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Research Article

Experimental investigation prosthetic socket reinforced with fumigated king pineapple rob x fiber and microcrystalline cellulose tested with ISO 10328 and finite element analysis

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Abstract

This study aimed to investigate the mechanical properties of prosthetic sockets reinforced with fumigated King Pineapple Rob X (KPRF) fibers and microcrystalline cellulose (MCC). The KPRF fibers were extracted from King Pineapple Rob X leaves using a manual retting method and subsequently subjected to fumigation treatments in a chimney for 0, 5, 10, and 15 hours, utilizing coconut fibers and shells as the combustion source. The composite prosthetic sockets were fabricated using an unsaturated polyester (UPR) matrix reinforced with the treated fibers and MCC. To ensure a homogenous distribution, the matrix and MCC were blended using a magnetic stirrer at 250 rpm and 40°C for 30 minutes. Post-fabrication, the composites were oven-dried at 60°C for 6 hours prior to specimen preparation. The analytical results from X-ray Diffraction (XRD) and Thermogravimetric Analysis (TGA) revealed an increase in the crystallinity index and enhanced thermal stability of the fibers following treatment. Scanning Electron Microscopy (SEM) observations confirmed that fumigation effectively purified the fiber surfaces by removing non-cellulosic impurities. Mechanical testing indicated that the FM 10 (10-hour fumigation) variant achieved the highest tensile strength, while the untreated (UT) specimens exhibited the lowest performance. Furthermore, water absorption tests demonstrated that untreated fibers had the highest moisture uptake, whereas fumigated fibers showed improved hydrophobicity. Structural evaluation according to ISO 10328 standards yielded a peak compressive strength of 38,866.60 N for the 10-hour fumigation group. Finally, Finite Element Analysis (FEA) validated the structural integrity of the socket, confirming its suitability for physiological patient loading.

1. Introduction

The King Pineapple Rob X is a tropical Indonesian plant that thrives in the coastal regions of Java, Sulawesi, Sumatra, and Yogyakarta. King Pineapple Rob X Fiber (KPRF) is typically harvested from seven-month-old plants with a leaf length of approximately 60 cm. The fibers are obtained through manual extraction from agave leaves, a process traditionally conducted by farmers in the Kulon Progo region of Yogyakarta Indonesia [1].

Recently, natural fiber-reinforced composites have gained widespread application due to several inherent advantages, including low production costs, abundant availability, sustainability, renewability, and promising mechanical properties. However, natural fibers also possess certain limitations as composite reinforcements, primarily stemming from their hydrophilic nature. This

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characteristic leads to high water absorption and poor interfacial compatibility with hydrophobic polymer matrices [2].

Various treatment models have been developed to enhance the interfacial bonding properties of natural fibers with polymer matrices, including permanganate [3], silane [4], alkali [5], and hot alkali [6] treatments, among others. The fiber fumigation process involves the combustion of coconut shells and husks to generate smoke. During this procedure, the fiber is isolated in a container away from the direct flame, as the treatment relies solely on smoke exposure. Fumigation is employed to reduce or eliminate surface impurities, resulting in a cleaner fiber morphology. This degradation process has been observed to reduce the cross-sectional area of the fibers, as seen in sago fibers. Furthermore, liquid smoke treatment on sago fiber has been reported to increase the crystallinity index after a five-hour exposure period [7]. Fumigation is employed to reduce or eliminate surface impurities, resulting in a cleaner fiber morphology. This degradation process has been observed to reduce the fiber cross-sectional area, a phenomenon previously documented in King Pineapple fibers. [8]

The results of X-ray Diffraction (XRD) analysis confirm that the smoking treatment effectively removes lignin and reduces hemicellulose content. As a consequence of fumigation, there is a measurable reduction in both moisture and carbonyl content within the fiber [9]. The smoking process also leads to a reduced contact angle, increased surface area, and enhanced surface roughness due to the loss of hemicellulose, lignin, and pectin [10]. Corroborating this, research suggests that increased surface roughness enhances wetting properties and governs liquid dispersion across the surface [11]. While fumigation treatment results in a decreased fiber diameter, this reduction in size does not significantly influence the observed contact angle [12].

A wide variety of composites are reinforced with natural fibers, such as King Pineapple Rob X (KPRF) [13], kenaf, coir, and hemp [14]. These fiber-reinforced composites are extensively utilized across various sectors, including sports equipment, transportation, construction, and the housing industry [15]. Recently, the development of prosthetic sockets has increasingly incorporated natural fibers such as banana, hemp, and coir as primary reinforcements [16]. Research indicates that natural fiber-reinforced prosthetic sockets exhibit tensile and compressive strengths comparable to those reinforced with synthetic fibers [17]. The primary advantages of utilizing natural fiber reinforcement in prosthetics include their lightweight nature, non-toxicity, abundant availability, and cost-effectiveness. Furthermore, certain studies suggest that the specific strength of natural fiber reinforcement can surpass that of glass fiber in prosthetic applications [18].

Prosthetic sockets reinforced with natural fibers were evaluated in accordance with ISO 10328 standards, following the methodology established in previous research [19]. The utilization of ISO 10328 is critical, as it provides a standardized benchmark for structural integrity in the absence of specialized strength testing protocols for composite sockets. Consequently, it is imperative to investigate the compressive performance of prosthetic sockets reinforced with fumigated King Pineapple Rob X fiber (KPRF) and microcrystalline cellulose (MCC). MCC offers distinct advantages by filling matrix voids and enhancing the overall load-bearing capacity of the composite [20]. The anticipated improvement in compressive strength is attributed to the fumigation treatment of KPRF, which results in a cleaner fiber surface and increased micro-roughness by removing impurities. Specifically, the fumigation process depletes hemicellulose, lignin, and pectin, thereby facilitating superior interfacial bonding strength between the fiber and the matrix. This chemical modification not only strengthens the bond but also enhances the inherent tensile strength of the fiber within the composite.

Furthermore, the integration of MCC serves as a structural filler that mitigates void formation, ultimately increasing both the tensile and compressive properties of the final material. The structural evaluation of prosthetic sockets via ISO 10328 testing and Finite Element Analysis (FEA) is fundamentally predicated on the empirical data derived from material characterization, specifically tensile strength, flexural strength, and the elastic modulus.

