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Comparative Study on Creep, Hardness, and Density Properties of Materials for Transtibial Prosthetic Socket Fabrication

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Keywords:
Below-Knee socket; Biomaterials; Epoxy; Lower limb socket; Plant fibers.

Highlights:

- *Suggesting new hybrid composite materials for manufacturing lower-limb prosthetic sockets.*
- *Natural and synthetic reinforcements to create hybridized prosthetic sockets.*
- *Utilized Ansys 2022-R and the finite element method (FEM) to analyze the performance of prosthetic limbs.*

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Abstract: This study investigates the utilization of natural fibers as reinforcements in polymer composites to produce prosthetic sockets and provide an environmentally friendly alternative to existing technologies. The laminates were fabricated using a blend of woven bamboo fiber, ramie fiber, glass fiber, carbon fiber, ultra-high molecular weight polyethylene (UHMWPE) fiber, and Kevlar fiber. This study entailed performing some mechanical tests, such as hardness, creep, and density tests, to investigate the influence of alternative fiber stacking arrangements on certain mechanical and physical properties. The study analyzed the influence of fiber composition and stacking methods on the overall performance of the laminates, shedding light on their suitability for diverse applications. The most promising examples, consisting of four ramie layers and two carbon fiber layers, exhibited outstanding mechanical capabilities, with a hardness of 86 MPa and a 1.239 gm/cm³ density. In contrast, lamination (2 bamboo +2 UHMWPE + 2 bamboo) has the lowest density value at 1.157. The results highlight the possibility of combining natural and synthetic reinforcements in composite structures to improve overall performance. A deliberate blend of natural and synthetic bio-composite reinforcements is suggested to enhance mechanical performance, especially in prosthetic limb engineering and materials science.

دراسة مقارنة لخصائص الزحف والصلادة والكثافة لمواد تُستخدم في تصنيع مقبس الأطراف الصناعية عبر قصبة الساق

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الخلاصة

تبحث هذه الدراسة في استخدام الألياف الطبيعية كتعزيزات في مركبات البوليمر لإنتاج تجاويف للأطراف الاصطناعية، وتوفير بديل صديق للبيئة للتقنيات الحالية. صُنعت الصفائح باستخدام مزيج من ألياف الخيزران المنسوجة، وألياف الرامي، والألياف الزجاجية، وألياف الكربون، وألياف البولي إيثيلين عالي الوزن الجزيئي (UHMWPE)، وألياف كيفلر. وتضمنت هذه الدراسة إجراء بعض الاختبارات الميكانيكية، مثل اختبارات الصلابة والزحف والكثافة، لدراسة تأثير ترتيبات تكديس الألياف البديلة على بعض الخصائص الميكانيكية والفيزيائية. وحللت الدراسة تأثير تركيب الألياف وطرق التكديس على الأداء العام للصفائح، مسلطةً الضوء على مدى ملاءمتها لتطبيقات متنوعة. وأظهرت النماذج الواعدة، المكونة من أربع طبقات من الرامي وطبقتين من ألياف الكربون، قدرات ميكانيكية متميزة، بصلابة ٨٦ ميجا باسكال وكثافة ١,٢٣٩ جم/سم^3. في المقابل، سجّلت الصفائح (٢ خيزران + ٢ + 2 UHMWPE خيزران) أقل كثافة عند ١,١٥٧. تُسلّط النتائج الضوء على إمكانية دمج التعزيزات الطبيعية والاصطناعية في الهياكل المركبة لتحسين الأداء العام. ويُقترح دمج التعزيزات الحيوية المركبة الطبيعية والاصطناعية بشكل مدروس لتحسين الأداء الميكانيكي، وخاصةً في هندسة الأطراف الاصطناعية وعلوم المواد.

الكلمات الدالة: تجويف أسفل الركبة، مواد حيوية، إيبوكسي، تجويف الطرف السفلي، ألياف نباتية.

