % NaOH bidirectional orientation
2 C	Treated with 5 % NaOH cross directional orientation

4. Testing of Composites

4.1. Tensile Test

Figure 6 shows a tensile test performed on each sample with ASTM D3039 standard. The test was carried out using a Brooks Testing Machine with a continuous crosshead speed of 2 mm/min and a 25 kN load in. The ultimate tensile strength (σt), maximum strain (ϵt), and Young's modulus (Et) were determined for each specimen.

Figure 6. Tensile testing

4.2. Hardness Test

Hardness test was carried out to determine the hardness of the composites using Brinell hardness test, a 2.5 mm diameter ball indenter used to create an indentation. For each specimen as shown in **Figure 7**, loads of 100 kgf, 150 kgf, and 187.5 kgf were applied at different places. The diameter of indentation was recorded and Brinell hardness number (BHN) was determined using the formula. The applied load was divided by the indentation surface area to give the BHN as given in Equation 1.

$$HB = \frac{2F}{\Pi D\left[D-(D^2-d^2)1^{\frac{1}{2}}\right]} \qquad (1)$$

Where F is load in kgf, D is steel ball diameter in mm and d is indentation diameter in mm.

Figure 7. Specimen for the hardness test

4.3. Water Absorption Test

Composites' water absorption tests were conducted in accordance with ASTM D570. Specimens were produced and dipped in distilled water to measure the composite's water absorption capability. Throughout the course of the 15-day test, the specimen's weight was noted every three days. The percentage of water uptake was computed by recording the difference between the final and initial weights before and after submersion in water. As shown in **Figure 8**, six specimens were analysed in each test, and the results of the analysis are provided. The testing was conducted for 15 days to achieve equilibrium. The computation was predicated by using Equation 2.

$$W_{a\%} = \frac{W_t - W_0}{W_0} x\ 100 \qquad (2)$$

Where *Wa* is water absorption percentage, *Wt* is weight of sample after immersion in gm, *Wo* is weight of sample before immersion in gm.

Figure 8. Specimen for the water absorption test

4.4. Thickness Swelling Test

All six samples shown in **Figure 9** with size 60 mm diameter and 4 mm thickness were prepared for the thickness swelling evaluation. The samples were measured for thickness as T0 before and T1 after being immersed into water using a Vernier calliper. Thickness swelling was determined using Equation 3.

$$T_{s\%} = \frac{T_t - T_0}{T_0} x\ 100 \qquad (3)$$

Where *Ts* is thickness swelling percentage, *Tt* is thickness of sample after immersion in mm, T_0 is thickness of sample before immersion in mm.

(a) (b)

Figure 9. Specimen preparation (a) Water absorption test, and (b) Specimen weighing

4.5. Impact test

In accordance with ASTM D256, the impact test was conducted in a Charpy impact setup. **Figure 10** illustrates how the specimens were prepared in accordance with standard size. The energy required to shatter the material was measured using the impact test. All six specimens undergo the test, and the outcomes were examined.

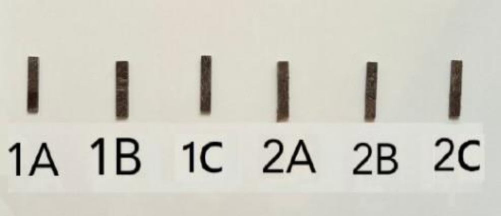


Figure 10. Specimen for the impact testing

4.6. SEM Analysis

SEM (Scanning Electron Microscope) images were used to study the distribution of fibres throughout the sample and the orientation of fibres in the composites. In this work, all the samples were prepared for the SEM analysis and the same were sent to CAARU centre, Sultan Qaboos University for testing.

4.7. Thermal Conductivity Test

All specimens were subjected to a thermal conductivity test in accordance with ASTM E1530-1. The guarded hot plate method was used to determine the specimens' thermal conductivity. The specimens utilized in this test have dimensions of 60 mm in diameter and 3 mm in thickness. The sample was heated from one side by an electrically heated plate. The metal plate that surrounds this plate has been heated to the same temperature as the plate itself. The temperature on the opposite side of the sample was also controlled by a cooled plate. In this method, hot fluid was circulated through the hot plate and cold fluid through the cold plate, with the sample placed in between. The temperature difference between the hot and cold sides was then recorded.