2. Materials and Methods

2.1. Material

Manually extracted King Pineapple Rob X (KPRF) fibers were sourced from CV Rami Kencana, Kulon Progo, Yogyakarta, Indonesia. Upon acquisition, the KPRF fibers were ambient-dried at room temperature for three days. Microcrystalline cellulose (MCC), with a density of 1.56 g/cm^3 and a particle size of 20 µm, was procured from PT Sigma Aldrich, Jakarta Indonesia.

The matrix phase consisted of BQTN 157 series Yukalac unsaturated polyester, with methyl ethyl ketone peroxide (MEKP) utilized as the catalyst; both were obtained from PT Justus Kimia Raya, Semarang, Indonesia. Additionally, the coconut shells and fibers used for the fumigation process were sourced from local markets in Purwokerto, Central Java Indonesia.

2.2. Fiber Fumigated Method

The King Pineapple Rob X (KPRF) fibers underwent a fumigation process within a fumigation chamber measuring 800 mm x 800 mm x 1500 mm (L,W,H). The smoking procedure was performed by burning coconut shells and husks, with the fibers positioned at the top of the chamber. To ensure the treatment relied solely on smoke exposure rather than direct heat, a distance of 80 cm was maintained between the fiber specimens and the ignition source. The fumigation chamber features an integrated digital temperature controller for real-time thermal monitoring within the specimen zone. To ensure optimal adsorption of phenolic compounds while preventing thermal degradation of the cellulose, the internal temperature is strictly regulated between 40°C and 60°C through manual adjustment of the ignition source intensity.

Fig. 1. Fumigation chamber

2.3. X-ray diffraction

X-ray diffraction testing of King Pineapple Rob X fiber was conducted at the Integrated Laboratory of Diponegoro University, Semarang. The X-ray diffraction testing process used CuKα radiation, or n = 1.54 A. The applied voltage during the test was 30 kV and a current of 30 mA, and the radiation intensity was recorded at 2 theta = 100 in two theta stages.

The crystallinity index (Cr.I) and degree of crystallinity (%) are calculated using the Segal method as shown in the following equation:

$$Cr.I = \frac{Ioo2 - Iam}{I_{002}} x\ 100\ \% \qquad (1)$$

The peak intensity of the sample is based on the Miller (002) index, with a range of 22-23 degrees at a 2-theta angle. The intensity of the nanocrystalline content is at a peak angle of 2-theta = 18 degrees.

2.4. Thermogravimetric Analysis

Thermogravimetric analysis (TGA) was performed to evaluate the thermal stability of fumigated and untreated King Pineapple Rob X (KPRF) fibers. Specimens (approximately 5–10 mg) were heated from 30°C to 600°C at a constant rate of 10°C/min under a nitrogen atmosphere to prevent oxidative degradation. The measurements were conducted using a PerkinElmer Diamond TG/DTA instrument at the Laboratory of Mathematics and Natural Sciences, Sebelas Maret University, Indonesia. To ensure reproducibility, all measurements were performed in quintuplicate, and the mean values were reported.

2.5. Composite Fabrication

The composite fabrication process was initiated by preparing King Pineapple Rob X (KPRF) fibers, which were chopped to a uniform length of 10 mm and randomly distributed within the mold cavity. The composite constituents were formulated at a weight fraction of 30 wt% KPRF, 5 wt% MCC, and 65 wt% unsaturated polyester (UP) matrix. To achieve a high degree of dispersion, the MCC and UP resin were blended via magnetic stirring at 250 rpm and 40°C for 30 minutes [21]. Subsequently, 1 wt% methyl ethyl ketone peroxide (MEKP) was incorporated as a catalyst. The catalyzed resin was then injected into the fiber-loaded mold using a vacuum infusion system to ensure minimal porosity. Following the infusion, the composites were thermally cured at 60°C for 120 minutes. Finally, the cured samples were precision-machined into specific geometries in accordance with the required testing standards for further characterization.

2.6. Scanning Electron Microscopy

Morphological analysis of both fumigated and non-fumigated King Pineapple Rob X (KPRF) fibers was conducted at the Diponegoro University Laboratory in Semarang, Indonesia. The fiber specimens were mounted on platinum-coated aluminum stubs and observed under a pressure of 2 bar for a duration of 2 minutes. The surface morphology was characterized using a JEOL JSM-6510LV scanning electron microscope (SEM).

2.7. Tensile and Flexural Strength

The mechanical properties, specifically tensile and flexural strengths, were evaluated using a Universal Testing Machine (UTM) at Sebelas Maret University, Surakarta, Indonesia. Tensile characterization was conducted in accordance with the ASTM D638-03 standard, while flexural strength was measured following the ASTM D790-03 protocol. Tensile and flexural tests were performed in quintuplicate for each composite configuration to ensure statistical reliability. The results were recorded as the arithmetic mean of the five replicates, with standard deviations calculated to represent data dispersion.

2.8. Prosthetic Molding

The fabrication of the prosthetic socket commenced with the preparation of the matrix, where microcrystalline cellulose (MCC) was blended with the polymer matrix using a magnetic stirrer at 250 rpm and 40°C for 30 minutes. Simultaneously, the molding setup was prepared by placing 10 mm chopped King Pineapple Rob X (KPRF) fibers into a negative socket mold previously lined with Astralon plastic for ease of release. Following the addition of the catalyst to the MCC-matrix mixture, the prosthetic socket was fabricated using a vacuum infusion system. Once the infusion process was complete, the molded socket underwent a thermal curing stage in an oven at 60°C for 3 hours to ensure optimal polymerization.

2.9. Prosthetic Socket Testing

A maximum compression test was performed on the prosthetic socket to evaluate its ultimate load-bearing capacity until structural failure or catastrophic damage occurred. The evaluation was conducted using a GOTECH GT-7001-LC10 Universal Testing Machine (UTM) at Wahid Hasyim University, Semarang Indonesia. The testing procedure was strictly governed by the ISO 10328 standard to ensure international compliance for prosthetic structural integrity.

2.10. Finite Element Analysis (FEA)

Finite Element Analysis (FEA) simulations were conducted based on the characterization results of two specific composite variants: FM 10 and UT, representing the optimal and suboptimal mechanical properties, respectively. The input parameters for the computational models were derived from empirical data, including tensile strength, flexural strength, density, and elastic modulus. These variants were selected to establish a performance range, allowing for a comparative structural evaluation of the prosthetic socket under "best-case" and "worst-case" material scenarios.