1.INTRODUCTION

Lower-limb prostheses are devices used to replace lost body components, aiming to restore their function and structure as much as feasible. Artificial prosthetics generally comprise several components, such as the socket, pylon, and foot. The trans-tibia prosthetic socket is important because it prevents the lower limb (stump) from bearing weight like a normal foot. The design of the prosthetic socket is a crucial element in determining the efficacy of the prosthetic fitting. The socket acts as the interface between the remaining limb and the prosthetic device, creating a link directly affecting the ability to bear weight. Hence, it is imperative to pay scrupulous attention to the design and construction of the socket to ensure optimal usefulness and comfort for the user [1]. Plant-based biomaterials may serve as a promising alternative to meet this demand. Typically, the prosthetic socket is connected to the residual limb. This socket fits around the remaining limb and is the anchor point for the rest of the artificial limb. It is essential because the lower limb (stump) cannot support weight like the foot. To ensure the prosthetic sockets are fitted correctly, it is essential to understand how they work biomechanically and what substances comprise their thickness and mass [2], which is essential for spreading the load evenly across the soft tissues and bones of the residual part of the lower limb. Most upper and lower limb prostheses are made of composites with a polymer matrix because they are vital for their weight [3]. Recently, scientists have been studying the possibility of using natural plant fibers like pineapple, bamboo, banana, sisal, henequen, jute, ramie, coconut (coir), rice husk, wood, and wheat straw as reinforcement materials in different polymer matrices. Lignocellulosic plant fibers are better than mineral fillers in many aspects when they are used as reinforcements in composites. These fibers are thin and have a high elasticity modulus and specific strength. They are also pretty rough. Moreover, they do not pose any health risks to the composites made from them. All lignocellulosic natural fibers comprise cellulose microfibrils in an amorphous lignin and hemicellulose matrix. This structure is similar to a single ramie fiber [4]. Even though they have a lot of potential natural resources like bamboo, which grows in Southeast Asian countries and makes up almost half of the world's bamboo forests, they are not used to their fullest. This material is crucial for maintaining ecological balance and sustaining socio-economic development. Woven bamboo and ramie fibers were used as glass and carbon fiber reinforcing materials in the current polypropylene study. The vacuum method made a socket for the lower limb below the knee. The researchers investigated how the mechanical and volumetric properties of the socket were affected by the order in which the fibers were layered [5]. They did this through tests and computer simulations. Thrombosis is a big reason why prostheses are needed worldwide, and when expensive materials are not available, it is essential to use cheaper materials that are easy to get. In places with earthquakes or wars, biomaterials made from plants could be a good alternative [6]. Materials made of composites, made from two or more parts that have their physical properties, have changed how orthopedic and prosthetic devices are made. Today's most influential popular multiphase resource in orthopedics is fiber, used in reinforced polymer composites. Carbon fiber is the most valuable reinforcement because it is stiff and strong in tension and compression. However, the materials usually used to make sockets, such as loin fibers, carbon fabric, and PMMA polymer resin, are not sustainable and can release harmful gases and dust that require expensive safety equipment. Because natural fibers are easy to find and can be recycled [7], it is essential to learn how to use them. Recent studies have examined using plant fiber-reinforced composites. To improve the modulus of elasticity and tensile strength, researchers changed the number of fiber layers and angles of direction. Laminations combining ramie, bamboo, carbon, and glass fibers have also been suggested to achieve physical and mechanical properties for prosthetic sockets for the lower limbs below the knee [8]. Faheed et al. [9] suggested using natural fibers to produce below-the-knee prosthetic sockets to substitute existing materials. The authors of this study concentrated on developing a prosthetic socket utilizing a composite material reinforced with natural fibers. The findings demonstrated that utilizing distinct reinforcing materials substantially affected the characteristics of the composite. Enhancing the volume percentage of materials resulted in enhancements in hardness, surface roughness, and density attributes. The optimal composite specimens comprised three flax layers and two carbon fiber layers, exhibiting a hardness property range of 86 MPa and a 1.276 g/cm3 density due to their outstanding mechanical qualities. Natural fiber-reinforced composites have the potential to serve as a suitable substitute for conventional materials in the production of below-the-knee prosthetic sockets. Chaid et al. [10] measured the moisture expansion coefficient of the lamination materials used in prosthetic sockets above the knee. Hoover equipment was used to create a socket using six distinct laminated composite materials. The reinforcement components consisted of fiberglass, purloin, and powder, whereas the matrix material was polyurethane resin. Ahmed and Oleiwi [11] and Widhata et al. [12] studied natural fiber-reinforced composites. The behavior of the composites was investigated concerning the effects of changing the number of jute fiber layers on mechanical and physical characteristics, which were the main mechanical properties of the material investigated in this study. The study's findings demonstrated that adding more layers of jute in response to tensile stress improved the mechanical properties of the composites. In this study, the prosthesis socket was made using a laminated process with various numbers of ramie and Bamboo layers in the composite to identify the most effective process for manufacturing composite materials for lower limb prosthetic sockets. This study, in contrast to others, studies the quality of synthetic and natural fibers. These materials' special qualities make this new sensing technique useful and efficient for prosthetic limbs.

2.MATERIAL AND METHOD

2.1.Material

Researchers used a woven mat made of ramie and bamboo fibers from Changzhou Doris Textile Co., Ltd to study below-knee laminating sockets. The laminated shell composite material combines natural and synthetic fibers (ramie and bamboo) (carbon, Kevlar, and glass fibers). The material also included a white knitted perlon stockinette, acrylic resin, a Polyvinyl Alcohol (PVA) bag from Otto-Bock Healthcare, hardening powder, and gypsum. These materials worked together to enhance the prosthetic socket's strength, longevity, and accuracy, aligning with materials engineering and industrial prosthetics. The extensive assortment was designed to enhance mechanical and functional characteristics, as specified in Fig. 2 [13].

2.2.Instruments

Apparatus utilized in this investigation:

1- A Jepson mold with a rectangular shape measuring 25 by 18 by 10 cubic centimeters.
2- The vacuum-forming system comprises a vacuum pump together with various types of stands, pipes, and tubes.
3- Dimensional digital venire and accurate weighing techniques for measuring the size and mass of samples.
4- The mechanical workshop at the University of Technology/Training and Workshop Center is equipped with various cutting gears designed specifically for this work with a CNC machine.

2.3.Procedure of Sample Manufacturing

The production process for the samples entailed multiple steps. Firstly, a gypsum mold was created and connected to a vacuum system via pressure tubes. Then, the inner layer of the PVA bag was placed onto the gypsum molds, and the vacuum system was used to apply suction, avoiding bubble formation and bonding between the resin and gypsum mold. The lamination lay-up added natural fibers, synthetic fiber, and person stockinet, as presented in Table 1 and illustrated in Fig. 1 (b) and (c) [14]. Following this, an external layer of PVA was applied, and then a length of cotton thread was used to fix the PVC bag, keeping the smaller tip on the valve. A vacuum system was utilized to suck out the air between all bags, leaving the top end open for resin supply. The polymethyl methacrylate resin was mixed with the hardener according to the standard ratio of 2-3, and the resulting mixture was then placed inside the external polyvinyl alcohol bag (PVA), where the matrix was distributed uniformly over the area of the lamination stockinet, as depicted in Fig.1 (d) [15]. The vacuum device was left running until the composite material solidified, after which the resulting lamination was removed from the gypsum mold. Twelve different types of laminated composite materials were produced, as demonstrated in Table 1 [16, 17].

