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Improving Mechanical Properties of Laminated Biocomposites for Artificial Lower Limb Socket

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Abstract: People need artificial limbs for many reasons, such as illness, injury, or a gene problem. However, these limbs must be changed often because the human body changes as it gains or loses weight. This study examines whether plant fibers could be used instead of metal to make sockets for lower limb prosthetics using a vacuum bagging process. The laminates were formed using woven ramie fiber, bamboo fiber, carbon fiber, glass fiber, Kevlar fiber, and ultra-high molecular weight polyethylene UHMWPE fiber. Several mechanical tests, such as impact, maximum shear stress, and flexural tests, were done to investigate the effect of different ways of stacking the fibers on certain mechanical and physical properties. The goal was to find out how changing the orientation and distribution of the fibers affected the composite's properties and how it worked. The outcomes of the tests were evaluated and analyzed to identify the optimal stacking pattern that would yield the desired properties for the composite material. The present investigation demonstrated that the incorporation of diverse reinforcing agents into composite materials exerted a significant influence on their mechanical strength. The composite's properties, such as flexibility, stress tolerance, and toughness upon fracture, improved proportionally with the increasing addition of these materials. The sample with the lamination of (2 perlon + 2 ramie + 2 carbon + 2 ramie + 2 perlon) fiber layers has shown a good impact strength of 81 KJ/m^2, a maximum shear stress of 6.07 MPa, and a fracture strength of 174.1 MPa. Novel findings regarding the effect of altering the orientation and distribution of these fibers on the composite's properties could develop more effective prosthetic materials.

تحسين الخصائص الميكانيكية للمركبات الحيوية الطبائقية لوقب الطرف السفلي الاصطناعي

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الخلاصة

يحتاج الأشخاص إلى أطراف صناعية لأسباب عديدة، مثل المرض أو الإصابة أو مشكلة في جيناتهم الوراثية. ومع ذلك، تحتاج هذه الأطراف إلى تغييرها بشكل متكرر لأن جسم الإنسان يتغير مع زيادة أو فقدان الوزن. تطرقت هذه الدراسة إلى أمكانية استخدام الألياف النباتية بدلاً من الالياف الصناعية لصنع وقب للأطراف الاصطناعية السفلية باستخدام تقنية الصب في الفراغ. تم تحضير مواد متراكبة طبائقية مختلفة باستخدام ألياف الرامي المنسوجة، وألياف البامبو، وألياف الكربون، وألياف الزجاج، وألياف الكفلر، وألياف البولي إيثيلين عالي الوزن الجزيئي الفائق UHMWPE. تم إجراء عدة اختبارات ميكانيكية، مثل مقاومة الصدمة، ومقاومة أقصى إجهاد قص، ومقاومة الانحناء، لمعرفة تأثير نوع وعدد طبقات التقوية على الخصائص الميكانيكية والفيزيائية للمتراكبات الطبائقية. تم تقييم وتحليل نتائج الاختبارات لتحديد نمط الترتيب الأمثل الذي سيؤدي إلى الخصائص المرغوبة للمادة المركبة. أظهرت الدراسة الحالية أن تغير نوع وعدد طبقات التقوية له تأثير كبير على الخصائص المقاسة وتحسن خصائص المتراكبة المتمثلة في المرونة وتحمل الإجهاد والصلابة ومتانة الكسر بشكل متناسب مع الزيادة المتزايدة لألياف التقوية. وجد ان التصفيح الهجين المصنوع من أربع طبقات من الياف البيرلون مع أربع طبقات من ألياف الرامي مع طبقتين ألياف الكربون يتمتع بخواص ميكانيكية جيدة مقاومة الصدمات تصل الى 81 كيلو جول/متر مربع، وأقصى إجهاد قص بقيمة 6.07 ميجا باسكال، وقوة الكسر بقيمة 174.1 ميجا باسكال. يمكن أن تساهم النتائج المستنبطة من الدراسة والمتعلقة بتأثير تغيير نوع ونمط توزيع الألياف على خصائص المتراكبات الطبائقية في تطوير مواد أكثر فعالية لتصنيع الأطراف الصناعية.

الكلمات الدالة: ألياف البامبو، الطرف السفلي، الخصائص الميكانيكية، ألياف نباتية، وقب الطرف الاصطناعي، ألياف الرامي.

