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Effect of Hot Water Treatment on Physical and Mechanical Properties of Oil Palm Empty Fruit Bunch Fibre Cement Boards

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ABSTRACT

The growing demand for sustainable construction materials has increased interest in fibre–cement composites reinforced with natural fibres. Oil palm empty fruit bunch (OPEFB) is an abundant agricultural by-product with strong potential for fibre cement boards. However, its hydrophilic nature and weak fibre–matrix adhesion limit dimensional stability and mechanical performance. While hot water treatment has been shown to improve fibre compatibility, most studies have focused only on untreated, 60°C, and 100°C conditions, leaving the effects of intermediate temperatures insufficiently explored. This study investigates the effect of hot water treatment at six temperatures (room temperature, 60°C, 70°C, 80°C, 90°C, and 100°C) for 60 minutes on the physical and mechanical properties of OPEFB fibre cement boards. Treatment effectiveness was evaluated using water absorption, thickness swelling, density, modulus of rupture, modulus of elasticity, and internal bonding tests, with standard sample dimensions of 100 × 100 mm, 50 × 50 mm, and 300 × 50 mm. The results showed that hot water treatment significantly enhanced dimensional stability and mechanical performance. Boards treated at 100°C exhibited the lowest water absorption (25.14%) and thickness swelling (0.39%), as well as the highest modulus of rupture (5.23 N/mm²), modulus of elasticity (4180.50 N/mm²), internal bonding strength (1.22 N/mm²), and density (1321.72 kg/m³). Treatments at intermediate temperatures (70–90°C) also produced substantial improvements, indicating that effective fibre modification can be achieved below boiling temperature. These findings demonstrate that hot water treatment is a cost-effective, solvent-free, and environmentally sustainable approach for enhancing OPEFB fibre cement boards, supporting their potential as eco-friendly construction materials.

Keywords: Oil palm empty fruit bunch; fibre cement board; hot water treatment; physical properties; mechanical properties

INTRODUCTION

Fibre cement boards have gained wide application in wall cladding, roofing, formwork, ceilings, and flooring due to their flexibility, durability, and resistance to fire, water, and biological degradation (Villena et al. 2020). This fibre cement board is particularly preferred over particleboards because of its availability, toughness, lightweight nature, low cost, and renewability (Ridzuan et al. 2023). Classified as artificial composite stone materials, the board is produced through the solidification of a mixture comprising cement, fibres and water. To evaluate their strength and deformability, nonlinear deformation models with high predictive reliability are frequently applied, as also used for concrete (Balea et al. 2021).

To further improve fibre cement composites, natural plant fibres have attracted growing attention due to their low density, high specific strength, and sustainability. As polysaccharide-based materials, plant fibres also influence cement hydration by moderating hydration heat release, thereby improving crack resistance in cementitious systems (Islam et al. 2024). In particular, plant fibres hold great promise as sustainable raw materials, especially in agriculturally strong nations such as Malaysia. The rising global emphasis on sustainability has further accelerated the adoption of natural fibre composites. Estimates indicate that the annual production of lignocellulosic fibres is approximately 2.1 × 10^{11} tons, far exceeding the 1.5 × 10^{8} tons of synthetic fibres. This abundance points to the advantages of natural fibres as substitutes for synthetic alternatives, reducing production costs while mitigating negative environmental impacts (Parveez et al. 2025).

Malaysia, as the world's second-largest exporter of crude palm oil (CPO) after Indonesia, contribokutes about 24% of total global production (Cheah et al. 2023). According to the Malaysian Palm Oil Board (MPOB), CPO production is expected to reach 19.5 million tonnes in 2025, slightly from 19.3 million tonnes in 2024. Similarly, according to the Malaysian Palm Oil Council (2025), Malaysia's crude palm oil (CPO) production increased by 5.05% in May 2025 compared to the previous month, while exports surged by 25.62%.

The palm oil industry represents the country's largest biomass producer, generating nearly 23 million tonnes of residues annually, with around 90% originating from plantations and the remaining 10% from milling activities. The industry contributes approximately 8% to the Gross National Income (GNI), underscoring its role as a key economic sector with vast biomass resources (Ali et al. 2020). Among the biomass by-products of this industry, oil palm empty fruit bunches (OPEFB) constitute nearly 20% of fresh fruit bunch weight, equivalent to about one tonne of OPEFB for every tonne of palm oil produced (Ng et al. 2020). Each hectare of plantation generates approximately 1.5 tonnes of OPEFB annually (Rusdianasari et al. 2023). Despite being rich in cellulose (40–65%), hemicellulose (15–25%), and lignin (12–20%) (Pramono et al. 2022), OPEFB is underutilised, with much of it being incinerated or used as mulch, contributing to environmental issues such as air pollution (Windiastuti et al. 2022).