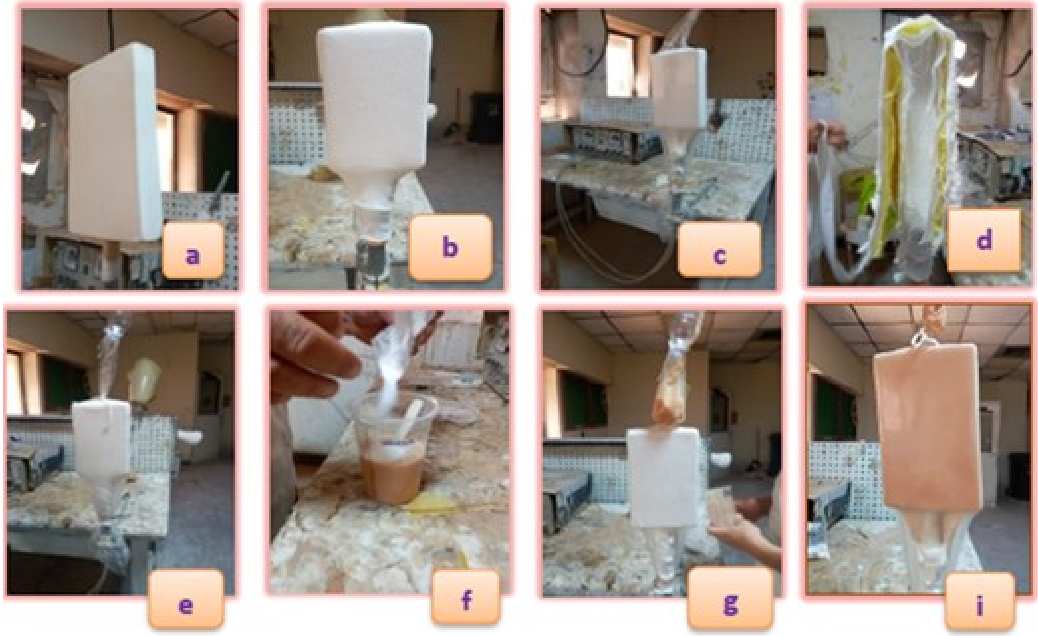


Fig. 1 The Process of Preparing Test Specimens for a Knee Prosthetic Socket and Depicts the Various Steps Involved in the Preparation Procedure.

Table 1 A List of Different Laminated Composite Materials was Used in this Work.

Lamination	Lay-up symbol	Sum of all Layers	No. of Lamination
Lamination 1	212	5	(2Perlon +1 Ramie +2perlon)
Lamination 2	222	6	(2Perlon +2 Ramie +2perlon)
Lamination 3	232	7	(2Perlon +3 Ramie fiber +2perlon)
Lamination 4	242	8	(2Perlon +4Ramie fiber +2perlon)
Lamination 5	22222	10	(2Perlon +2Ramie + 2Carbon +2Ramie + 2Perlon)
Lamination 6	22222	10	(2Perlon +2Ramie + 2Glass +2Ramie +2Perlon)
Lamination 7	22222	10	(2Perlon +2Ramie + 2Kavler +2Ramie +2Perlon)
Lamination 8	22222	10	(2Perlon +2Ramie + 2 UHMWPE +2Ramie +2Perlon)
Lamination 9	212	5	(2Perlon +1Bamboo +2perlon)
Lamination 10	222	6	(2Perlon +2 Bamboo + 2perlon)
Lamination 11	232	7	(2Perlon +3Bamboo + 2perlon)
Lamination 12	242	8	(2Perlon +4Bamboo + 2perlon)
Lamination 13	22222	10	(2Perlon +2 Bamboo + 2 Carbon+2 Bamboo +2Perlon)
Lamination 14	22222	10	(2Perlon +2 Bamboo + 2Glass +2 Bamboo +2Perlon)
Lamination 15	22222	10	(2Perlon +2 Bamboo + 2Kevlar+2 Bamboo +2Perlon)
Lamination 16	22222	10	(2Perlon +2 Bamboo + 2 UHMWPE +2 Bamboo +2Perlon)

2.4.Mechanical Properties.

Material classification and identification can be achieved by assessing its mechanical properties, including estimating its performance under particular conditions.

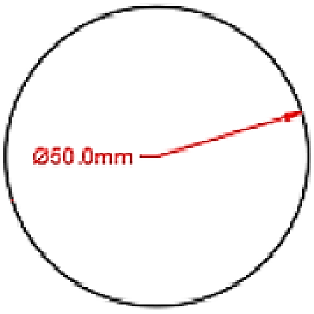
2.4.1.Hardness Test

A material's hardness can be used to measure its total mechanical performance. The property is an inherent attribute of a solid substance. The term "scratch resistance" refers to a surface's ability to withstand scratches and resist the penetration of external forces [18, 19]. The experiments entailed utilizing the Shore-D technology to bond composite pieces together. The device indenter experienced a force of 50 Newtons for 15 seconds. Measurements were conducted at seven distinct sites on the surface of the composite samples to ascertain the mean value of these values. Figures 2 (a) and (b) illustrate the standard laminated composite and the samples made according to the ASTM (D-2240 standard) [20].

2.4.2.Creep Test

The laminated composite samples underwent a tensile creep test, where they were exposed to a load of 15 N and kept at room temperature (±25 °C) for 168 hours, or until the tensile creep reached varying values. Next, a graph was created to display the creep curve. Tensile creep curves allow for calculating the creep rate in laminated composite samples by establishing the correlation between strain and time. Figure 2 shows using the ASTM standard (D2990-17) to create creep-laminated composite specimens [21, 22]. This test was conducted in the Department of Materials Engineering laboratories at the University of Technology, as depicted in Fig. 3.