5. Results and Discussions

5.1. Hardness Test

Upon performing a hardness test on the different specimens, it was discovered that the 2B composition, 1B composition, and 1C composition had the highest Brinell hardness number under loading conditions of 187.5 kgf. The combination of varying amounts of DPF and NaOH clearly increased the specimen's hardness. All specimens' BHNs are displayed in **Figure 11**.

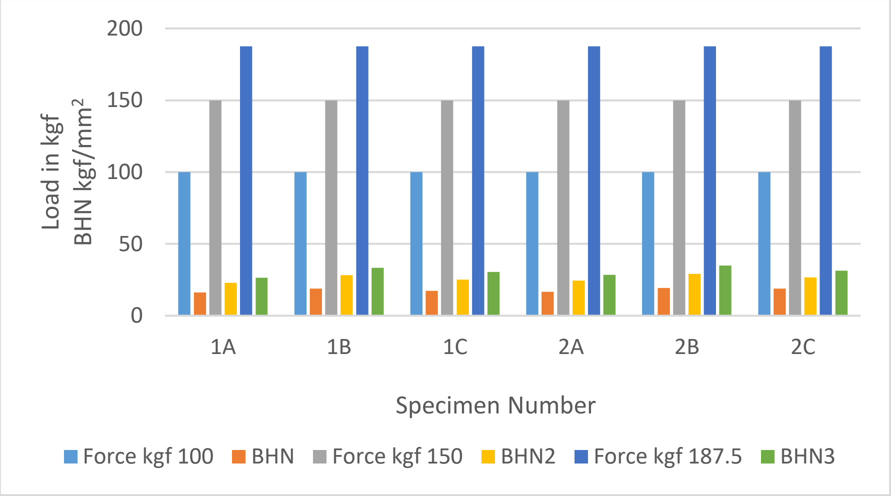


Figure 11. Hardness test

5.2. Tensile Test

Tensile test was carried out for different specimens and the results are shown in **Figure 12**. It is observed from the test results that date palm fibres with untreated condition in unidirectional orientation i.e 1A and 1C have shown good tensile strength. For treated fibres, the results have shown significant decrement, this may be because of NaOH treatment for longer period of 24 hours. In **Figure 13**, it is observed that percentage of elongation is higher in the 1A specimen, as in this case the fibre orientation is unidirectional, and load is applied along the direction of fibres. The value for 2C is decreased and this may be due to the excessive treatment of fibres with NaOH. Therefore, from the result, natural fibres with unidirectional orientation with NaOH treatment for limited period is suitable for the application to the buildings to withstand the applied load in different seasonal conditions.