Natural fibres such as OPEFB therefore offer sustainable and cost-effective alternatives to synthetic fibres and asbestos, with the added advantages of renewability and reduced health risks (Ridzuan et al. 2023). Their incorporation into cement composites improves toughness by limiting micro-crack propagation and enhancing durability (Rocha et al. 2022). However, the fibre's hydrophilic nature presents challenges, causing dimensional instability, poor wettability, and weak fibre–matrix bonding (Ramakrishna 2022; Geremew et al. 2021). These limitations are largely due to hydroxyl groups present in cellulose and other polysaccharides, which interfere with cement hydration and curing, leading to reduced mechanical performance (Chen et al. 2022). To overcome these drawbacks, natural fibre surface modification is necessary. Fibre surface treatments are designed to alter fibre morphology and improve its resistance to alkaline environments (Islam et al. 2024).

Such treatments address the hydroxyl-related challenges by partially substituting hydroxyl groups to impart hydrophobicity, eliminating fatty acids and surface contaminants, and enhancing fibre–matrix compatibility (Mahardika et al. 2024). This procedure improves adhesion, reduces water absorption, and stabilises mechanical properties (Raghoo et al. 2021; Mohammadi et al. 2024). Without these modifications, fibres act more as voids than reinforcements in composites, impairing the overall performance (Hasan et al. 2022).

Furthermore, intramolecular hydrogen bonding among fibre constituents often causes agglomeration, restricting dispersion in the matrix and resulting in inconsistent properties. Fibre surface modifications such as chemical, physical or physicochemical treatment are therefore required to remove weak boundary layers and improve compatibility (Chand & Fahim 2020). The outer layers of lignocellulosic fibres, typically covered by lignin, waxes, and oils, are inherently incompatible with the cement matrix, which, upon untreated incorporation, leads to unstable interfaces (Boey et al. 2022).

Although chemical treatments improve fibre–matrix bonding, this treatment can also degrade fibre constituents by dissolving amorphous components, increasing cellulose content, and ultimately weakening mechanical strength. To mitigate these drawbacks, thermal treatments have been explored to preserve fibre composition, geometry, and cellular structure within cementitious matrices (Ezugwu, 2023). Hot water treatment has proven to be simple, cost-effective, and effective in enhancing fibres with high cellulose content while reducing ketones and other organic matter (Ezugwu, 2023). Hot water treatment, as a mild physical modification, alters fibre structure without changing chemical composition. It removes surface extractives while avoiding solvents, thus preserving key components such as cellulose and lignin (Camillo et al. 2023). Recognised as environmentally sustainable due to its solvent-free nature, low operational cost, and ability to solubilise hemicellulose (Gao et al. 2022), hot water treatment maintains the structural integrity of the primary cell wall while eliminating non-cellulosic components that degrade at lower temperatures.

Importantly, it does not generate toxic by-products, offering a safer and eco-friendly alternative to conventional chemical treatments (Santos et al. 2018). Previous studies have established that hot water treatment improves the physical and mechanical performance of fibre cement boards by removing hemicellulose, lignin, waxes, and other hydroxyl-rich substances from fibre surfaces (Ismail et al. 2025; Azmi et al. 2024; Budiman et al. 2021). This modification enhances fibre–matrix adhesion, reduces water absorption, and improves the physical and mechanical properties of the composites, including thickness swelling (TS), water absorption (WA), modulus of rupture (MOR), modulus of elasticity (MOE), and internal bonding (IB). Several researchers have reported superior performance of fibre cement boards treated with hot water at 100°C compared to untreated or cold-water-treated fibres (Hartono et al. 2018; Omoniyi, 2019; Zheng et al. 2023).

However, despite this growing evidence, two clear research gaps remain. First, most existing studies on hot water treatment of natural fibres have focused on fixed conditions, typically comparing untreated fibres with cold-water, 60°C, and 100°C treatments. Consequently, the effects of intermediate treatment temperatures (70°C, 80°C, and 90°C) remain insufficiently explored, even though these conditions may offer comparable performance improvements with lower energy consumption and reduced risk of fibre degradation. Second, although OPEFB fibres are abundant, renewable, and highly suitable for fibre–cement composites, systematic investigations examining their behaviour across different hot water treatment temperatures are still limited, as prior studies have predominantly focused on wood-based or other lignocellulosic fibres. These limitations highlight a clear research gap in optimising OPEFB fibre cement boards through temperature-controlled hot water treatment.

Furthermore, while duration has been shown to influence treatment outcomes, excessive soaking times can degrade fibre constituents and increase processing costs (Drpić et al. 2022). Previous findings indicate that a 60 minute treatment period provides an optimum balance, sufficient to remove surface extractives and enhance fibre-matrix compatibility (Elmoudnia et al. 2023; Hartono et al. 2018; Zheng et al. 2023), while minimising fibre damage and energy consumption (Drpić et al. 2022). For this reason, the present study applies a fixed 60 minute duration and focuses on the influence of temperature variation.