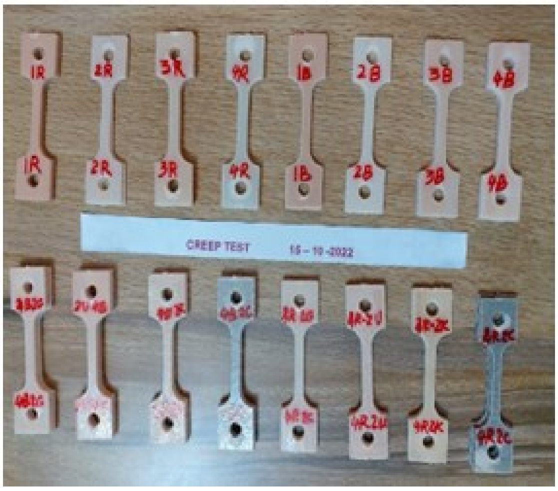

(a)



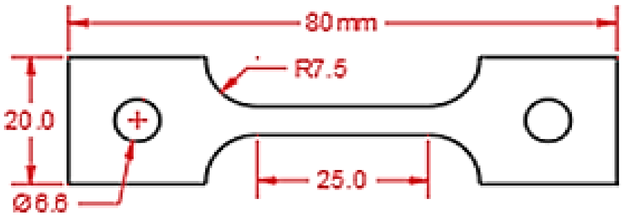
(b)


(c)

Fig. 2 (a) The Samples Subjected to the Hardness Test Before the Experiment, (b) the Standard Dimensions of the Samples, and (c) the Device Used to Measure the Shore-D Hardness.


(a)


(b)



(c)

Fig. 3 (a) The Pre-Creep Samples, (b) The Creep Testing Apparatus, and (c) The Standard Sample Dimensions.

2.5.Physical Characteristics

Physical attributes can be recognized without altering the matter's identity. Physical qualities include material properties, such as density and water absorption.

2.5.1.Density Test of Reinforced Composite Samples

The density test is performed using the ASTM D792 standard, utilizing the displacement technique based on the fundamental principles of Archimedes' theory. For this experiment, any sample size with a volume equal to or greater than 1 cm3 can be used. The testing procedure entailed measuring the weight of the samples in the atmosphere and subsequently measuring their weight again after submerging them in purified water, as depicted in Fig. 4. The equation provided can be used to acquire density data. As expressed by the following equation:

$$Specific\ gravity = \frac{m_1}{(m_1 + w + m_2)}$$

*Density (ρ_c)= (Specific gravity) * (997.5)*

where:

m_1 is the specimen's mass in air *(in grams)*.

m_2 is the mass of the specimen in grams, together with the sinker, if applicable, in water (*in grams*).

W *is the* mass of the immersed sinker if used and partially the immersed wire (*in grams)*.

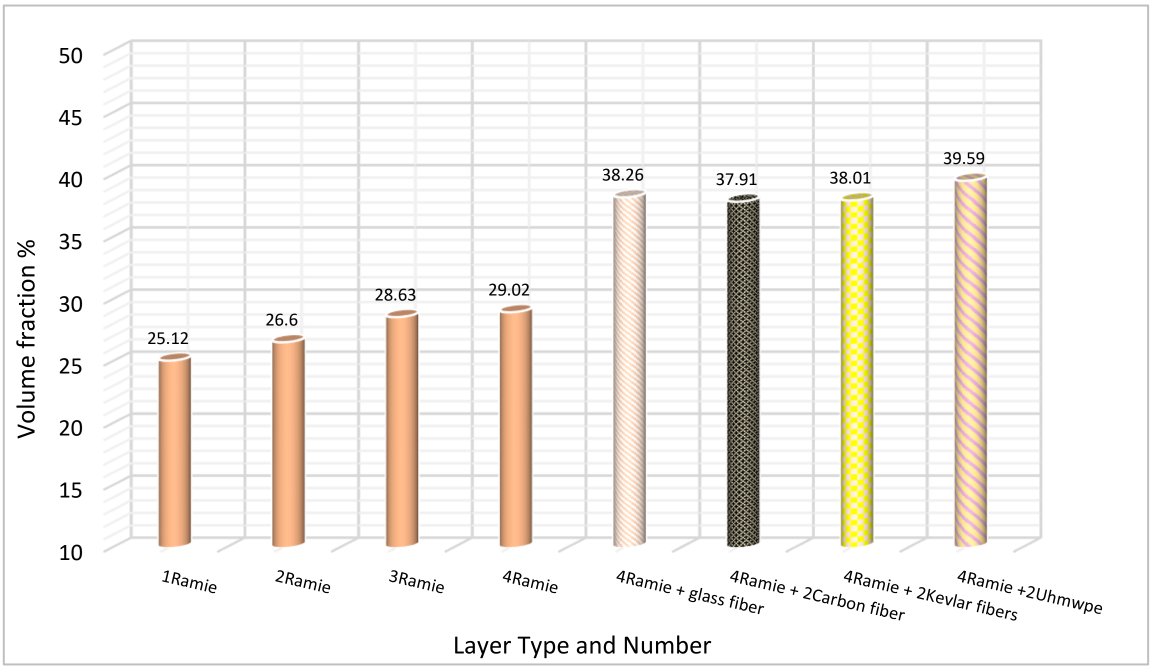
(a) (b)

Fig. 4 (a) The Samples before they were Put in Water; (b) The Weight Determination Device.

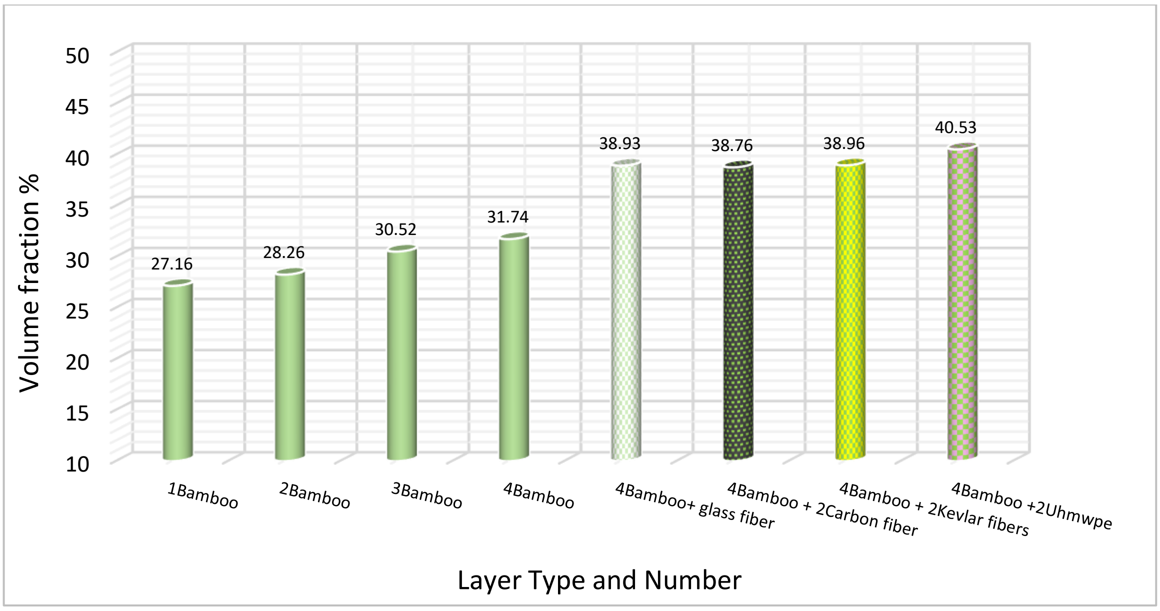
3.EXPERIMENTAL RESULT FOR MODIFIED LAMINATED COMPOSITE