1.INTRODUCTION

The prosthetic socket is the connection point between the amputee's remaining limb and the walking prosthesis. Lower or upper limb amputations are often the result of explosive limb diseases or injuries, with femoral bone resection above the knee and tibial bone resection below the knee being the most common types [1]. The below-knee socket that holds the residual limb is often custom-made according to the patient's anthropometric measurements. Three main parts make up a prosthetic limb, as shown in Fig. 1: the socket, which attaches the lower leg to the mechanized support system; the extension or pylon, which lengthens the body to compensate for the missing limb; and the prosthetic device itself and the foot or ankle, which makes contact with the ground and makes walking possible [2].

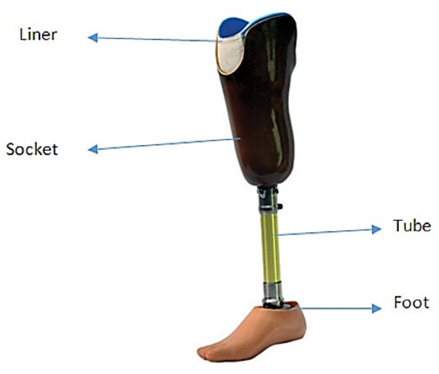

Fig.1 Lower limb prosthetic components below the knee part [2].

Lower-limb amputations happen above or below the knee because lower-limb injuries or diseases happen above or below the knee. The prosthetic socket is crucial in ensuring the optimal fit of the prosthetic device to the amputee's residual limb by connecting it to the supporting structure. To ensure the soft tissues and bone of the remaining limb can bear the crucial stress, prosthetists need expertise in biomechanical socket design and materials [3]. In orthopedics, fiber-reinforced composites are widely employed as multi-phase materials. Polymer-based composites have gained popularity for upper and lower-extremity applications owing to their favorable biocompatibility and exceptional strength per weight ratio [4]. Natural fibers have emerged as a preferred choice due to their lower density, superior stiffness and strength per weight ratios, cost-effectiveness, and eco-friendliness. In circumstances where expensive materials are scarce, and a persistent need for quick amputation, such as in war and earthquake, plant-based polymers and fibers may serve as a viable alternative [5].
Researchers have explored this area. Al-Obaid et al. [6] studied the effect of natural pistachio shell particles (PS) on the mechanical properties of epoxy composites. They used tensile, flexural, hardness, and impact tests. The results showed that the PS/epoxy composite either got better or worse in terms of its mechanical properties. Similarly, Oleiwi et al. [7] developed five layered composite materials used in the below-knee prosthetic sockets vacuum molding. The matrix materials

were a mix of epoxy with polymethyl methacrylate PMMA and reinforcements like synthetic carbon fiber, fiberglass, hybrid fiber carbon plus glass, micro-silica particles, and perlon. The mechanical properties, including fracture toughness, maximum shear stress, fatigue characteristics, and tensile strength, were evaluated experimentally. The lamination with synthetic glass fiber showed the best theoretical, numerical, and experimental outcomes, making it the most suitable candidate for enhancing the features of the below-knee socket. Odusote et al. [8] demonstrated the potential of pineapple-epoxy composites to replace fiber-glass-polyester sockets for above-knee limbs where higher Ultimate strength is crucial. Nurhanisah et al. [9] showed that a prosthetic socket made from kenaf fibers with synthetic glass fiber composite improved features and could be used as a lower limb prosthetic socket. Rosalman [10] studied the ability to use kenaf fiber instead of glass fiber and evaluated the traditional materials used to create sockets through various tests. The objective of this research was to assess the significance of utilizing eco-friendly materials in the production of receptacles for lower limb prostheses. Utilizing hybrid fiber composites, which can withstand greater stresses and provide superior mechanical properties, reducing production costs while maintaining peak performance is possible.

2. Experimental Methodology

This section presents the used materials, tools, and preparation steps to make sockets with useful mechanical properties. It also explains the mechanical properties used to evaluate the sockets' properties, such as hardness, impact resistance, and surface roughness. By following a rigorous production and evaluation process, high-quality and durable sockets can be obtained.