Accordingly, there is no clear guidance on how different hot water treatment temperatures below the boiling point influence the physical and mechanical performance of OPEFB fibre cement boards, as most existing studies have focused either on limited temperature conditions or on other lignocellulosic fibres. To address these gaps, the present study investigates the physical and mechanical properties of OPEFB fibre cement boards treated with hot water at different temperatures (room temperature, 60°C, 70°C, 80°C, 90°C, and 100°C) for 60 minutes, in order to determine whether intermediate temperatures can offer performance benefits comparable to boiling treatment while reducing processing costs and fibre degradation.

METHODOLOGY

OPEFB FIBRE PREPARATION

Figure 1 provides a schematic overview of the OPEFB fibre preparation, hot water treatment conditions, fibre cement board fabrication, and subsequent physical and mechanical testing. This illustrates the overall experimental procedure used in this study. Oil palm empty fruit bunch (OPEFB) used in this study were obtained from Pamol Kluang Palm Oil Mill, located in Kluang, Johor, Malaysia. The OPEFB were collected in January 2024 and subsequently transported to and processed at the Timber Fabrication Laboratory, Faculty of Civil Engineering and Built Environment (FKAAB), Universiti Tun Hussein Onn Malaysia (UTHM) for material preparation, fibre cement board fabrication, and experimental testing.

The raw OPEFB were sun-dried for 2–3 days to remove excess moisture, shredded, and further refined using a hammer mill with shear and impact action. The fibres were sieved to eliminate dust, and only those passing through a 7-mesh (R7M) and retained on a 14-mesh (R14M) sieve (8.88–16.5 mm) were selected, as this size range has been reported to provide optimal properties for fibre cement board (Maynet et al. 2023; Akasah et al. 2019). Sieving was conducted using a wire mesh mould on a vibration table for 2 minutes, after which the retained fibres were collected and stored for treatment.

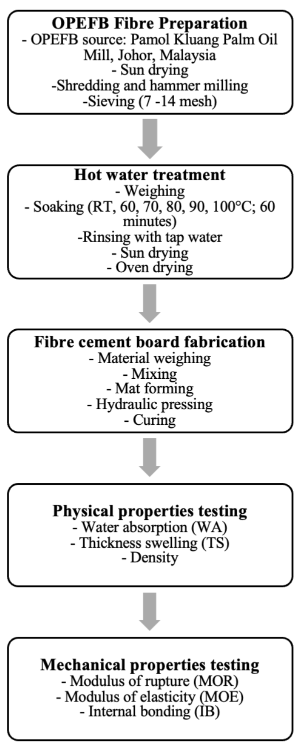

FIGURE 1. Experimental procedure flowchart

HOT WATER TREATMENT

OPEFB fibres were treated with hot water at six different temperatures: room temperature (RT), 60°C, 70°C, 80°C, 90°C, and 100°C, with each treatment lasting for 1 hour. The treatment procedure was based on the methods of Bakar et al. (2024) and Omoniyi (2019). The water volume for each treatment was calculated following the ratio proposed by Cabral et al. (2018), in which 31.25 g of fibre required 1 L of water. The water bath was then heated to the specified temperature (±1 °C), and the pre-weighed fibres, placed in a net, were fully submerged for 1 hour. After treatment, the fibres were rinsed with tap water to remove residual impurities and subsequently sun-dried on a canvas liner to promote uniform drying. Once sufficiently dried, the fibres were placed on trays and oven-dried at 100°C for 24 hours to eliminate remaining moisture.

OPEFB FIBRE CEMENT BOARD FABRICATION

The OPEFB fibre cement boards were fabricated based on a targeted density of 1300 kg/m³ and a cement-fibre ratio of 3.5:1. All weighed materials were mixed in a drum mixer and evenly distributed into a 350 × 350 mm wooden mould placed on a 400 × 600 mm reinforced steel plate lined with a cast acrylic sheet. The mixture was spread through a wire mesh mould and formed into three layers, which were levelled using a wooden stick. The mat was pre-compressed with a plywood plate, after which the wooden mould was removed, and another acrylic sheet was placed on top of the pre-formed sample. A steel gap bar was positioned on the base plate to control the thickness at 12 mm, and the assembly was clamped securely with bolts. The sample was then compressed using a hydraulic press to achieve a thickness of 12 ± 1 mm, in accordance with BS EN 634-1:1995. After 24 hours, the clamps were removed, and the boards were cured for 28 days under ambient conditions (28 ± 1°C, 65 ± 5% relative humidity). Following curing, the boards were cut into the required dimensions for laboratory testing.

