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Effect of Different Fiber Reinforcements on Some Properties of Prosthetic Socket

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HIGHLIGHTS

- It has become a necessity to use alternative materials when costly materials are not available and there is a high demand for prostheses.
- Biomaterials, having fibers derived from plants, may offer the needed substitute.
- Altered types and numbers of reinforcing materials had an abundant influence on the properties of the composite prosthetic socket.

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ABSTRACT

In the perspective of environmental advance, significant attentiveness is being displayed in the usage of natural fibers like reinforcement in polymer composites. This paper focuses on building a prosthetic socket arranged from natural fiber-reinforced composite as an effort to substitute material currently accessible in the manufacturing of the socket. The vacuum bagging procedure was adopted to yield a below-knee socket. The laminates encompass woven flax, sisal, cotton, carbon, person, and glass fabric. The impact of diverse fiber layering sequences on some of the physical and mechanical characteristics was assessed. Laminated specimens were characterized by tests such as (hardness, surface roughness, density, water absorption). The results of this study showed that consuming altered forms of reinforcing materials had an abundant influence on the properties of prepared composite and the values of (hardness, surface roughness, and density) properties improved with increasing of the volume fraction of materials and the best composite specimens were three layers of flax with two layers of carbon fiber, were the hardness property ranges 86 MPa and density of (1.276 gm. /cm3) due to their exceptional mechanical properties. The results of the present study advocate that the arrangement of natural and synthetic reinforcements allows the preparation of bio-composites with enhanced performance.

1. Introduction

Lower limb artificial prosthetics are appliances that are employed to substitute the role or form of absent parts as much as possible. Artificial prosthetic constituents include several fragments making the socket, pylon, and foot. The trans-tibia prosthetics socket is considered a vital part consequently the lower limb (stump) does not partake the comparable weight-bearing abilities as the foot [1, 2]. The design of the prosthesis socket is deliberated as one of the major aspects in defining the type of fitting since the socket proposes a coupling amid the residual limb and prosthesis [3].

To achieve effective fitting procedures for prosthetic sockets, an understanding of the biomechanical construction of such sockets and the suitable materials, including their mass and thickness, to achieve the necessity for required load dispersal in the soft tissues and bone of the remaining limb [4].

Recently, developments in the progress of composite materials have qualified main enhancements in the design of contemporary orthopedics and prosthetic expedients. Composites are defined as an engineered material prepared from two or more elements, each contributes diverse physical properties, which can be joined [5, 6]. Recently, fiber-reinforced polymer composites are considered one of the most widely used multi-phase resources in orthopedics. Correspondingly, most of the upper- and lower-limb prostheses are prepared from polymer matrix composites [7, 8]. Among conventional fiber reinforcements used in orthopedics, fiberglass was considered the most common and cost-effective composite reinforcement. While being one of the heavy's types of reinforcements, it is easy to soak with resin and achieve in many practices and qualities. Fiberglass offers durability and flexibility, due to the fibers being twice as strong under compression as in tension.

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Nevertheless, for orthopedic appliances, carbon fiber is considered the most valued form of reinforcements since it supplies stiffness and the ability to hold its shape under the influence of stress due to its remarkable strength under both tension and compression [4]. These materials were created from non-sustainable bases along with generating irritant radiations of harmful gases and dust. Therefore, it needed expensive specialist in health and safety equipment. The need to use alternative and accessible materials should be considered when costly materials are not available and high claim for prostheses, as in earthquake or combat and battle districts, biomaterials, holding resins and fibers, derivatives from plants may offer the needed substitute [9]. These types of materials are satisfactory due to their incomparable strength to weight features [7] in addition to their exceptional biocompatibility [8].

The need to use alternative and accessible materials should be considered when costly materials are not available and high claim for prostheses, through in earthquake or combat and battle districts, biomaterials, having resins and fibers, were derived from plants may offer the needed substitute [9].