2.1. Materials

This study used a woven mat made of natural fiber ramie and bamboo fibers to make the lower limb lamination socket. The mat was brought from Changzhou Doris Textile Co., Ltd., China. Carbon fiber, glass fiber, Kevlar fiber, and UHMWPE fiber were also used. The matrices utilized in the fabrication procedure combined PMMA, hardener, and perlon. These materials were selected for their desirable mechanical properties and compatibility with the lamination process, as shown in Fig.2.

2.2. Experimental Apparatus

1. A rectangular positive Jepson mold with dimensions of 27 x 18 × 4 cm^3 was utilized in this study.
2. The vacuum-forming system comprised a vacuum pump as well as a range of stands, pipes, and tubes.
3. To measure the dimensions and weight of the samples, a sensitive weighing device, and a digital vernier were used.
4. The mechanical workshop was conducted in the technical training center of the university, which was equipped with various cutting gears operated by a CNC machine.

Fig. 2 Materials Utilized in This Study.

2.3. Manufacturing Of Composite Laminates

Upon determining the weights of the reinforcement and matrix in accordance with the desired volume fractions, samples were made using vacuum modeling. As described in Table 1, the lamination process was subsequently, and a Jepson mold was positioned and protected at the vacuum entrance, with pipes attached to the pressure system for sample creation. A Polyvinyl alcohol PVA sheet was placed on the mold, as shown in Fig. 3(c). Pressure sensors were calibrated at room temperature and pressure to 40000 Pa. The application of Perlon fiber in two layers, one layer of ramie fiber and two layers of Perlon, was carried out, as demonstrated in Fig. 3(b). Fig. 3 (e) shows how a PVA bag sheet was put on the top of the composite material layers and tied together with a rope.

Fig. 3 The Process of Preparing Lamination Specimens for Prosthetic Sockets and Depicts the Various Steps Involved in the Procedure.

The matrix, composed of PMMA polymer and hardening granules, was blended in a predefined ratio, where 2–3 parts powder was combined with 100 parts resin and equitably provided through a tube into the layers. After 15 minutes, cubic lamination was obtained, as shown in Fig. 3(d). After the laminations had cooled, they were cut into pieces for testing all laminations.

3.Evaluation

The mechanical properties of a material refer to its response to applied external forces. By evaluating the material's mechanical characteristics, including its predicted performance under specific conditions, it is possible to classify and identify the material according to established criteria.

Table 1. Several Categories of Composites.

Lamination	Layers	Lamination lay-up procedures
Lamination. (1)	5	(2Perlon +1 Ramie fiber +2perlon) layers. (1R)
Lamination. (2)	6	(2Perlon +2 Ramie fiber +2perlon) layers. (2R)
Lamination. (3)	7	(2Perlon +3 Ramie fiber +2perlon) layers. (3R)
Lamination. (4)	8	(2Perlon +4Ramie fiber +2perlon) layers. (4R)
Lamination. (5)	10	(2Perlon +2Ramie fiber2 +fiber Glass+2Ramie fiber+ 2Perlon)layers. (4R+2G)
Lamination. (6)	10	(2Perlon +2Ramie fiber + 2Carbon fiber+2Ramie fiber +2Perlo) layers. (4R+2C)
Lamination. (7)	10	(2Perlon +2 Ramie fiber + +2Kevlar fibers+2 Ramie fiber +2Perlo) layers. (4R+2K)
Lamination. (8)	10	(2Perlon +2Ramie fiber + 2uhmwpe fibers+2Ramie fiber +2Perlo) layers. (4R+2U)
Lamination. (9)	5	(2Perlon +1Bamboo fiber +2perlon) layers. (1B)
Lamination (10)	6	(2Perlon +2 Bamboo fiber + 2perlon) layers. (2B)
Lamination. (11)	7	(2Perlon +3Bamboo fiber + 2perlon) layers. (3B)
Lamination. (12)	8	(2Perlon +4Bamboo fiber + 2perlon) layers. (4B)
Lamination (13)	10	(2Perlon +2 Bamboo fiber + 2fiber Glass+2 Bamboo fiber +2Perlon)layers. (4B+2G)
Lamination (14)	10	(2Perlon +2 Bamboo fiber + 2Carbon fiber+2 Bamboo fiber +2Perlon)layers(4B+2C)
Lamination (15)	10	(2Perlon +2 Bamboo fiber + +2Kevlar fibers+2 Bamboo fiber +2Perlon) layers(4B+2K)
Lamination (16)	10	(2Perlon +2 Bamboo fiber + 2uhmwpe fibers+2 Bamboo fiber +2Perlon) layers. (4B+2U)

3.1. Flexural Strength Testing

At-room-temperature flexural test was performed following ASTM (D-790) guidelines. The test aims to measure each lamination's flexural modulus and flexural strength. The test was conducted using a Lybold Harris No. 36110 test apparatus that exerts 5,000 N of force at a feeding speed of 0.5 cm/min until the sample fails. The test results generated a curve that comprehensively explains the material's reaction to flexural stress. The figures in Fig.4 depict the samples employed in the experiment and the standard tests.