PHYSICAL PROPERTIES TESTING

The water absorption (WA) test was carried out in accordance with BS 5669:1979. As specified in the standard, the required dimensions of the sub-samples were 100 × 100 mm. Each sub-sample was immersed in water at room temperature for 24 hours and subsequently weighed to an accuracy of 0.01 g, both before and after immersion in distilled water. The WA value was then determined using the formula presented in Equation 1, where W_f is the weight of the sample after soaking in water (g) and W_i is the weight of the sample before soaking in water (g).

$$\mathrm{WA} = \frac{W_f - W_i}{W_i} \times 100\% \quad (1)$$

The thickness swelling (TS) test was carried out in accordance with BS EN 317:1993, which specifies the procedure for evaluating the increase in thickness of a sample after full immersion in water. For this analysis, three samples from each treatment temperature were prepared, each measuring 50 × 50 mm. The samples were then immersed vertically in clean, still water with a pH of 7 ± 1 and a controlled temperature of 20 ± 1°C. After 24 hours, the thickness of each sample was measured, and the swelling percentage was calculated using Equation 2, where t_1 represent the thickness of the sample before immersion (mm) and t_2 represent the thickness of the sample after immersion (mm).

$$TS = \frac{t_2 - t_1}{t_1} \times 100\% \quad (2)$$

The density of the samples was evaluated as the ratio of mass to volume at a constant moisture content. Following the procedure outlined in BS EN 323:1993, each sample was prepared in a square shape with a nominal side length of 50 mm. Density was calculated using the measured side length, thickness, and mass of each specimen. Thickness was recorded at the intersection of the diagonals to ensure accuracy. The formula applied for density determination is presented in Equation 3, where m is the mass of the sample (g), b_1 and b_2 are the side lengths of the sample (mm), and t represent the thickness of the sample (mm).

$$\rho = \frac{m}{b_1 \times b_2 \times t} \times 10^6 \quad (3)$$

MECHANICAL PROPERTIES TESTING

The mechanical properties of the OPEFB fibre cement boards were tested using an Instron Universal Testing Machine. The modulus of rupture (MOR) and modulus of elasticity (MOE) were determined in accordance with BS EN 310:1993 through a static bending test, which measures the maximum load a sample can withstand at its midpoint. Following the curing process, samples were cut to the standard dimensions of 300 × 50 mm. The width and thickness of each sample were measured, and the span length between the centres of the supports was set to within 1 mm of 20 times the nominal panel thickness. This span was measured with an accuracy of ±0.5 mm. The load was applied at a constant crosshead speed, adjusted to reach the maximum load within 60 ± 30 seconds. Deflection was continuously measured, and the maximum load was recorded to an accuracy of 1%. The MOR value was calculated using Equation 4, where F_{max} is the maximum load applied (N), l_1 is the span between the supports (mm), b is the sample width (mm), and t is the specimen thickness (mm). Similarly, Equation 5 was used to determine the MOE value, where $F_2 - F_1$ represents the load increment within the linear portion of the load–deflection curve (N), with F_1 and F_2 corresponding to approximately 10% and 40% of the maximum load, respectively, and $a_2 - a_1$ is the increment of deflection at the mid-length of the sub-sample (corresponding to $F_2 - F_1$).

$$MOR = \frac{3\,F_{max}\,l_1}{2\,bt^2} \quad (4)$$

$$MOE = \frac{l_1^{\,3}\,(F_2 - F_1)}{4\,bt^3\,(a_2 - a_1)} \quad (5)$$

The internal bonding (IB) test was conducted according to BS EN 319: 1993 standard with a dimension size of 50 mm × 50 mm. A steel block was glued to the sample using the epoxy glue and was left for 24 hours until the glue was fully cured to prevent rupture on the glue line. The glued test piece was stored under controlled conditions of (65 ± 5) % relative humidity and a temperature of (20 ± 2) °C. The test piece was then placed in the Instron Universal Testing Machine (UTM Instron) by securing it in the grips, and a force was applied until rupture occurred. The loading rate was set to reach the maximum load within (60 ± 30) s. Equation 6 was used to calculate the IB of the sample, where F_{max} is the breaking load (N), a and b are the length and width of the test piece (mm).

$$IB = \frac{F_{max}}{a \times b} \quad (6)$$

Three fibre cement board samples were prepared and tested for all the physical and mechanical properties in each hot water treatment temperature. The study's values for WA, TS, density, MOR, MOE, and IB are the average of three samples.

RESULT AND DISCUSSION

WATER ABSORPTION

Figure 2 presents the effect of hot water treatment temperature on the water absorption (WA) of OPEFB fibre cement boards. Overall, a decreasing trend in WA was observed with increasing treatment temperature, indicating improved resistance to moisture uptake after fibre modification as evidently highlighted by the previous researchers (Budiman et al. 2021; Omoniyi, 2019; Azmi et al. 2024). The control sample (RT) recorded the highest WA (42.75%), whereas the fibreboard treated at 100°C achieved the lowest WA value (25.14%). This substantial reduction highlights the effect of hot water treatment temperature on fibre properties and its contribution to the dimensional stability of fibre cement board.

The result can be attributed to the removal of hydrophilic substances such as hemicellulose, lignin, oil, waxes, and pectin, which are responsible for moisture retention in fibres. At higher treatment temperatures, the elimination of these compounds becomes more pronounced, thereby lowering the WA of the composites. This explanation is consistent with findings by Yimer & Gebre (2023) and Boucetta et al. (2021), who reported that reductions in WA are associated with changes in fibre surface morphology following the removal of hydrophilic components. Another contributing factor is the reduced water intake capacity of the fibre, caused by the structural shift from flexible cellulose–hemicellulose bonds to stronger cellulose–cellulose bonds.