3.1.Characteristics of the Samples Physical Features

Figure 6 demonstrates how choosing the reinforcing material used in the composite prosthetic socket affects the average thickness of the composite specimens. No notable variations were noticed among all reinforcements. The bonding performance of the matrix material appeared to vary depending on the specific components used, as observed by comparing their thicknesses. Furthermore, incorporating ramie fibers in the lamination results in a modest enhancement of its absorption capacity, increasing its thickness. It is worth noting that the hybrid reinforcement, which combines ramie plus Kevlar fibers, exhibited the highest thickness among all the options [23]. Figure 5 depicts the changes in the volume fraction of composite specimens as the kind of reinforcing material is altered. This fluctuation was determined using theoretical calculations using the law of mixture [24, 25]. The figure illustrates that the specimens reinforced with a hybrid combination of Bamboo and UHM (Ultra-High Modulus) have the highest volume fraction [26].



(a)



(b)

Fig. 5 (a), (b) The Lamination Volume Fraction Fluctuation.

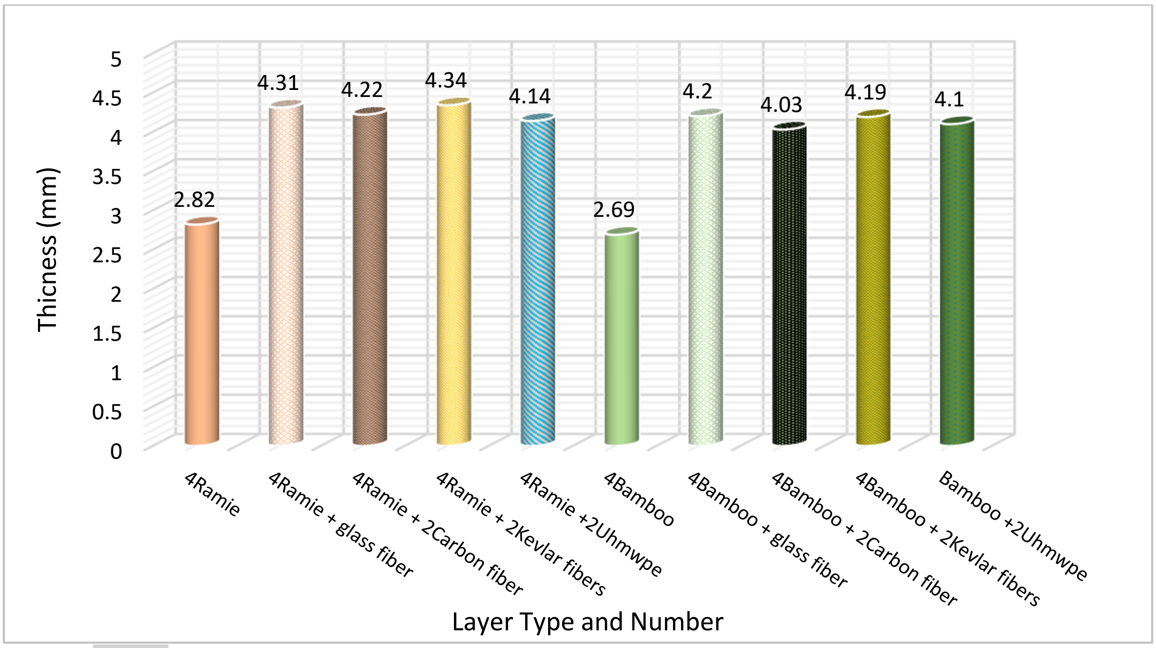


Fig. 6 The Reinforcing Material's Impact on the Composite Specimens' Thickness.

3.2.Mechanical Test Results on Modified Laminate Composites

3.2.1.Results and Discussions of Hardness Test

Figures 7 and 8 show that the hardness property values increased as the number of Ramie and Bamboo layers increased. The increase in hardness is directly proportional to the rise in fiber volume percentage, occurring as the number of fiber layers increases [27, 28]. However, the variances in hardness of these specimens can be linked to the changes in the characteristics of flax, sisal, cotton, glass, and carbon fibers. When the fifteen laminations were compared, it was observed that the combination of four layers of ramie and carbon fiber showed the highest hardness levels. The presence of carbon fibers is responsible for this result, therefore proving their involvement in efficiently transferring loads from the matrix to the fibers [29]. The combination of flax and carbon fibers enhanced the hardness of the composites, highlighting the significant role of fiber content in altering the mechanical properties of laminated materials.