3.2. Maximum Shear Stress Test

Shear stress is a phenomenon that arises when a force is exerted on a specimen of material along a plane that is parallel to the surface of the material. This term is commonly used in the material testing domain. The sample may crack or break under such pressure. The shear stress test was conducted at room temperature per the American Society for Testing and Materials D2344 standard guidelines.

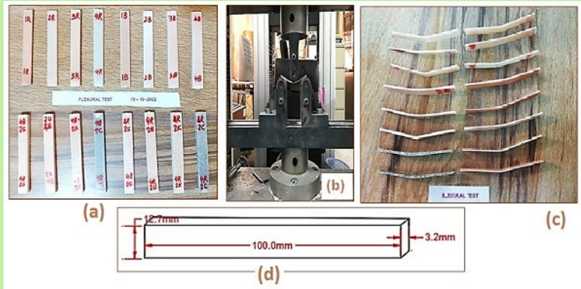

Fig. 4 Samples before Putting Them Through Tensile Testing, B- Apparatus, C- after Putting them Through a Tensile Test, and D - Standard Sample.

The study employed a Leybold Harris hydraulic press with model number 36110 in combination with a narrow beam apparatus. The applied controlled force to the specimen was carried out using a hydraulic press, while the slender beam was utilized to conduct precise assessments of its mechanical response. The highest shear stress was determined by applying the load to the sample until it broke. The biggest load was acquired using a bending instrument. The calculated maximum shear stress was then factored into further analyses. The shear stress test samples, both experimental and standard, are depicted in Fig 5.

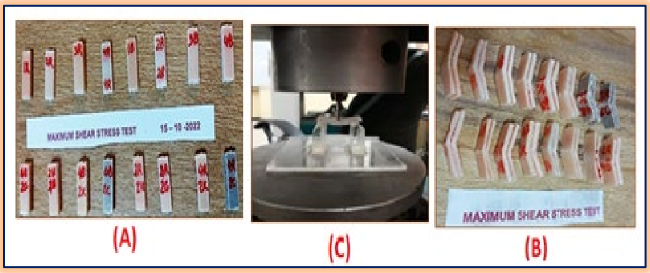

Fig. 5 (A) The Sample before Testing, (B) The Sample after Testing, and (C) The Apparatus Used for The Bending Test.

$$\tau_{max} = \frac{3P}{4bd} \qquad (1)$$

where τ is the shear stress at its highest value (MPa), and *P* is the fractional load (N).

3.3. Impact Test

A laminated specimen's impact strength and energy absorption needed to rupture can be calculated using the impact test. The specimens were fractured utilizing a specialized apparatus, and the examination was carried out under normal environmental conditions adhering to the ISO 179 criterion. The Izod impact test equipment (XJU series pendulum) utilizes a vertical beam with a cantilevered end to secure the test sample in place at one end. The experimental sample was exposed to an impact energy of 0.0055 kJ and an impact velocity of 3500 millimeters per second upon release of the pendulum from its maximum height. The fracture toughness of the sample was determined by utilizing the energy required for its fracture. The impact test samples used in this investigation and the standard test sample are shown in Fig. 6.

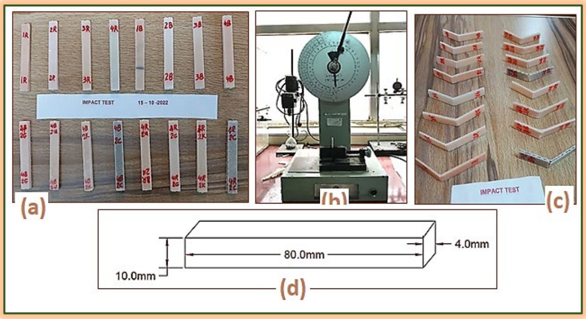

Fig. 6 (a) Samples Before Being Subjected to Impact, (B) Apparatus, (C) after-Impact Samples, and (D) Typical Sample.