The researchers in this field, (Loewi et al.) studied the behavior of natural fibers reinforced composite by altering the number of Jute fiber layers and their angles (±45° & 0°/90°). Mechanical (Tensile, Impact, Compression, Flexural, Creep, and Hardness), and physical (Density and Hot Disk) properties were acquired for this drive. The results proved that the mechanical properties enhanced with raising the number of Jute reinforcing layers and at the direction (0º/90º) of fibers concerning tensile load [10]. (Jumna et al.) Suggested lamination (1 bamboo 2 fiber carbon 1 bamboo) and debated it with the currently obtainable lamination (4 Purloin 2 fiber carbon 4 purloin) to obtain physical qualifications, mechanical and fatigue features for the manufacture of above the knee prosthetic socket [11]. (Fidel et al.) Calculated the moisture expansion coefficient of the above-knee prosthetic socket lamination materials. Six laminated composite materials were used in constructing a socket employing a vacuum device. The reinforced materials of these laminations were Purloin, Fiberglass, and Nano carbon powder, while the matrix material was polyurethane resin [12]. (Irwin, et al.) Produced a prosthesis socket made from natural fibers, ramie natural fiber reinforced epoxy (RE) composite to construct a socket with fiberglass polyester composites (FGP). The production process was preceded by using the filament winding technique. Tensile and flexural tests were applied to laminations. The results displayed that socket prosthesis prepared of RE has the uppermost tensile and flexural strengths when related to FGP composite materials [13]. Roadman aimed to use woven kneads natural fiber as a substitute for glass fiber to produce the socket of a prosthetic leg. Sandwich lamination procedures were used to prepare the specimens. Tensile, flexural, impact and moisture content tests were used to associate with conservative materials used to make prosthesis sockets [14]. (Kashmir et al.) Submitted to improve the mechanical properties of the socket by changing the type of composite material and changing the arrangement of the layers by tensile and fatigue test also measuring the interface pressure between the socket and the remaining part of the amputation. Purloin, carbon, Bamboo, Fiberglass stockinet were used as reinforcement materials while Lamination resin 80:20 polyurethane was used as a matrix material. The results suggested that the best-suggested material to be selected is from the suggested group (Two layers of bamboo, one layer of carbon fiber, two layers of bamboo, one carbon fiber, two layers of bamboo with lamina) due to its high mechanical properties [15]. (Wichita et al) investigated the potential to replace the conventional materials with composites of methyl methacrylate polyester resin with water hyacinth fibers as reinforcing materials and to characterize their mechanical behavior to evaluate their suitability for socket prosthesis applications. Tensile and bending tests were used to fulfill this purpose. From this study, they concluded that the resin and water hyacinth fiber composite socket has the potential to replace the standard layup [16].

War, land mines, main usual tragedies, for instance, earthquakes and deluges, in addition to chronic illnesses, including vascular infections. For example, diabetic difficulties, arteriosclerosis, and thromboembolism are altogether donating aspects to the universal request for prostheses [17, 18]. The outcomes of our experimentations in which we survey the probability of creating a lower prosthetic limb socket made from renewable materials were presented. The hybrid fibers (which consist of combining natural, synthetic) used in the manufacture of composites can endure a greater load in various directions depending on the type of reinforcement, and the contiguous matrix keeps them in the preferred position and alignment, performing as a medium to transfer higher load among reinforcements.

The focus was to first recognize suitable resin polymer and natural fiber arrangements by conducting a series of tests. The test sockets that were prepared to utilize stockinet woven were from the best fiber. The goal here is to prove that prosthetic limb sockets can be built from renewable, low-hazard resources minus conceding the strength of these composite materials.

2. Experimental Part

This section describes the materials, equipment, and manufacturing steps of socket manufacturing, which could partake helpful mechanical properties. Also, describe the details of the mechanical and morphological tests.

2.1 Materials used

Materials used in the below-knee lamination socket for this research are flax, sisal, and cotton fibers which were made by (Changzhou Doris textile co.,ltd Company), as a woven mat. They were dipped in 5% of NOAH solution for about two hours at room temperature. After the alkaline treatment, these fibers were thoroughly washed by running water so the fiber is stronger and more durable and achieves better bonding with matrix materials.

The additional materials needed are unidirectional carbon fabric (a type of carbon reinforcement that is non-woven features all Fibres running in a single, parallel direction manufactured by Otto bock company), glass Fibre (manufactured by Otto bock company), Person stockinet (item name from the company is (623T5) manufactured by Otto bock company), Lamination resin: Polymethyl methacrylate (PMMA), hardening powder (Otto bock health care 617P37), polyvinyl alcohol (PVA) bag (Otto bock health care 99B71), and Jepson for casting.

2.2 Equipment Used in This Study

1) A positive Jepson mold with rectangular figure and size 25*20*10 cm^3.
2) Vacuum forming system, which consists of a vacuum pump and diverse kinds of stands, pipes, and tubes.
3) Digital Venire and sensitive weighing maneuver for measuring the dimension and weight of samples.
4) Mechanical workshop done in the University of technology/training and workshop center includes different gears for cutting by CNC machine.

2.3 Fabrication of Laminate Composites

The masses of reinforcement and matrix material are calculated based on the obligatory volume fractions. Specimens were prepared by a vacuum modeling procedure with lamination lay-up given in Table 1. For fabricating the specimens, the gypsum mold is set and fixed at the entrance of the pressure vacuum and associated with the pipes of the pressure system. PVA layer was positioned on the positive mold, and then pressure valves were released to a value of 4o kappa at room temperature as shown in Figure 1a. Reinforcement layers were applied (two layers of purloin fiber) then one layer of cotton fiber another two layers of purloin fiber as shown in Figure 1b. A layer of PVA bag is placed above composite material layers, then using the string to tie up the end of the PVA bag. The matrix materials which hold a mix of PMMA polymer resin and hardening powder combined conferring to the known standard ratio in which every 100 parts of acrylic resin commingled with (2-3) parts of powder and then inserted into the layers and evenly disseminated thru the small tube and after continue for 10 minutes and a cubic composite material is acquired as shown in Figure 1c. After cooling the composite materials were cut off to obtain manufacturing samples to allow testing. This procedure was repeated for all the laminations.