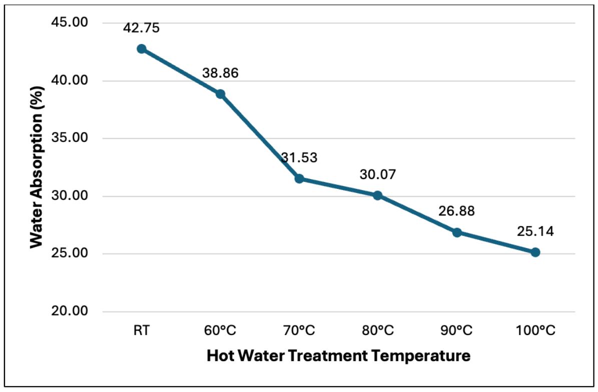

FIGURE 2. Water absorption based on different temperatures of hot water treatment

Similarly, Lahouioui et al. (2020) noted that higher WA values often result from weak interfacial bonding between fibres and the cement matrix, which allows water molecules to penetrate more easily. By contrast, the removal of hydroxyl groups at elevated treatment temperatures improves adhesion between fibre and matrix, enabling stronger binding at the fibre surface. This suggests that hydroxyl group content plays a critical role in both water retention and fibre–matrix interfacial bonding in fibre cement board. Castoldi et al. (2022) further emphasised that reducing fibre moisture absorption enhances durability and dimensional stability by minimising damage within the fibre–cement interfacial zone. Taken together, these findings indicate that OPEFB fibre cement board treated with hot water at 100°C demonstrates the highest dimensional stability, as reflected by its lowest WA value, due to improved fibre properties and stronger fibre–cement interactions.

THICKNESS SWELLING

The thickness swelling (TS) performance of fibre cement board subjected to different hot water treatment temperatures is illustrated in Figure 3. A distinct trend can be observed, where TS decreases progressively with increasing treatment temperature. The control sample (RT) recorded the highest mean TS value of 6.05%, while the sample treated at 100°C achieved the lowest at 0.39%. After 24 hours of water immersion, swelling was markedly reduced as treatment temperature increased, declining from 6.05%, 4.07%, and 3.44% at lower temperatures to 1.64%, 1.13%, and 0.39% at higher temperatures. These findings are consistent with previous research, which reported that fibres or particles treated with hot water exhibited superior TS performance in fibre cement board composites compared to untreated or cold water-treated boards (Hartono et al. 2018; Azmi et al. 2024; Ismail et al. 2025; Omoniyi, 2019; Budiman et al. 2021).

The minimum swelling, 0.39%, recorded in boards treated at 100°C, aligns closely with the TS range reported by Omoniyi (2019), where OPEFB-cement composites treated with 8% NaOH demonstrated TS values between 0.3% and 0.5%. Similarly, composites treated with hot water yielded values ranging from 0.3% to 0.6%. This indicates that hot water treatment at 100°C can achieve comparable improvements to chemical modification, offering excellent performance while maintaining environmental advantages. The enhanced dimensional stability at higher temperatures can be attributed to the significant reduction or removal of hydroxyl groups in the fibre structure, thereby limiting its ability to absorb and retain water. Untreated fibres, with their high hydroxyl group content, readily attract water molecules through hydrogen bonding (Saha & Rahman, 2026), while water can also diffuse into both the cement and fibre phases (Hasan et al. 2021).

At lower treatment temperatures, fibres retain more hydrophilic substances, resulting in higher water absorption. This process is further aggravated as pores formed on treated fibres allow water to pass through rather than be stored (Sawawi et al. 2020), and moisture penetrates the fibre lumen, causing multidimensional swelling and thickness expansion (Ghori et al. 2023). In contrast, fibre treatment improves fibre–matrix interfacial bonding, which reduces voids and cracks, restricts swelling, and limits moisture ingress (Ghori et al. 2023). Hot water soaking also removes inhibitory substances from fibre surfaces, improving compatibility with the cement matrix and lowering TS values (Budiman et al. 2021). Overall, higher treatment temperatures enhance swelling resistance and dimensional stability, ensuring better performance of fibre cement boards in humid environments. Overall, the results confirm that fibre cement board treated at 100°C achieves the greatest dimensional stability, as reflected in its lowest TS mean value.