4. Results and Discussions

4.1. *Physical Attributes of the Samples*

Figures. 7 and 8 demonstrate how the composite's reinforcements affect its thickness and density. There are insignificant discrepancies in the reinforcements used. However, thickness comparisons suggest that the matrix adheres more strongly to some materials than others. Layering with ramie fibers also increased density and thickness by increasing absorption capacity by a small amount. The hybrid bamboo plus glass reinforcement displayed the maximum density, while the ramie plus glass group had the greatest thickness [11]. As a function of reinforcement type, volume fraction changes are obtained in Fig. 9. The graph clearly shows that the volume of the hybrid ramie with glass reinforcement is the greatest.

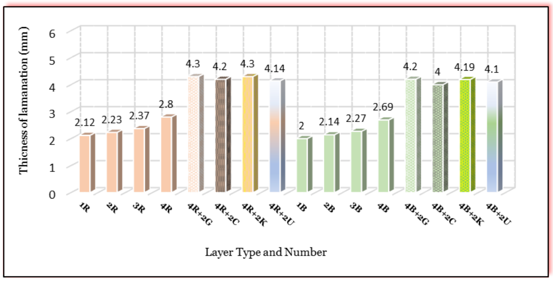

Fig. 7 Alterations in Specimen Thickness Due to Different Reinforcements

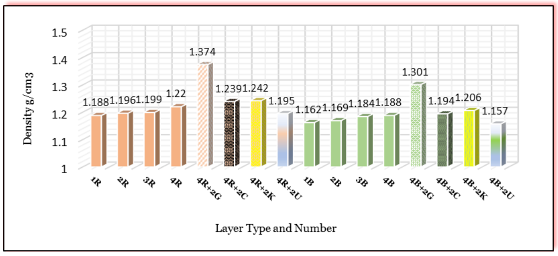

Fig. 8 Alterations in Specimen Density Due to Different Reinforcements [12].

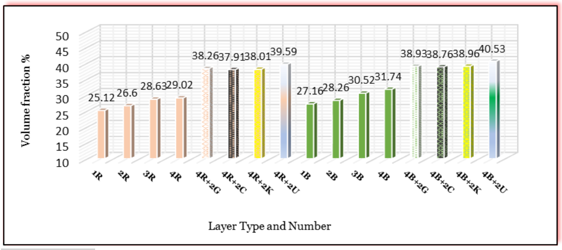

Fig. 9 Alterations in Specimen Volume Fraction Due to Different Reinforcements

4.2.1. *Flexural Strength Result*

The flexural strength was enhanced through the augmentation of ramie and bamboo quantities. The enhancement of strength in laminated materials is attributed to the bonding process and characteristics of the lamination groups. The variability in the properties of woven fibers, such as ramie, bamboo, carbon, Kevlar, glass, and UHMWPE, contributes to this effect. According to Fig.10, it can be observed that the flexural strength of ramie laminations consistently surpassed that of bamboo hybrid laminations as the volume percentage increased due to the difference in flexural strength between ramie and bamboo fibers, with the flexural strength of ramie being more than that of bamboo fibers [13]. When the 16 groups were compared, it was found that the best bending strength was found in 4 ramie and 2 carbon because the material had carbon fibers, which can help stress move from the matrix to the fibers. In contrast, the use of bamboo reinforcements provided the lowest bending strength. Overall, these findings underscore the importance of carefully selecting the type and volume of reinforcement materials in order to achieve optimal flexural strength in composite materials [14].

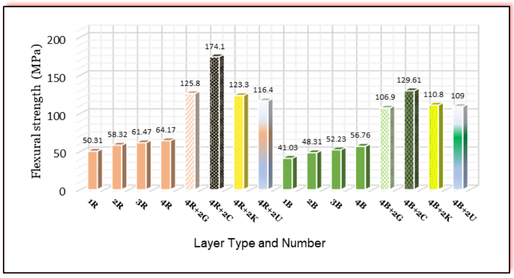

Fig. 10 Flexural Strength Improved by Adding Natural and Synthetic Fibers.