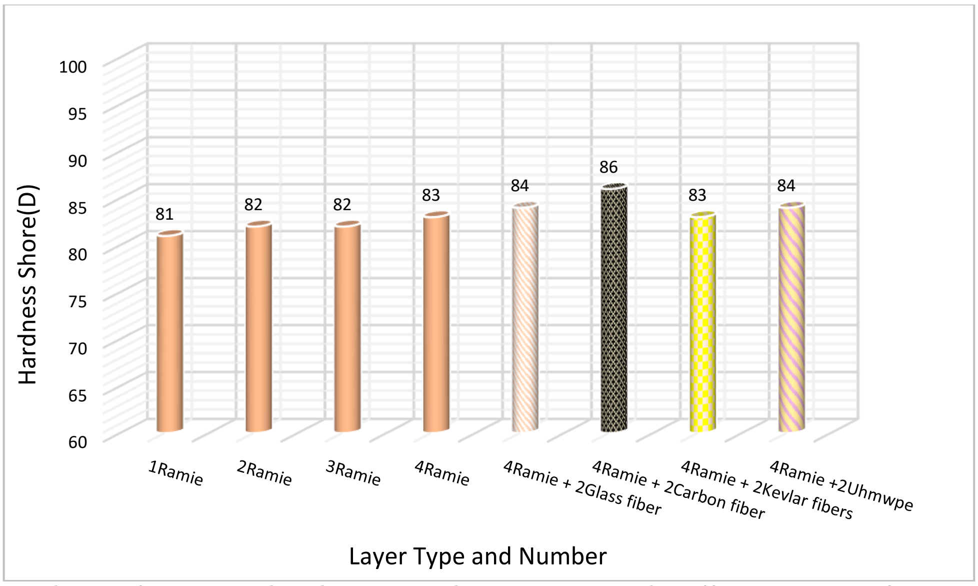


Fig. 7 Hardness of Laminated and Laminated Composites with Different Layers of Ramie Fibers.

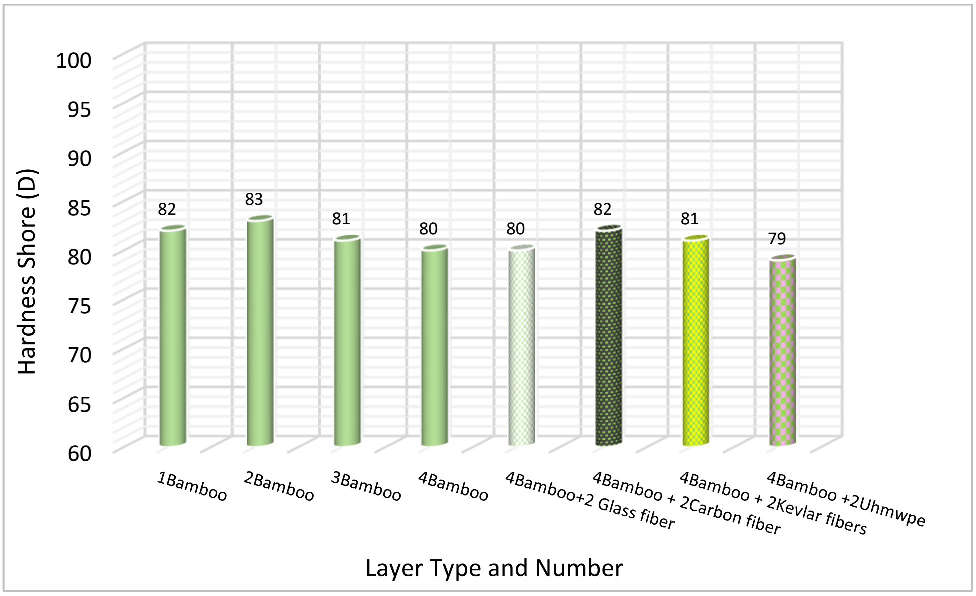


Fig. 8 Hardness of Laminated and Laminated Composites with Different Layers of Bamboo Fibers.

3.2.2. Results and Discussions of Creep Tests for Modified Composites

Viscoelastic deformation—a combination of elastic and viscous mechanisms— causes polymers to creep over time under a steady load. Tensile creep investigations on layered composites showed elastic and viscous strain zones. Controlled tensile creep experiments at 15 N for 168 hours were performed on 48 specimens. Reinforcement layers like hybrid or natural fibers like ramie and bamboo prevented creep curves from having a tertiary zone. This lack was due to these layers inhibiting tertiary zone formation. Inserting ramie fiber layers reduced creep strain, especially with more layers, while keeping steady perlon layers, as shown in Figures 9 and 10. Four ramie layers reduced creep strain by 0.0163%. Ramie or hybrid fibers prevent molecular chain joining during lamination. Hybrid composites with four ramie layers and two glass or carbon layers had low creep strain. A hybrid lamination of four bamboo, four ramie, and two carbon layers had the lowest creep strain of 0.011, demonstrating carbon fiber's better creep resistance. The literature showed that the carbon fiber had superior creep resistance to other fibers, as shown in Figures 11 and 12.

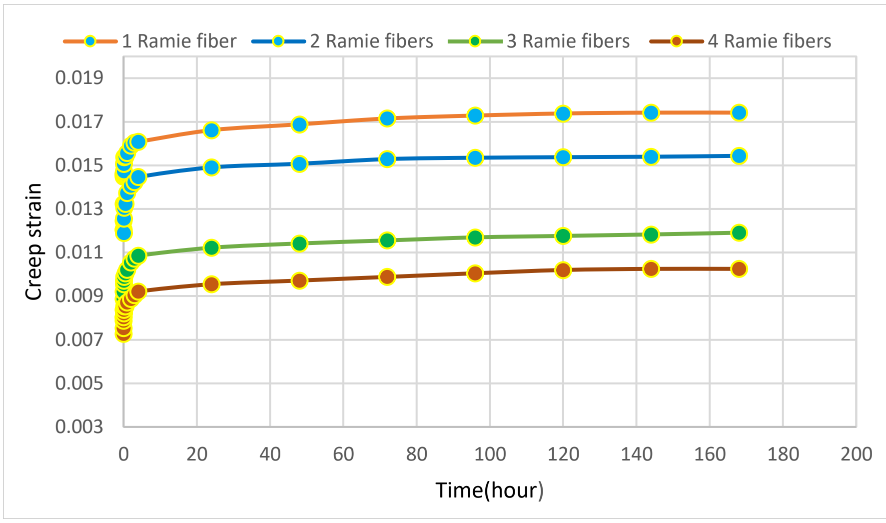


Fig. 9 Creep Strain of Laminated Composite Specimens Reinforced by Ramie Fibers.