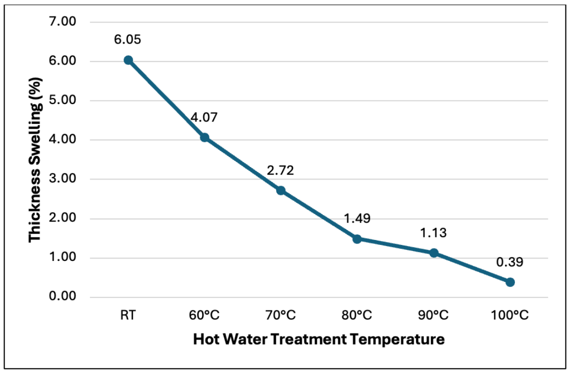

FIGURE 3. Thickness swelling based on different temperatures of hot water treatment

DENSITY PROPERTIES

The clear result that density increased with higher treatment temperatures can be seen in Figure 4. The control sample (RT) recorded the lowest density at 1092.60 kg/m³, while the density rose steadily to 1180.08 kg/m³ (60°C), 1228.85 kg/m³ (70°C), 1261.91 kg/m³ (80°C), 1314.22 kg/m³ (90°C), and 1321.72 kg/m³ (100°C). This trend is consistent with Budiman et al. (2021), who reported increasing density values in cement boards reinforced with untreated, cold water-treated, and hot water-treated coconut coir, noting that density improved with higher treatment temperatures.

For untreated boards, density values ranged from 1236–1244 kg/m³, while cold water-treated (RT) samples ranged from 1238–1256 kg/m³, and hot water-treated (100°C) samples ranged from 1240–1264 kg/m³. Omoniyi (2019) attributed this phenomenon to delignification, which enhances molecular packing and orientation. Similarly, Budiman et al. (2021) mentioned that as treatment temperature increases, more impurities are eliminated, resulting in stronger adhesion between the cement matrix and fibre surface. Sahu et al. (2023) also noted that fibre treatment can cause partial collapse of the cellular structure, reducing fibre width and void content, which contributes to higher density.

In this study, density increased more substantially between RT and 80°C (7.41%, 3.97%, and 2.62%, respectively), whereas only a slight increase (0.57%) was observed between 90°C and 100°C. Notably, the boards treated at 90°C (1314.22 kg/m³) and 100°C (1321.72 kg/m³) achieved actual densities close to the nominal design density of 1300 kg/m³, unlike the lower-temperature treatments (RT, 60°C, 70°C, 80°C), which fell below this benchmark. According to Hasan et al. (2021), achieving a density equal to or greater than 1300 kg/m³ is critical for enhanced mechanical strength in cement composites. Therefore, the results confirm that hot water treatment at 90°C and 100°C yields fibre cement board with suitable density, reflecting stronger fibre–matrix bonding and superior physical and mechanical properties.

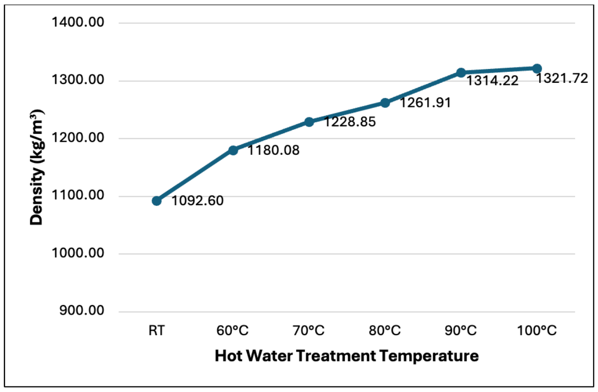

FIGURE 4. Density properties based on different temperatures of hot water treatment

MODULUS OF RUPTURE

The modulus of rupture (MOR) reflects the flexural strength of the OPEFB fibre cement boards. As shown in Figure 5, the MOR values increased consistently with higher hot water treatment temperatures. The mean MOR rose from 2.7048 N/mm² for the untreated sample (RT) to 3.8591 N/mm² (60°C), 4.1874 N/mm² (70°C), 4.6406 N/mm² (80°C), 5.0924 N/mm² (90°C), and peaked at 5.2265 N/mm² (100°C). This trend is consistent with the findings of Budiman et al. (2021), Hartono et al. (2018), who also reported higher MOR values with increasing treatment temperature, progressing from untreated to cold and hot water-treated samples. As noted by Ismail et al. (2025), the presence of these extractives significantly reduces MOR performance, whereas higher treatment temperatures facilitate their removal, thereby enhancing fibre–matrix compatibility.

Similar findings were reported by Pinto et al. (2025), who explained that fibre modifications involving lignin removal roughen the fibre surface and enlarge the superficial area, thus improving fibre–matrix contact and enhancing mechanical strength. Furthermore, the mechanical properties of

fibre cement board are closely tied to the intrinsic strength of the fibre itself, particularly its cellulose content, which contributes to higher tensile capacity. Balagopal et al. (2022) also emphasised that fibre characteristics, including type, length, diameter, strength, stiffness, and volume fraction, play critical roles in determining composite performance. Similar relationships between fibre tensile strength and bending strength of composites have been documented by Kurpińska et al. (2022).