3. Results and Discussion

3.1. X – Ray Diffraction Testing

Smart building spaces are enclosed, and satellite signals are difficult to penetrate, relying on PDR The Segal method was employed to determine the crystallinity index derived from the X-ray diffraction (XRD) profiles. The XRD patterns for both the fumigated (smoked) and untreated King Pineapple Rob X (KPRF) fibers were analyzed using OriginPro 2023b software, as illustrated in Figure 1.

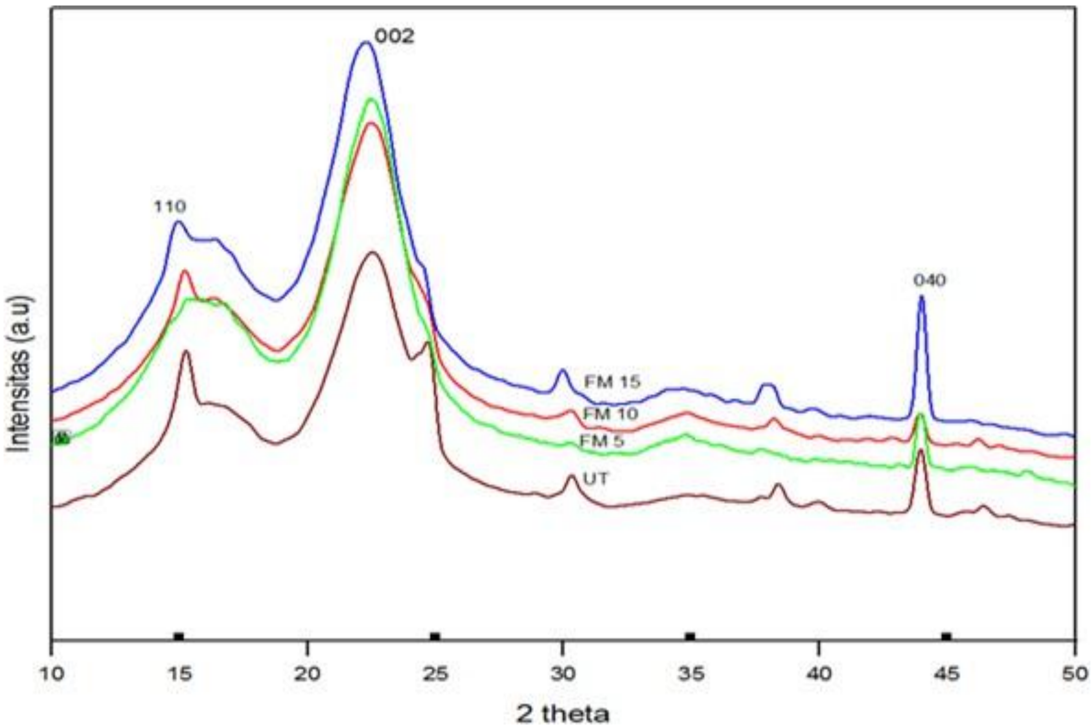


Fig. 2. X-Ray Diffraction test results

Figure 1 illustration the X-ray diffraction (XRD) patterns, revealing the structural characteristics of both untreated and fumigated (smoked) King Pineapple Rob x fibers. The diffraction profiles exhibit three prominent peaks, located at approximately 15o, 22.12o, and 44o. The specific diffraction peak within the 22o – 23o range signifies the cellulose structure, which is a characteristic feature of native cellulose (Cellulose I) [22]. Detailed numerical data derived from the XRD analysis are summarized in Table 1.

Table 1. X-Ray Diffraction test results

Treatment	Code	$I_{(002)}$		$I_{(am)}$		Crystallinity Index
		2θ (°)	Intensity	2θ	Intensity	
Untreatment	UT	22,32	1162	18,88	470	59,55%
Fumigated 5h	FM 5	22,56	1734	18,40	648	62,62%
Fumigated 10h	FM 10	22,36	1562	18,80	572	63,52%
Fumigated 15h	FM 15	22,22	1748	18,60	668	61,78%

The King Pineapple Rob X (KPRF) fiber exhibited a notable increase in its crystallinity index following the fumigation process, rising from 59.55% to 63.52% (FM10). This enhancement in crystallinity is attributed to the thermal and chemical effects of the fumigation treatment, which facilitate the degradation of the amorphous regions within the fiber and promote the rearrangement of its crystalline structure [23]. Furthermore, the degradation of non-crystalline components resulted in a reduction of the fiber's cross-sectional area. A similar phenomenon has been observed in liquid-smoked sago fibers, which demonstrated a significant increase in crystallinity after a 5-hour treatment period [24].

The enhancement in crystallinity during the thermal treatment of graphitized carbon derived from coconut smoke is primarily attributed to the elimination of impurities entrapped during the smoking process [25]. Conversely, a decrease in the crystallinity index was observed after 15 hours of fumigation. This decline is likely due to prolonged exposure to excessive temperatures, which may induce structural degradation of the crystalline regions.

3.2. Scanning Electron Microscope Test Results

SEM observations were conducted using a JEOL JEC-3000FC field emission sputter coater/analyzer system, operated at an accelerating voltage of 20 kV with a magnification of 450x. The images were captured with an acquisition time of 50 seconds during the characterization of the fumigated (smoked) specimens, the results of which are presented in Figure 3.