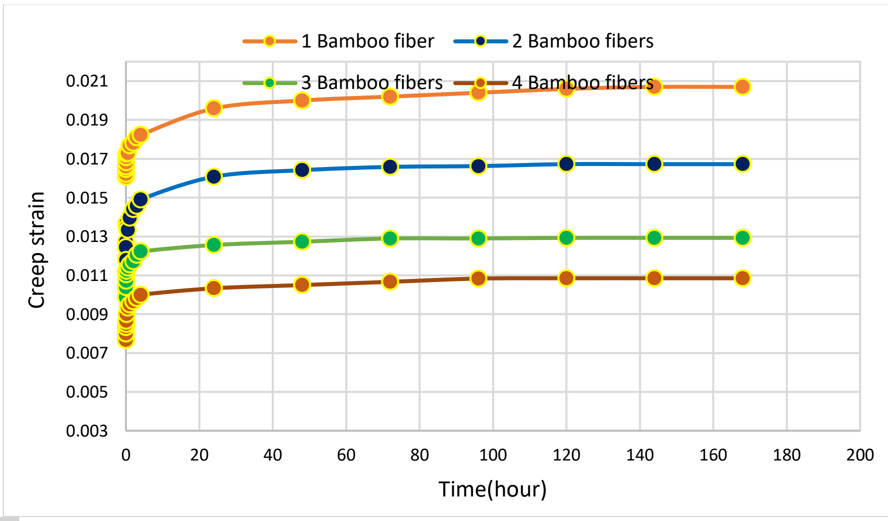


Fig. 10 Creep Strain of Laminated Composite Specimens Reinforced by Bamboo Fibers.

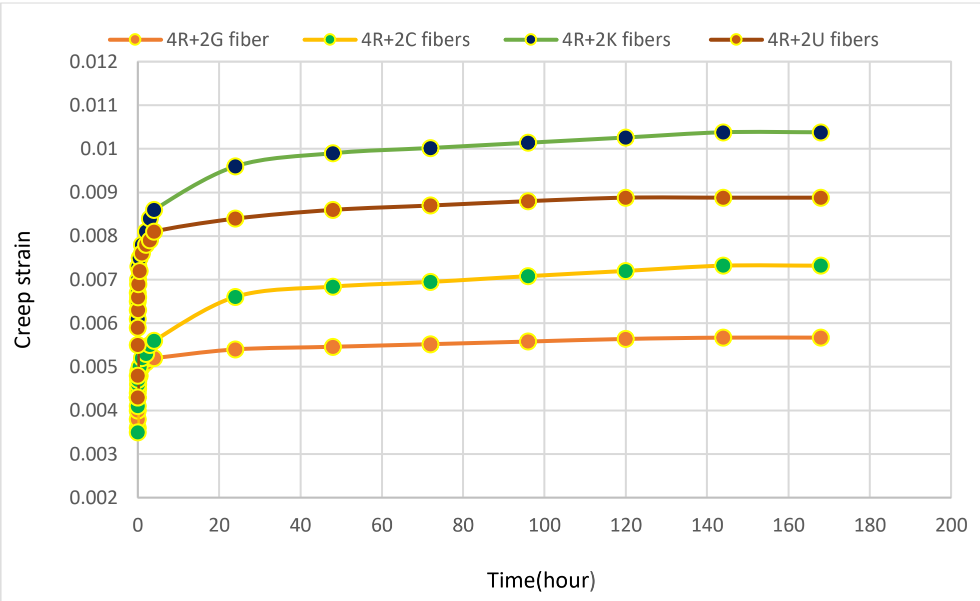


Fig. 11 Creep Strain of Laminated and Laminated Composites with Different Layers of Ramie Fibers.

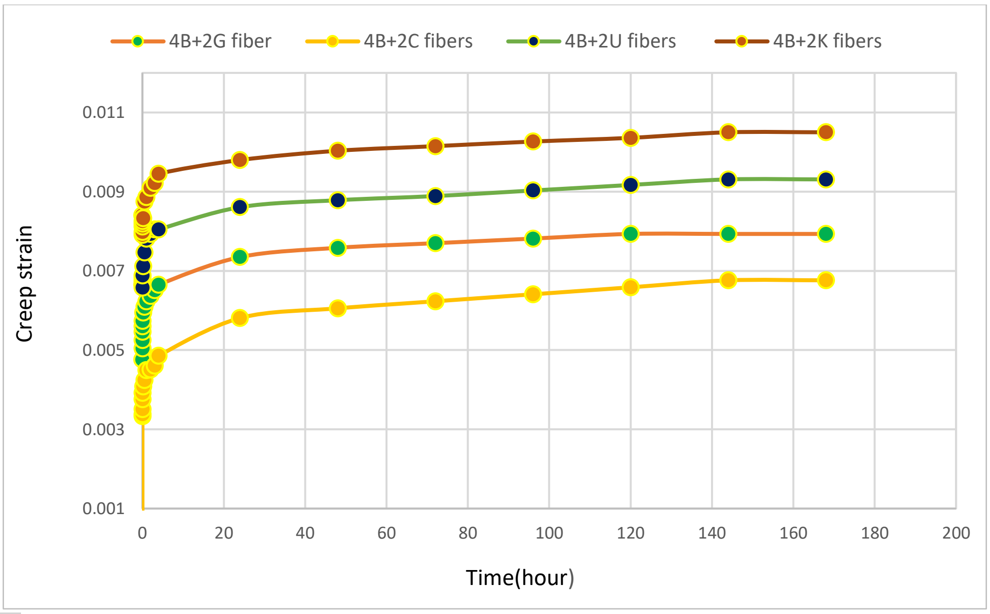


Fig. 12 Creep Strain of Laminated and Laminated Composites with Different Layers of Bamboo Fibers.