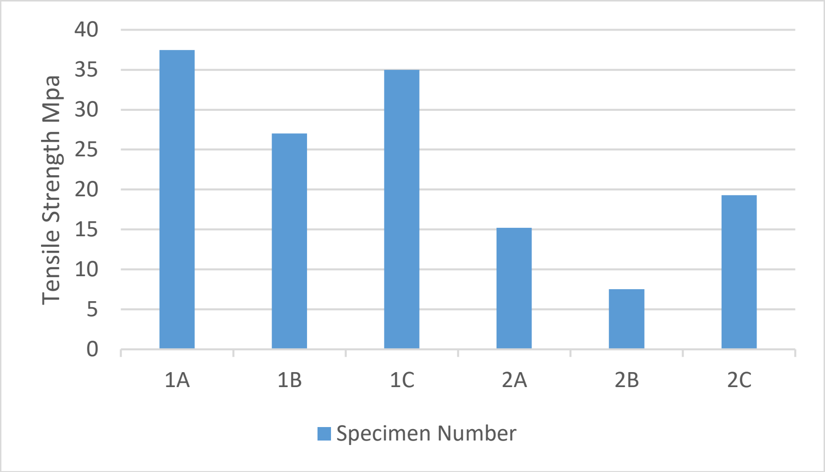


Figure 12. Tensile test

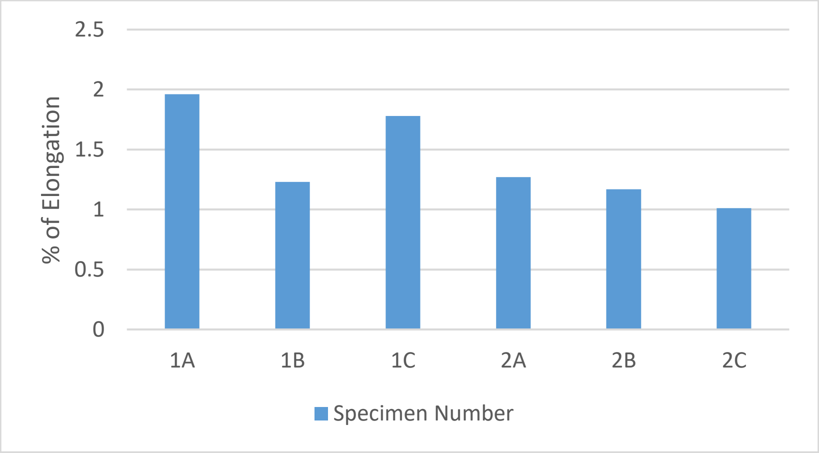


Figure 13. Percentage of elongation

5.3. Water Absorption Test

The results of the water absorption test shown in **Figure 14** indicate that with the exception of 2A, all untreated and treated hybrid composites exhibited a significant percentage of water absorption. Every inspection up to 15 days has showed that 2B has the greatest water absorption value and 2C has the second-highest value. This pattern indicates that composites with greater DPF contain the highest water absorption content. Many water molecules are absorbed by the DPF's hollow structure. On the fifteenth day, the measured water absorption was less than 10%, indicating that 1C and 1B had the lowest water absorption of all the hybrid composites.

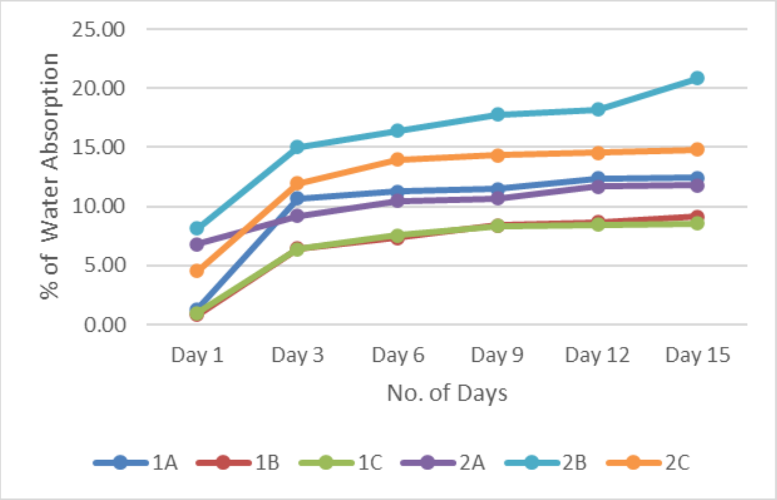


Figure 14. Water absorption

5.4. Thickness Swelling Test

Both treated and untreated hybrid composites were found to be structurally unstable based on the findings of a thickness swelling test performed on the specimens, which are shown in **Figure 15**. The pattern of water absorption was remarkably similar for thickness swelling. The untreated 1C hybrid composite exhibited the greatest thickness swelling among the treated and untreated hybrid composites. Over time, the swelling increased, peaking at 10% on the fifteenth day. Although the swelling patterns of the composites in the other untreated hybrid composites were comparable, 1C displayed the greatest thickness swelling, which may have been caused by a higher percentage of cellulosic material. Following the fibre treatment, 2A showed the least amount of swelling (4%) among all the hybrid composites, whereas 2B showed the most swelling.

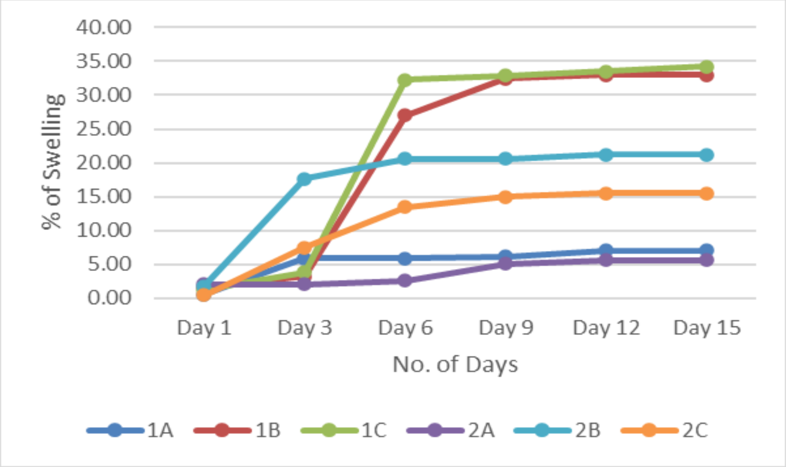


Figure 15. Thickness swelling

5.5. Impact Test

The results of the impact test are displayed in **Figure 16**. It has been noted that, out of all the untreated hybrid composites, 1B exhibited the highest impact strength. Due to its hollow core, which acts as a shock absorber and preserves the basic structure of both fibre and composites, DPF offers superior impact resistance qualities compared to other natural fibres (Ghori *et al.*, 2022). Because of their weaker fibre combination and interfacial bonding, 2A and 2C had lower impact properties. Out of all the hybrid composites that were treated, 2B was shown to have the best impact characteristics.