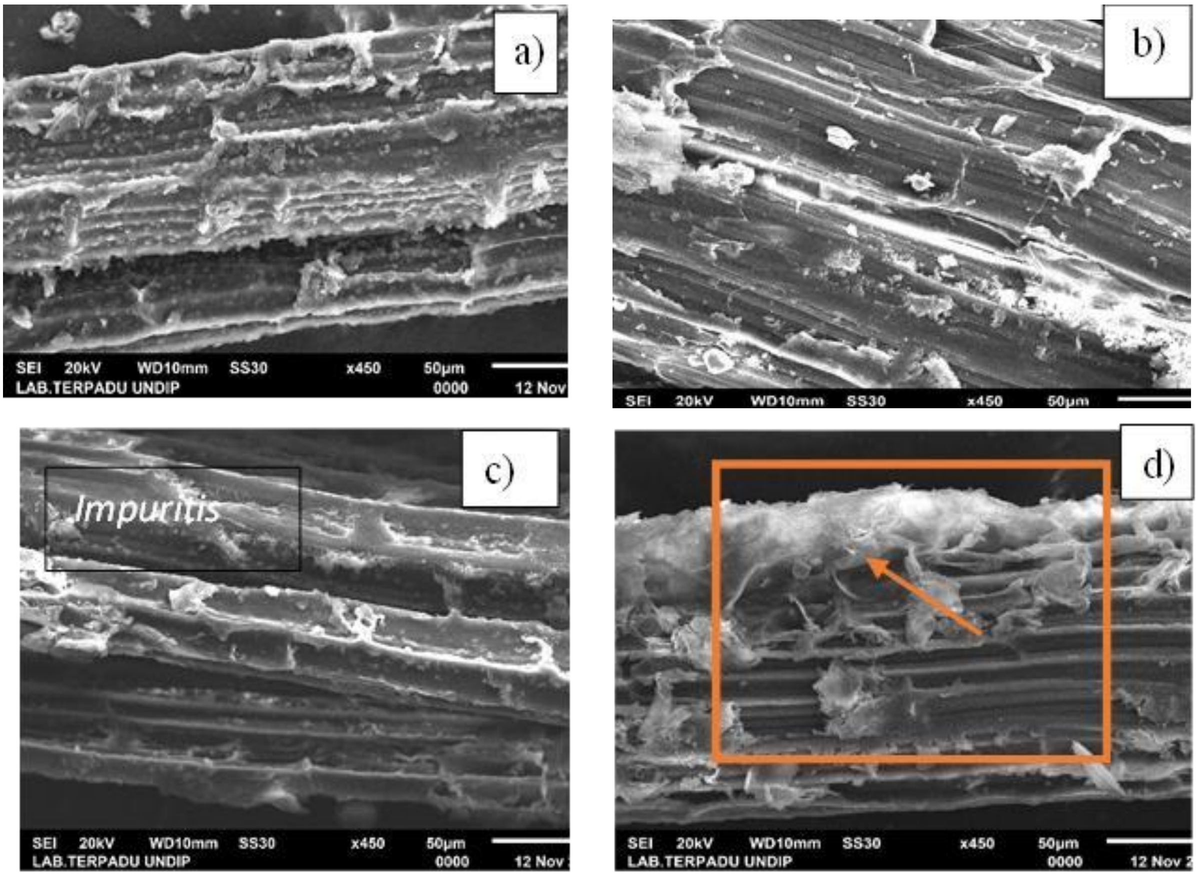


Fig. 3. SEM King Pineapple Rob X fiber fumigation treatment and untreatment

The SEM micrographs are presented in Figure 3. Figure 3(a) illustrates the untreated King Pineapple Rob X (KPRF) fiber, which remains encapsulated by non-cellulosic components such as lignin, pectin, and hemicellulose. The network and fibril structures appear tightly bound, with the UT (untreated) fibers exhibiting a characteristic smooth and regular rectangular surface pattern. The fibers subjected to 5 hours of fumigation (Figure 3b) and 10 hours of fumigation (Figure 3c) show a progressive transition toward surface roughness. As shown in Figure 3(b), the 5-hour treatment results in a cleaner surface, although some residual impurities persist. In contrast, the 10-hour fumigation (Figure 3c) reveals significantly cleaner rectangular grooves with a distinctly rough and porous morphology. This textured surface is expected to facilitate mechanical interlocking between the fiber and the matrix, thereby enhancing the interfacial bonding [26]. The

10-hour treatment proved most effective in purifying the fibers as the cementing materials (lignin and hemicellulose) began to degrade and dissipate.

The fumigation treatment significantly impacts the fiber by reducing moisture content and increasing density [27]. Similar to the thermal treatment of kenaf fibers, the fumigation process purifies the surface through the removal of impurities such as wax and hemicellulose [28]. In Cantula fibers, the degradation of hemicellulose, lignin, and pectin during fumigation results in a rough surface topography, which facilitates superior mechanical adhesion between the matrix and the fiber surfaces. However, the 15-hour fumigation treatment (as shown in Figure 3d) indicates the re-emergence of impurities or surface residues. Prolonged exposure to fumigation may lead to fiber contamination and a subsequent reduction in mechanical strength. This degradation in performance is attributed to a weakened interfacial bond between the fiber and the matrix.

3.3. TGA (Thermogravimetric Analysis) Test Results

The thermogravimetric analysis (TGA) and derivative thermogravimetric (DTG) curves for both untreated and fumigated (smoked) King Pineapple Rob X fibers are presented. The thermal decomposition behavior and characteristic temperatures were analyzed using OriginPro 2023b software, as illustrated in Figure 4.

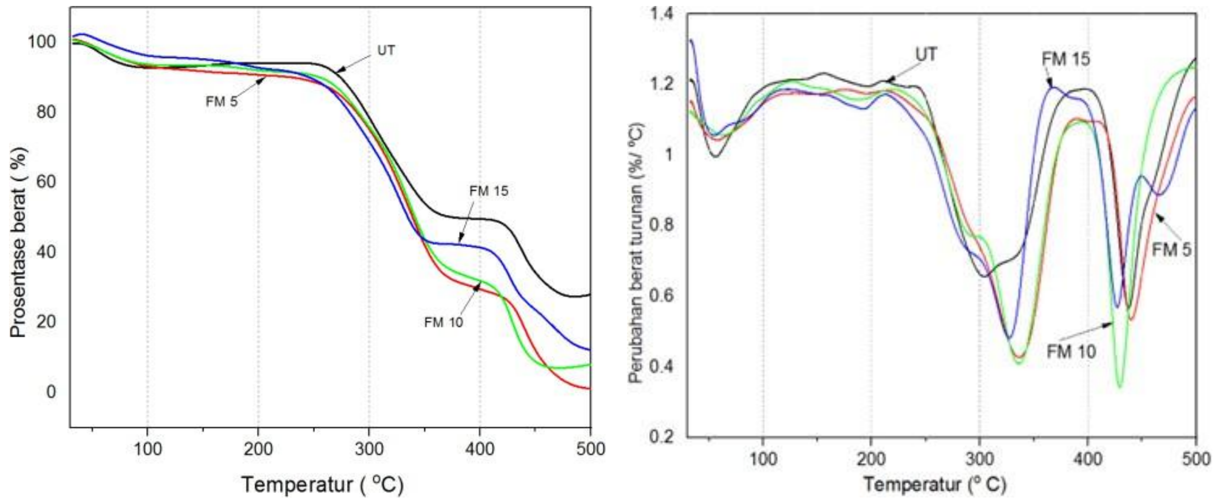


Fig. 4. Thermogravimetry Analysis (TGA) dan DTGA

The untreated (UT) fiber exhibited a weight loss of 7.31% at temperatures below 100°C. This initial mass reduction, observed between 20°C and 100°C, is attributed to the evaporation of absorbed moisture, as previously described by Gomes [29]. In comparison, the fumigated specimens showed lower initial weight loss during this desorption stage. The FM 5 (5-hour treatment) recorded a weight loss of 6.42%, while the FM 10 (10-hour treatment) showed a reduction of 5.83%. The lowest moisture desorption was observed in the FM 15 treatment, with a weight loss of only 5.12%.