3.3.Modified Composite Materials' Physical Properties.

Figures 13 and 14 show that the Density values increased with the number of Ramie and Bamboo layers. The Density was directly proportional to the rise in fiber volume percentage when the number of fiber layers increased [27, 28]. However, the variances in Density of these specimens can be related to differences in the characteristics of Ramie, Bamboo, glass, and carbon fibers. When the sixteen laminations were compared, the combination of four Ramie and two carbon fiber layers displayed the highest Density. The carbon fibers are responsible for this result, proving their involvement in efficiently transferring loads from the matrix to the fibers [29]. The combination of Ramie and carbon fibers enhanced the Density of the composites, highlighting the significant role of fiber content in altering the mechanical properties of laminated materials.

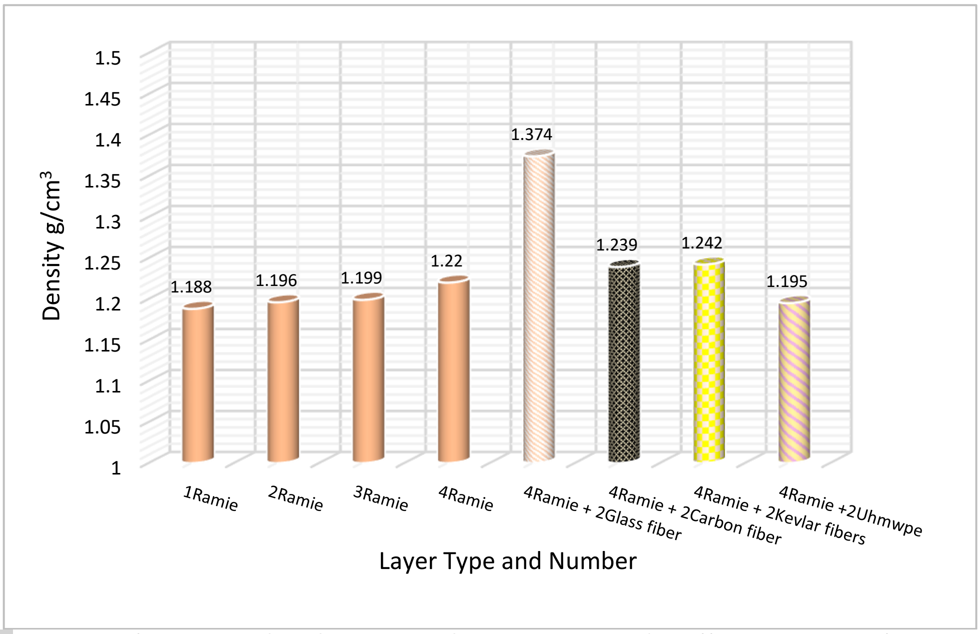


Fig. 13 Density of Laminated and Laminated Composites with Different Layers of Ramie Fibers.

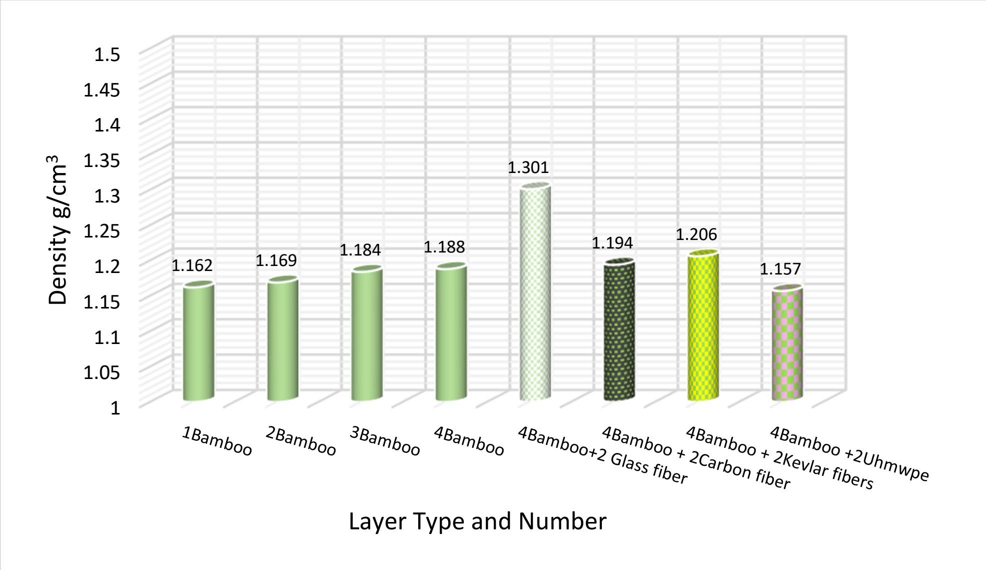


Fig. 14 Density of Laminated and Laminated Composites with Different Layers of Bamboo Fibers.

6.CONCLUSIONS

This study presents a selection of sixteen composite materials for evaluating and identifying the most suitable replacement for the currently used material in socket manufacturing. The goal of choosing a composite material is to find a stronger, lighter substitute capable of withstanding the heavy loads of patients when utilized in socket production. The primary conclusions of this investigation are as follows:

1- Among the tested materials, the hybrid had four layers of ramie plus two layers of glass fiber reinforcement and had the most significant density, thickness, and volume percentage.
2- The hardness of the socket varied depending on the materials used in the stacking arrangement: 2 perlon fibers, 2 Ramie fibers, 2 Carbon fiber fibers, 2 Ramie fibers, and 2 perlon fibers, having a significant impact.
3- The creep strain of hybrid laminated materials reached its highest value in lamination 1, measuring 0.021, and its lowest value in lamination 8, measuring 0.0055.
4- The Ramie plus Glass hybrid laminated composite materials had the highest density values, reaching 1.376 g/cm3.

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