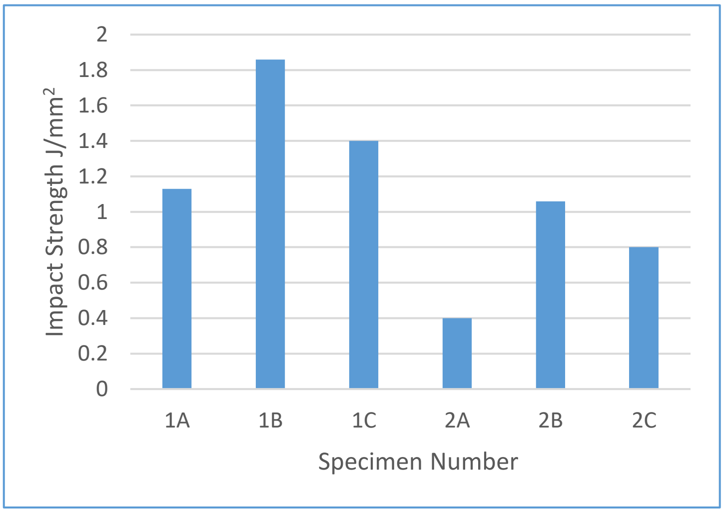


Figure 16. Impact test

5.6. SEM Analysis

The SEM analysis shows the orientation of fibres in different combinations, as the fibres are neatly distributed throughout the mold, and it forms good composite. The distribution of fibres throughout the sample is evident from the SEM images, and the relationship between the fibre and matrix is also described. Some regions are devoid of reinforcement, but there is no discernible void content. Because most fibres are broken and very few are pulled out, the interfacial connection between natural fibres and epoxy increased. However, the composites had a lot of void contents, which may lead to poor mechanical performance. Hairline fissures between the fibres and matrix are seen in the treated fibres, indicating inadequate interfacial bonding, as shown in **Figure 17**.