This desorption stage is primarily associated with the evaporation of moisture from the fiber surface. Previous studies by Islam reported an 8% moisture evaporation for hemp fibers observed between 25°C and 150°C [30], while other thermogravimetric data recorded a 12% moisture loss for bamboo pulp. In this study, the fumigated fibers exhibited lower desorption compared to the untreated specimens. Furthermore, the onset temperature for moisture desorption in untreated fibers was lower than that of the treated fibers.

The second stage of decomposition for the untreated (UT) fiber commenced at 258.4°C (at 95.12% weight), with a continuous mass reduction until 385.1°C (at 49.51% weight). Consequently, the weight loss during the first major decomposition phase for the untreated fiber was 45.61%. This value is lower than previously reported findings for untreated Cantula fiber at the same temperature, which reached 56.9%.

For the fumigated specimens, the decomposition of FM 10 occurred at 267.3°C, while FM 15 began at 263.22°C. These higher decomposition temperatures are closely linked to the enhanced thermal stability of the fibers, indicating that fumigation improves the thermal properties relative to untreated fibers. The degradation observed between 200°C and 380°C is widely associated with the thermal breakdown of hemicellulose and lignin [31].

3.3. Tensile and Flexural Streng Composites

The characterization results for the composite reinforced with fumigated King Pineapple Rob X (KPRF) fibers are summarized in Table 2.

Table 2. Tensile and Flexural Strength

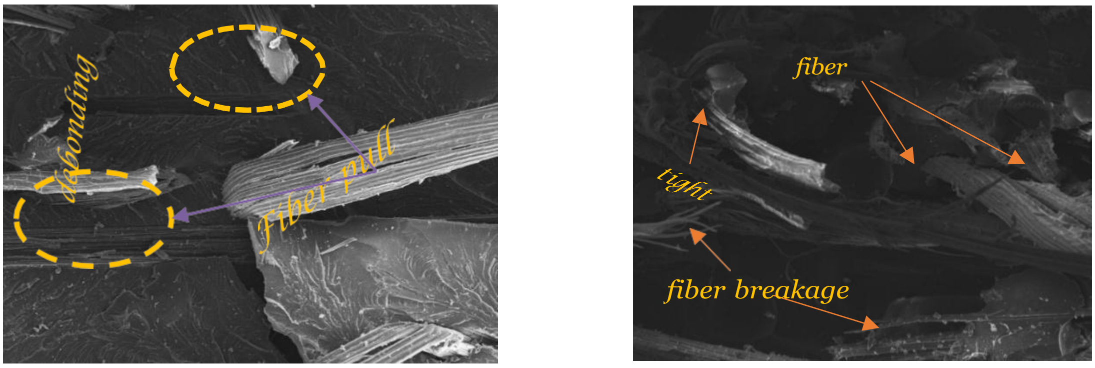
Nu.	Treatment	Tensile Strength (MPa)	Modulus of elasticity (MPa)	Flexural Strength (MPa)	Modulus of elasticity (MPa)
1	UT	63.65	1380.22	67.92	1878.93
2	FM 5	64.75	1572.32	76.23	2388.98
3	FM 10	70.67	1963.28	89.43	2525.78
4	FM 15	67.78	1928.72	78.14	2252.98

Table 2 presents the results of the tensile and flexural strength evaluations for both fumigated and untreated fiber composites. The data indicate a significant enhancement in both tensile and flexural properties following the fumigation treatment. This improvement in mechanical strength is attributed to the purification of the King Pineapple Rob X (KPRF) fiber surfaces and the subsequent strengthening of the interfacial bonding between the fiber and the matrix. The removal of hemicellulose and other non-cellulosic impurities resulted in a rougher fiber topography, which is beneficial for mechanical interlocking. Furthermore, the acetic acid content derived from the coconut shells facilitates the breakdown of hemicellulose, lignin, and pectin chains [30]. The fumigation process also reduces the moisture content through evaporation and induces the formation of micro-pores. These pores can be infiltrated by the matrix, leading to superior interfacial adhesion and increased composite structural integrity [32].

The incorporation of Microcrystalline Cellulose (MCC) into the composite enhances interfacial compatibility, which contributes to improvements in tensile, flexural, and impact strengths, as well as thermal stability [33]. However, the tensile and flexural strengths exhibited a declining trend when the fumigation duration was extended to 15 hours. The findings indicate that while fumigation treatment generally enhances the flexural strength of the composite—largely due to the synergistic effect of MCC addition—this strength is time-dependent. Furthermore, the elastic modulus increased proportionally, following a similar trend to the flexural strength, which is consistent with previous characterizations of Agave sisalana fibers [34].

3.5. Microscopic Observation of Cantula Fiber Reinforced Composites and MCC

Microscopic characterization was performed on composites reinforced with both untreated and fumigated King Pineapple Rob X fibers. Specifically, the fracture surfaces resulting from tensile testing were examined using Scanning Electron Microscopy (SEM) to analyze the failure mechanisms. The morphological observations for the composite reinforced with untreated KPRF and microcrystalline cellulose (MCC) are illustrated in Figure 5. Microscopic observations of the untreated (UT) King Pineapple Rob X (KPRF) fiber composites with MCC addition reveal a predominance of smooth fiber surfaces, fiber pull-out, and debonding at the fracture sites. Debonding, characterized by the detachment of fibers from the polymer matrix, indicates that the composite's mechanical integrity is compromised, as the failure occurs at the interface rather than through the reinforcement itself [35]. The high frequency of interface separation and debonding suggests that the fibers still retain significant amounts of hemicellulose, lignin, and pectin.