4.2.2. Flexural Modulus Result

Fig.11 shows the effect of the number of ramie, bamboo, carbon, glass, Kevlar, and UHMWPE fibers layers added to PMMA composites on the flexural modulus. The results suggest that the flexural modulus increased as the reinforcing layers increased. Also, compared to ramie and bamboo fiber-reinforced laminations, the bending modulus of ramie-reinforced composite materials was the highest due to ramie fiber's superior compatibility and mechanical properties [15].

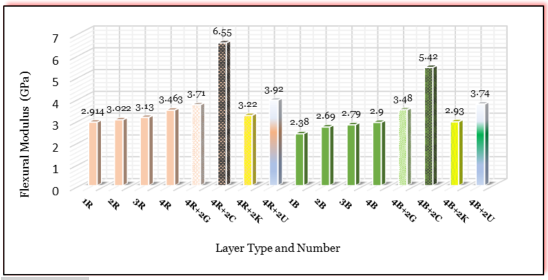

Fig. 11 Flexural Modulus Improved by Adding Natural and Synthetic Fibers.

The flexural modulus values of the ramie with the synthetic carbon group were the highest of the sixteen laminations tested due to the high modulus of the carbon fibers; the composite lamination was resistant to the propagation of fractures under various pressures. As a result, the flexural moduli of the composite specimens were increased [16]. In contrast, composites manufactured with bamboo reinforcements had the lowest flexural properties, which means that bamboo reinforcements insignificantly improved the matrix material's properties and that the matrix's bending properties are a big part of how well the composites work overall. These results showed the importance of carefully choosing the type and number of reinforcing materials to get the best flexural modulus from composite materials.

4.3. Maximum Shear Stress

As seen in Fig. 12, the shear stress in a composite with natural fiber layers grew as the number of layers grew. Maximum shear stress was the greatest when ramie fibers, as opposed to bamboo fibers, were incorporated into a PMMA matrix due to the ramie fibers' outstanding compatibility and adhesion with the matrix and their capacity to prevent crack development inside the matrix [17].
Due to synthetic carbon fibers' superior mechanical and physical characteristics, the maximum shear stress of a composite made of carbon and ramie fibers was even greater than that of the other sixteen instances. However, the maximum shear stress was the lowest in the composite of a single layer of bamboo fibers because bamboo reinforcement had a lower maximum shear stress in the PMMA matrix due to its weak bonding strength. These findings, taken as a whole, stress the significance of the judicious selection of reinforcing fiber type and number in improving the composite material's mechanical properties.

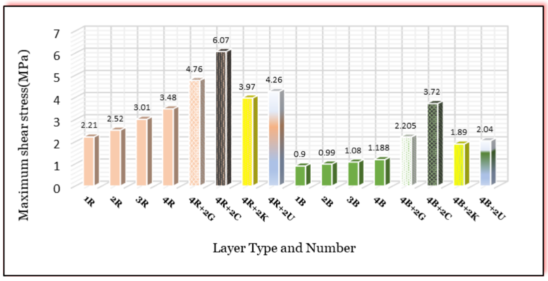

Fig. 12 Maximum Shear Stress Improves with The Addition of Natural and Synthetic Fibers.

4.4. Experimental Results of The Impct Test

4.4.1. Test for Impact Resistance

Figure. 13 shows the impact resistance of test specimens that were changed, which shows that the strength improved as the volume fraction increased. This improvement is due to increased absorbed energy with reinforcement layers, preventing crack dissemination and enhancement.

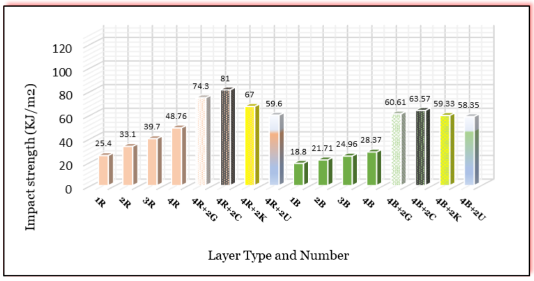

Fig. 13 Impact Strength Improves with The Addition of Natural and Synthetic Fibers

By comparing the composite materials reinforced with ramie and bamboo fibers, it was observed that the ramie fiber-reinforced materials exhibited the highest impact strength, which can be attributed to ramie fibers having more significant impact strength than bamboo fibers. The group with ramie with carbon fibers exhibited the maximum impact strength among the sixteen laminations evaluated, which can be credited to the more significant impact strength of ramie and carbon fibers compared to the PMMA matrix, thus strengthening the hybrid specimens' resistance to impact loads and increasing their effective impact strength [18]. However, out of the sixteen lamination groups, the one with the lowest impact strength was the one that used bamboo reinforcement due to the bamboo fibers' low toughness, which in turn led to low impact strength in this lamination.