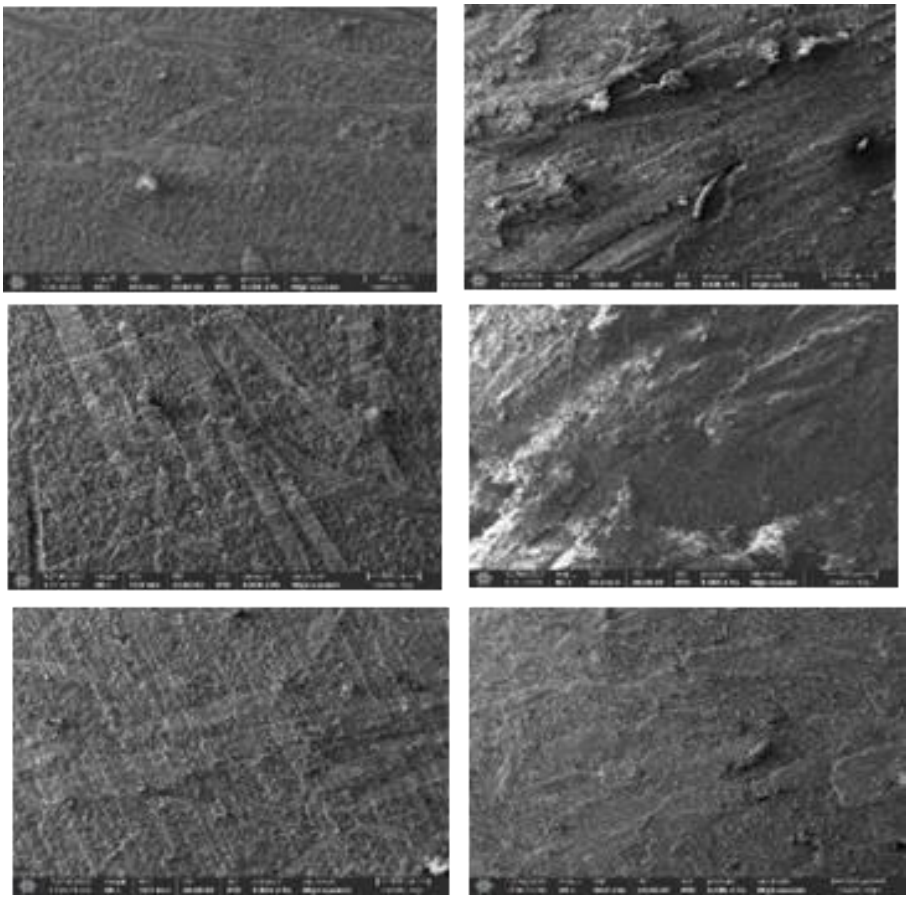


Figure 17. SEM analysis

5.7. Thermal Conductivity

A Thermal conductivity test was carried out on all six specimens and results are tabulated as shown in **Figure 18**. it is observed that the thermal conductivity of 1C and 2C has shown least value stating that they have good thermal resistance properties, as the volume of fibres and orientation of fibres affect the thermal conductivity of the composites.1A and 2A has shown higher value of thermal conductivity.

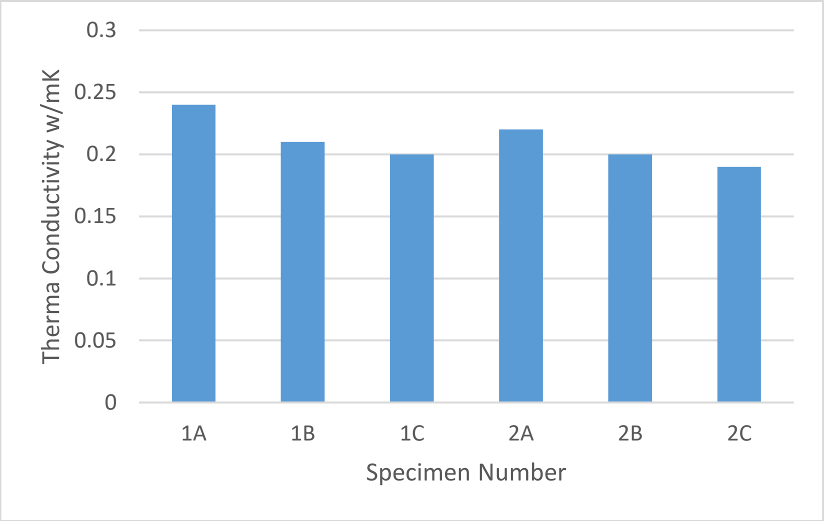


Figure 18. Thermal conductivity

6. Conclusion

The growing demand for sustainable composite materials has encouraged the exploration of natural fibres, such as date palm fibre, as alternatives to synthetic reinforcements. This study aims to evaluate the mechanical, physical, and thermal properties of untreated and NaOH-treated fibre-reinforced composites. Composite specimens with different fibre orientations and proportions were prepared and subjected to hardness, tensile, impact, water absorption, swelling, and thermal conductivity tests, along with SEM analysis to examine fibre distribution and interfacial bonding. The experimental findings revealed that specimens 1B, 1C, and 2B achieved higher Brinell hardness numbers, while tensile strength was most pronounced in 1A and 1C. Water absorption was lowest in 2A but highest in 2B and 2C, reflecting the influence of fibre content. Impact strength was greatest in specimen 1B, with treated hybrid composite 2B showing enhanced performance when fibre treatment was optimized. Thermal conductivity results indicated improved thermal resistance in specimens 1C and 2C compared to others. Overall, the results highlight the potential of optimally treated and well-oriented natural fibre composites to deliver superior mechanical and thermal performance, while excessive treatment may compromise fibre integrity and reduce properties. Future studies can be extended to optimize fibre treatment parameters and investigate hybridization with other natural fibres to further improve the mechanical, thermal, and moisture resistance properties of the composites.

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Credit Author Statement

Conceptualization and methodology, Alharthi, S.A. and Doddamani, D.; software and validation, Alsaadi, T.M.; formal analysis, Alkalbani, S.R.; investigation, Almahrami, M.K.; resources, Almahrami, M.K.; data curation, Alkalbani, S.R.; writing—original draft preparation, Alharthi, S.A.; writing—review and editing, Almahrami, M.K., Maliger, R. and Doddamani, D.; visualization, Alsaadi, T.M.; supervision and project administration, Maliger, R. and Doddamani, D.

Conflicts of Interest

The authors declare no conflict of interest.

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