(a) (b)

Fig. 5. SEM observations (a) UT (b) FM 10

These residual non-cellulosic components maintain the fiber's hydrophilic nature, leading to poor interfacial adhesion with the hydrophobic matrix. Microscopic observations of the fracture surfaces of composites reinforced with fumigated fibers revealed a higher frequency of fiber breakage (fiber paths). Instances of strong interfacial bonding were more prevalent compared to the fiber pull-out and debonding observed in untreated specimens. This suggests a significantly enhanced adhesion between the fumigated King Pineapple Rob X (KPRF) fibers and the matrix. The improved bond strength is primarily attributed to the reduction of hemicellulose, lignin, pectin, and other non-cellulosic impurities. Thermal treatment via fumigation at elevated temperatures effectively purifies the fibers by degrading these amorphous components [36].

Furthermore, the integration of microcrystalline cellulose (MCC) serves to infill micro-voids and minimize the entrapment of air bubbles, resulting in a more homogenous and refined composite structure. A dense and smooth composite cross-section indicates robust intermolecular cross-linking, which contributes to the overall increase in mechanical strength. The addition of MCC, characterized by its high purity cellulose content, further bolsters the mechanical performance through improved interfacial compatibility between the polymer matrix and the cellulose particles.

3.6. Water Absorption in Composites with Fiber Treatment Fibers

Another critical factor influencing the structural stability of composites is water absorption. The rate of moisture uptake in composites is governed by several variables, including the presence of voids, fiber characteristics, fiber loading, matrix viscosity, and environmental conditions. To evaluate this property, water absorption tests were conducted by immersing the specimens for 30 days in aqueous solutions with a pH range of 0.5 to 7. The experimental results of the water absorption analysis are illustrated in Figure 6.

The experimental results presented in Figure 5 illustrate the moisture absorption profiles of the specimens. The pure matrix exhibited the lowest water absorption, whereas the composite reinforced with untreated KPRF showed the highest absorption rate. The minimal water uptake observed in the UPR and UPR-MCC samples is attributed to the uniform microstructural distribution and the inherently hydrophobic nature of the resin components.

The data indicate that water penetrates the composite following a linear pattern during the first week, with the rate of diffusion beginning to decelerate by the third week of immersion. Sorption equilibrium was reached between 28 and 30 days. For all analyzed samples, the initial phase of the water absorption process followed a linear trend before slowing down and eventually approaching saturation after prolonged immersion. This behavior is consistent with the Fickian diffusion model [37], which is characterized by a rapid initial moisture uptake followed by a saturation plateau in the subsequent stage. The moisture absorption rate of the fiber-reinforced composites is observed to increase in correlation with the duration of the fumigation treatment. Thermogravimetric Analysis (TGA) validated the reduction of inherent moisture within the fibers post-treatment, as evidenced by the lower desorption rates in fumigated specimens. Paradoxically, this lower initial water content in the fibers correlates with a specific trend in the overall composite absorption capacity. The water absorption behavior is significantly influenced by the thermal history of the fibers; as confirmed by the desorption data, the heat treatment process modifies the fiber's capacity for subsequent moisture uptake [38].

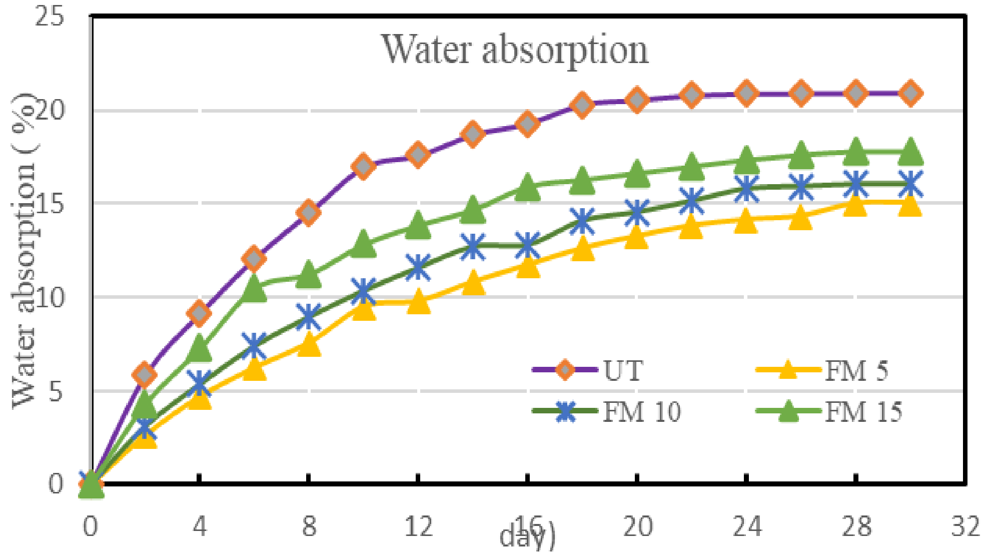


Fig. 6. Water absorption

3.8. Prosthetic Socket Testing

The maximum compressive strength test was conducted on the prosthetic sockets to determine the ultimate load-bearing capacity before the onset of structural failure or catastrophic damage. Both the untreated (UT) fiber-reinforced sockets and those subjected to 10 hours of treatment were evaluated. The compressive test setup and the resulting deformation behavior for the untreated specimens are illustrated in Figure 6.

(a) (b)

Fig. 7. Prosthetic socket (a) UT (b) FM 10

The compressive test results for the untreated (UT) fiber-reinforced prosthetic socket reached 24,650.56 N, significantly higher than the 16,621 N recorded for water hyacinth fiber-reinforced sockets at a 0o orientation. For further comparison, Campbell's prosthetic socket reinforced with ramie stockinette exhibited a maximum load of only 6,180 N, which led to failure at the socket adapter [39]. These results far exceed the structural qualification criteria established by ISO 10328, which specifies threshold values of 3,421 N for ductile failure and 4,426 N for brittle failure. The prosthetic socket reinforced with 10-hour fumigated (FM10) fibers and microcrystalline cellulose (MCC) is illustrated in Figure 7(b).

This specific configuration yielded a peak compressive strength of 38,866.6 N, surpassing the performance of the untreated (UT) fiber sockets. This substantial enhancement in compressive capacity aligns with the composite coupon test results. The superior performance is attributed to the purified state of the fumigated fibers, resulting from the removal of non-cellulosic impurities such as hemicellulose, pectin, and lignin. Furthermore, the fumigation process induces a rougher surface topography and improves individual fiber tensile strength, thereby strengthening the interfacial bonding within the composite. The inclusion of MCC further optimizes the structure by infilling voids and fostering a more robust matrix-filler interaction.