For example, cotton fibre, with its relatively low tensile strength, produced the weakest cement composites, while Ramie fibre, known for its high tensile strength, resulted in superior bending strength. Weak fibre tensile strength reduces bonding efficiency with the cement matrix, making composites prone to rupture. Conversely, stronger fibres enhance the fibre–matrix bond, improving structural integrity and resistance to failure. In conclusion, these findings demonstrate that increasing the tensile strength of OPEFB fibres through higher hot water treatment temperatures directly enhances the mechanical performance of fibre cement board. Among all treatments, fibre cement boards treated at 100°C achieved the highest MOR value, confirming the superior effectiveness of this treatment condition.

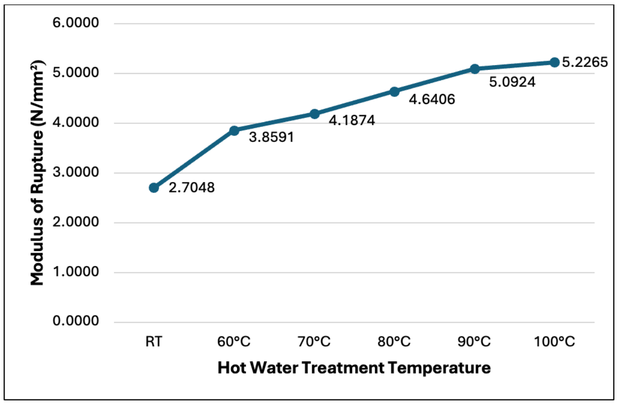

FIGURE 5. Modulus of rupture based on different temperatures of hot water treatment

MODULUS OF ELASTICITY

The modulus of elasticity (MOE) indicates the stiffness of the fibre cement boards, where higher MOE values reflect greater rigidity and compatibility with the cement matrix. As presented in Figure 6, a clear increasing trend was observed, with MOE rising from 2467.50 N/mm² (RT) to 2641.00 N/mm² (60°C), 2934.83 N/mm² (70°C), 3408.83 N/mm² (80°C), 3715.33 N/mm² (90°C), and reaching a maximum of 4180.50 N/mm² at 100°C. As expected, the untreated sample recorded the lowest stiffness, while fibre cement boards treated at higher temperatures exhibited superior MOE values, confirming the influence of hot water treatment on fibre compatibility. These findings are consistent with previous research, where MOE increased progressively from untreated to hot water-treated composites (Budiman et al. 2021; Hartono et al. 2018; Azmi et al. 2024).

Notably, the maximum MOE obtained in this study (4180.50 N/mm² at 100°C, 60 minutes) was higher than those reported by Budiman et al. (2021), which ranged from 2337.42 to 3509.41 N/mm² under similar treatment conditions. This discrepancy may be attributed to differences in fibre type and processing parameters. The most significant increase occurred between 70°C and 80°C, where MOE rose by 474.00 N/mm², suggesting a critical temperature range for improving fibre stiffness. The improvement in stiffness with increasing treatment temperature can be explained by enhanced fibre–cement bonding. Hydrophilic substances on untreated fibres hinder adhesion, while their removal through hot water treatment facilitates stronger interfacial bonding.

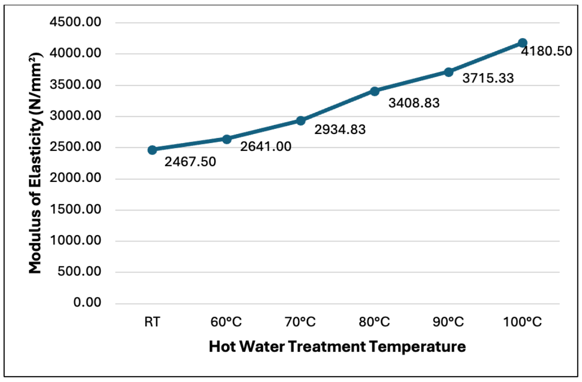

FIGURE 6. Modulus of elasticity based on different temperatures of hot water treatment

Omoniyi (2019) attributed this effect to changes in the degree of polymerisation, extraction of lignin and hemicellulose, and structural modification of the cellulosic fibrils. Increased molecular orientation and reduced spiral angle of fibres further contributed to improved fibre–matrix interaction. This explanation is consistent with previous findings, where soluble substances (Yel et al. 2020), residual oil (Awang et al. 2023), and morphological impurities (Maynet et al. 2021) in untreated fibres were shown to hinder cement hydration, reduce wettability, and disrupt fibre–cement bonding, respectively. Szafraniec et al. (2022) added that cellulose hydroxyl groups, when uniformly distributed in the cement matrix, enhance stiffness by strengthening interfacial bonding. Collectively, these findings confirm that hot water treatment at 100°C produced the highest MOE, indicating maximum stiffness and the best overall performance of OPEFB fibre cement board.