4.4.2. Durability under Fracture Stress

Figure.14 shows how flexural modulus and impact strength can be used to find a relationship between the fracture toughness value and the reinforcement type and amount. The results indicate that increased natural fiber quantity increased the material fracture toughness, which can be attributed to the fact that both flexural modulus and impact strength increased with the quantity of fiber, irrespective of their type. Therefore, it can be concluded that increasing the number of fiber layers improved the fracture toughness. It is imperative to acknowledge that these discoveries hold considerable importance in comprehending the correlation between reinforcement and fracture toughness within materials science. The study revealed that increased volume fraction resulted in higher fracture toughness values when comparing ramie hybrid laminations to bamboo laminations. The incorporation of ramie fibers into the composite resulted in further enhancement of the mechanical characteristics of the hybrid materials. The inherent property of ramie fibers having a greater capacity to withstand fracture than the PMMA matrix can explain the observed enhancement. The incorporation of ramie fibers into hybrid laminates improved the fracture toughness values. The discoveries provided insight into the reinforcement influence on improving composite materials' mechanical characteristics. According to the findings presented in Fig. 14, further analysis revealed that the ramie containing synthetic carbon groups exhibited the highest level of durability when subjected to fracture stress. The rationale behind this is that carbon fibers exhibited a superior flexural modulus.

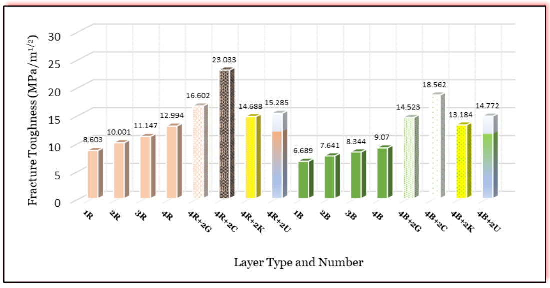

Fig. 14 The Resistance to Fracture Improves with the Addition of Natural and Synthetic Fibers.

The propagation rate of cracks was comparatively lower in specimens composed solely of natural fibers as opposed to those containing synthetic carbon fibers. The statement above implied that incorporating hybrid carbon groups into ramie resulted in high fracture toughness values.

This study found that, out of the sixteen lamination groups, one layer of bamboo reinforcement had the least ability to resist breaking because bamboo reinforcement had a low fracture toughness, which made it not work as well with the PMMA matrix [19]. On the other hand, the results show that lamination materials can be used to make prosthetic sockets that are safe and effective for clients. Also, using natural materials in this way helps the environment stay healthy and allows them to be reused repeatedly [20]. These results show that lamination materials have the potential to be a good choice for making prosthetic sockets.

5.CONCLUSIONS

1. The group with ramie reinforced with glass exhibited the highest thickness and volume fraction.
2. Changing the type of reinforcement significantly affected the measured properties, as demonstrated by the results. With values of 23,003 MPa/m1/2, the fracture toughness of four layers of ramie fiber and two layers of carbon was the highest. 3. The impact resistance was enhanced when reinforced with natural fibers (bamboo and ramie) and achieved its highest levels with two layers of carbon fibers (80 kJ/m² and 63.57 kJ/m², respectively).
3. Compared to bamboo, glass, Kevlar, and ultra-high molecular weight polyethylene (UHMWPE) fibers, the laminate of six layers (2 perlon + 2 ramie + 2 carbon + 2 ramies + 2 perlon) using resin PMMA exhibited maximal shear stress of 6.07 MPa.
4. Ramie had the highest maximum shear stress properties for carbon hybrid composites, which reached a maximum of 6.07 MPa, and a maximum impact strength of 81 kJ/m² was achieved with 4 layers of ramie and 2 layers of synthetic carbon fiber.
5. Overall, the study highlights the potential of plant fiber-reinforced composites for prosthetic sockets and the importance of carefully selecting and arranging the materials to achieve optimal mechanical properties

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