The compression test results, which reached 38,866.6 N for the FM10+MCC variant, directly correlate with the increased tensile strength following the fumigation process. This enhanced fiber surface roughness improves mechanical interlocking with the matrix, effectively preventing delamination failure when the socket is subjected to high axial loads. Furthermore, the addition of Microcrystalline Cellulose (MCC) serves as a filler that minimizes voids, thereby increasing the elastic modulus of the composite. Additionally, the lower water absorption observed in the fumigated fibers contributes to long-term structural integrity. This reduced water uptake ensures that the interfacial bond between the fiber and the matrix remains stable and resistant to hydrolytic degradation, maintaining consistent compression strength for the prosthetic socket even in humid environments.

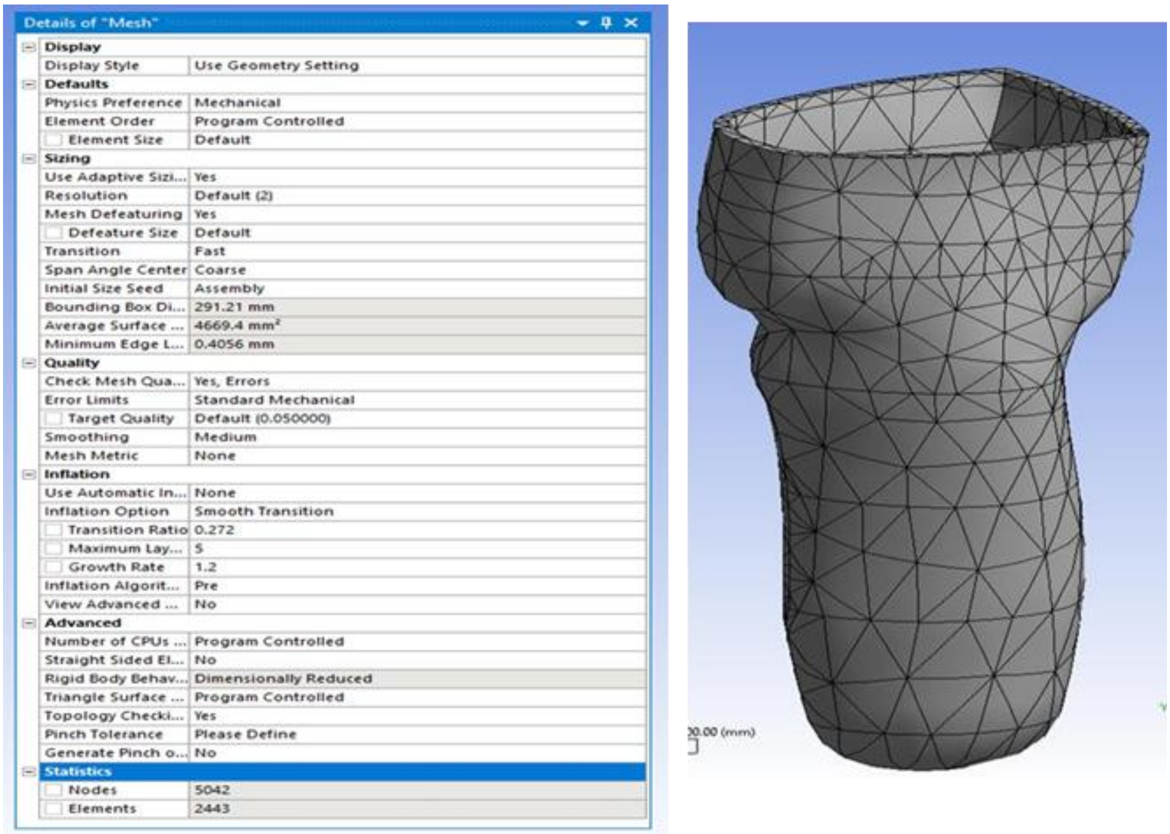
3.9. Finite Element Analysis (FEA)

Finite Element Analysis (FEA) was conducted to evaluate the stress distribution and structural integrity of the prosthetic socket under simulated loading conditions. The computational model was developed to validate the experimental compressive test results and to visualize the areas of maximum stress concentration. The numerical simulation was performed using ANSYS 2023 R2, where the socket was modeled as a composite structure with the mechanical properties derived from the experimental characterization of the FM10 – MCC reinforced material. Based on the experimental characterization of the composite's tensile strength, flexural strength, elastic modulus, and density, the input parameters for the Finite Element Analysis (FEA) were derived from the specimen exhibiting the highest mechanical performance. This approach ensures that the computational model accurately reflects the maximum structural potential of the optimized composite reinforcement.

Mesh sensitivity is critical for ensuring the numerical accuracy of the simulation results in this study. The prosthetic socket was discretized using hexagonal elements to provide superior convergence and computational stability. The results of the meshing process, including the specific distribution of nodes and elements, are illustrated in Figure 8.

The discretization process yielded a computational mesh consisting of a total of 5,042 nodes and 2,443 elements. The utilization of this specific mesh density ensures a balance between computational efficiency and the resolution required to accurately capture the stress distribution across the FM10-MCC reinforced prosthetic socket. Figure 9 is the result of a simulation to determine the maximum voltage on the socket.

Figure 9 illustrates the maximum stress distribution across a prosthetic socket reinforced with KPRF fibers fumigated for 10 hours and microcrystalline cellulose. The simulation shows a peak stress of 2.19 MPa, with the principal loading point (fulcrum) indicated by the arrowed line. The maximum strain recorded for the prosthetic socket treated with FM10 was 1.03 x 10-3 mm.