INTERNAL BONDING

Internal bonding (IB) strength provides insight into the fibre–matrix bonding quality of the boards. The findings presented in Figure 7 indicate a clear linear increase in IB strength with rising treatment temperature. Specifically, IB values improved from 0.2633 N/mm² (RT) to 0.4981 N/mm² (60°C), 0.6980 N/mm² (70°C), 0.8032 N/mm² (80°C), 1.0990 N/mm² (90°C), and 1.2220 N/mm² (100°C). These results are consistent with earlier studies by Budiman et al. (2021) and Ismail et al. (2025), which also reported higher IB values in composites subjected to hot water treatment compared to untreated samples. The IB trend aligns with the improvements observed in MOE and MOR, reinforcing the positive effect of hot water treatment on fibre–cement bonding. The increase in IB strength can be explained by the fibre's ability to bridge cracks during the pullout process, which enhances tensile strength and contributes to the composite's toughness (Li et al. 2025).

At lower bonding quality, fibre–matrix debonding occurs prematurely, allowing cracks to propagate (Lin et al. 2023). Conversely, stronger fibre–matrix adhesion enables effective stress transfer from the matrix to the fibres, thereby improving mechanical performance. This improvement is largely associated with fibre surface modification, which strengthens the fibres and enhances bonding. Impurities naturally present in untreated fibres are gradually removed as the hot water temperature increases. This process also produces rougher fibre surfaces, both of which contribute to improved adhesion between fibre and cement. Previous studies consistently highlight the limitations of untreated fibres in composite applications. Residual impurities and high extractive content have been shown to weaken interfacial bonding and reduce compatibility (Peter et al. 2020; Hasan et al. 2021).

Similarly, poor fibre–matrix interaction in untreated fibres leads to insufficient load-bearing capacity, whereas chemically or thermally treated fibres demonstrate stronger bonding (Jamadi et al. 2021). Surface characteristics also play a crucial role, with rougher fibre surfaces providing greater anchorage for mechanical interlocking (Camargo et al. 2020), while hydroxyl-rich fibres disrupt adhesion and hinder effective stress transfer during processing (Rocha et al. 2022). Overall, hot water treatment at 100°C was the most effective, producing fibres with improved surface characteristics and reduced impurities, thereby maximising fibre–matrix compatibility and yielding the highest IB strength in OPEFB fibre cement board.

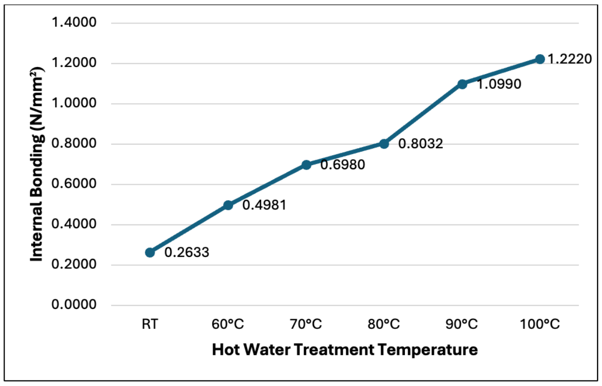

FIGURE 7. Internal bonding based on different temperatures of hot water treatment

Despite the promising improvements observed, this study was performed under laboratory-scale conditions using a fixed hot water treatment duration of 60 minutes, with performance assessment limited to short-term physical and mechanical properties of OPEFB fibre cement boards. As such, long-term durability, ageing effects, and variability associated with large-scale manufacturing were not investigated and warrant further examination in future work. The findings clearly indicate that hot water treatment at 100 °C yields the optimum enhancement in both physical and mechanical performance. Nevertheless, the substantial improvements observed at treatment temperatures between 70 °C and 90 °C suggest a degree of flexibility for potential industrial application, particularly where considerations of energy efficiency and processing constraints are relevant. Furthermore, the simplicity and solvent-free nature of the hot water treatment process highlight its practical feasibility for integration into existing fibre cement board production systems.

CONCLUSION

This study examined the influence of hot water treatment at different temperatures on the physical and mechanical properties of OPEFB fibre cement boards, with particular emphasis on a wider range of treatment temperatures, including intermediate conditions. The findings show that fibre treatment improved dimensional stability and bonding performance, with hot water treatment at 100°C producing the best overall mechanical and physical performance. However, treatments at 70°C to 90°C also achieved substantial improvements, indicating that effective fibre modification can be realised at temperatures lower than boiling. This addresses the research gap between earlier studies conducted only at 60°C and 100°C and demonstrates a more sustainable and cost-efficient treatment route.

Using a 60 minute treatment duration, supported by earlier research, further enhanced fibre–matrix compatibility by reducing hydroxyl groups and improving adhesion. The treated composites exhibited superior stability and performance as the temperature of hot water increased, confirming the significant role of fibre modification in cement board production. Overall, hot water-treated OPEFB fibres are shown to be a practical, renewable, and eco-friendly reinforcement for cement composites, suitable for construction applications, with hot water treatment at 100°C recommended for optimum performance. Future work should focus on durability under service conditions and industrial-scale implementation.

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DECLARATION OF COMPETING INTEREST

None.

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