Details of "Mesh"	
Display	
Display Style	Use Geometry Setting
Defaults	
Physics Preference	Mechanical
Element Order	Program Controlled
Element Size	Default
Sizing	
Use Adaptive Sizi...	Yes
Resolution	Default (2)
Mesh Defeaturing	Yes
Defeature Size	Default
Transition	Fast
Span Angle Center	Coarse
Initial Size Seed	Assembly
Bounding Box Di...	291.21 mm
Average Surface ...	4669.4 mm²
Minimum Edge L...	0.4056 mm
Quality	
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Error Limits	Standard Mechanical
Target Quality	Default (0.050000)
Smoothing	Medium
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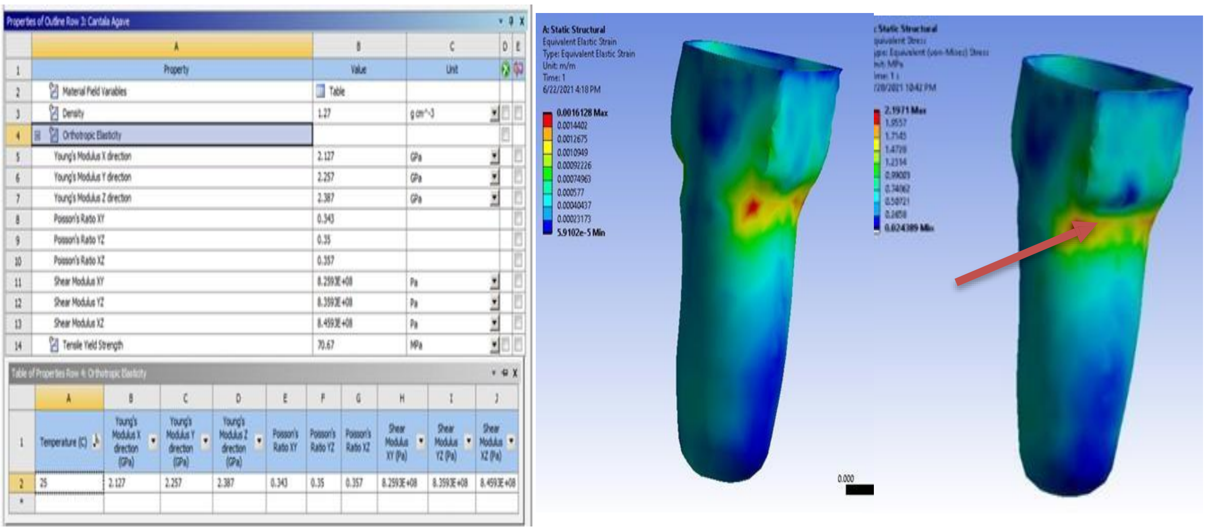
Inflation	
Use Automatic In...	None
Inflation Option	Smooth Transition
Transition Ratio	0.272
Maximum Lay...	5
Growth Rate	1.2
Inflation Algorit...	Pre
View Advanced ...	No
Advanced	
Number of CPUs ...	Program Controlled
Straight Sided El...	No
Rigid Body Behav...	Dimensionally Reduced
Triangle Surface ...	Program Controlled
Topology Checki...	Yes
Pinch Tolerance	Please Define
Generate Pinch o...	No
Statistics	
Nodes	5042
Elements	2443

Fig. 8. Results of meshing socket prosthesis FM 10-MCC



	A	B	C	D	E
1	Property	Value	Unit		
2	Material Field Variables	Table			
3	Density	1.27	g cm^-3		
4	Orthotropic Elasticity				
5	Young's Modulus X direction	2.127	GPa		
6	Young's Modulus Y direction	2.257	GPa		
7	Young's Modulus Z direction	2.387	GPa		
8	Poisson's Ratio XY	0.343			
9	Poisson's Ratio YZ	0.35			
10	Poisson's Ratio XZ	0.357			
11	Shear Modulus XY	8.2593E+08	Pa		
12	Shear Modulus YZ	8.3593E+08	Pa		
13	Shear Modulus XZ	8.4593E+08	Pa		
14	Tensile Yield Strength	70.67	MPa		

	A	B	C	D	E	F	G	H	I	J
1	Temperature (C)	Young's Modulus X direction (GPa)	Young's Modulus Y direction (GPa)	Young's Modulus Z direction (GPa)	Poisson's Ratio XY	Poisson's Ratio YZ	Poisson's Ratio XZ	Shear Modulus XY (Pa)	Shear Modulus YZ (Pa)	Shear Modulus XZ (Pa)
2	25	2.127	2.257	2.387	0.343	0.35	0.357	8.2593E+08	8.3593E+08	8.4593E+08

Fig. 9. Maximum voltage on the FM 10 socket, strain, and stress

4. Conclusion

The comprehensive investigation into the development of prosthetic sockets reinforced with King Pineapple Rob X (KPRF) fibers and microcrystalline cellulose (MCC) has yielded several significant findings regarding the potential of natural fiber composites in biomedical applications. Natural fibers utilized in this study offer distinct commercial and technical advantages, including low density, sustainability, cost-effectiveness, and lower solidity compared to conventional synthetic fibers. The research successfully demonstrates that the thermal and mechanical performance of these fibers can be substantially enhanced through a controlled fumigation treatment process. The characterization of the fibers revealed that fumigation treatment for 10 hours (FM 10) serves as an effective purification method. X-ray Diffraction (XRD) and Thermogravimetric Analysis (TGA) results confirmed a significant increase in the crystallinity index and enhanced thermal stability. This improvement is primarily attributed to the systematic degradation and removal of non-cellulosic constituents, specifically hemicellulose, lignin, and pectin, which are typically responsible for the hydrophilic nature and thermal instability of natural fibers. Scanning Electron Microscopy (SEM) further validated these findings, showing a cleaner and rougher fiber topography post-fumigation, which is essential for creating a robust mechanical interlock and a stronger interfacial bond between the fiber and the unsaturated polyester matrix. Furthermore, the synergy between fumigated KPRF and the incorporation of microcrystalline cellulose (MCC) was found to be a critical factor in the composite's superior mechanical properties. The MCC particles function as a secondary reinforcement that effectively seals micro-voids and reduces the entrapment of air bubbles within the matrix, thereby optimizing the structural homogeneity of the material. This resulted in a significant increase in both tensile and flexural strengths. Environmental durability was also improved, as evidenced by the water absorption tests, where the fumigated composites exhibited a marked decrease in moisture uptake compared to untreated specimens, indicating improved hydrophobicity. The structural reliability of the final prosthetic socket was rigorously evaluated according to the ISO 10328 standard. The FM 10 reinforced socket demonstrated an extraordinary peak compressive strength of 38,866.60 N, which far exceeds the minimum requirements for prosthetic structural integrity and outperforms previous studies involving other natural fibers. This experimental finding was further validated by Finite Element Analysis (FEA) using Ansys 2023 R2, which revealed a maximum stress of 2.19 MPa and a minimal strain of 1.03 x 10-3 mm. These computational results confirm that the stress distribution remains well within the material's elastic region, providing a high factor of safety. In conclusion, the combination of 10-hour fumigated King Pineapple Rob X fibers and MCC provides a high-performance, safe, and sustainable material solution for advanced prosthetic socket applications.

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