Table 1: Types of Composite Materials

No. of Lamination	Total No. of layers	Lamination lay-up	Lamination layup procedures
Lamination 1	5	4 perlon+1 cotton (1CO)	(2P +1CO+2P) layers
Lamination 2	6	4perlon+ 2cotton (2CO)	(2P +2CO+2P) layers
Lamination 3	7	4perlon+3 Cotton (3CO)	(2P +3CO+2P) layers
Lamination 4	9	4perlon+3 Cotton+2 Carbon (COC)	(2P +1CO+1C+1CO+1C+1CO+2P) layers
Lamination 5	9	4perlon+3Cotton+2 Fiber Glass(COG)	(2P +1CO+1G+1CO+1G+1CO+2P) layers
Lamination 6	5	4perlon+1flax (1F)	(2P +1F+2P) layers
Lamination 7	6	4perlon+2 Flax (2F)	(2P +2F+2P) layers
Lamination 8	7	4perlon+3flax (3F)	(2P +3F+2P) layers
Lamination 9	9	4perlon+3 Flax+2 Carbon (COC)	(2P +1F+1C+1F+1C+1F+2P) layers
Lamination 10	9	4perlon+3flax+2 Fiber Glass (FG)	(2P +1F+1G+1F+1G+1F+2P) layers
Lamination 11	5	4perlon+1sisal (1S)	(2P +1S+2P) layers
Lamination 12	6	4perlon+1sisal (2S)	(2P +2S+2P) layers
Lamination 13	7	4perlon+1sisal (3S)	(2P +3S+2P) layers
Lamination 14	9	4perlon+3 Sisal+2 Carbon (SC)	(2P +1S+1C+1S+1C+1S+2P) layers
Lamination 15	9	4perlon+3flax+2 Fiber Glass (SG)	(2P +1S+1G+1S+1G+1S+2P) layers

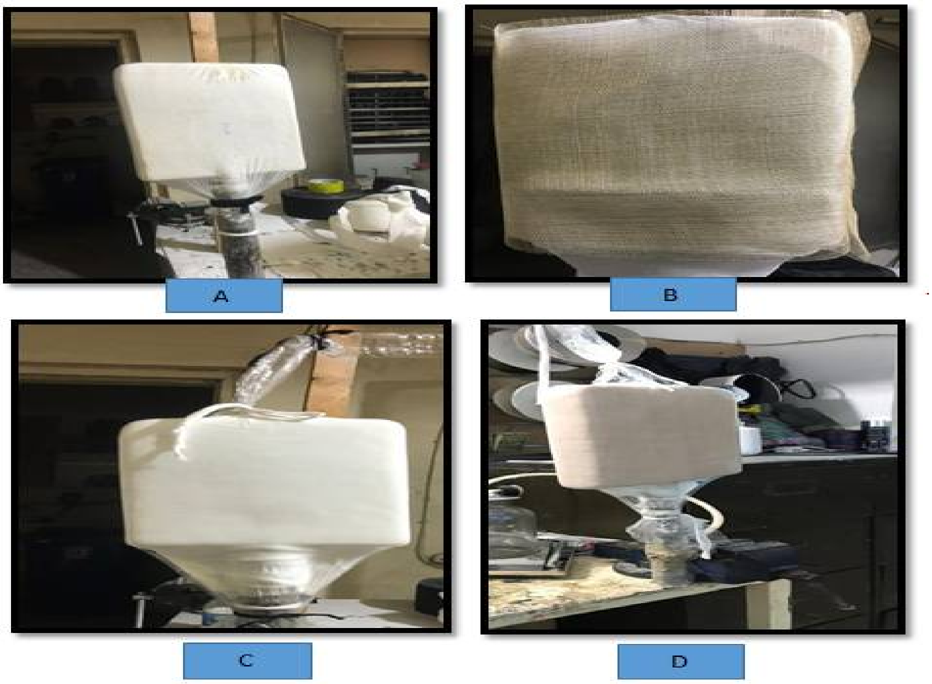

Figure 1: The Steps of Test Specimens Preparation

2.4 Mechanical properties

The mechanical features of a material are those properties that implicate a response to an applied load. The mechanical characteristics used to define the utility of a material, service life that can be expected, help categorize and recognize the material.

2.4.1 Hardness Test

The hardness of the material can be symbolic of its overall mechanical performance. It is the property of a solid material stating surface resistance to scratch and permeation from an applied force [19].

The tests were continuing with (Shore –D) device to laminated composite samples by entombing the device indenter with a load equivalent to 50 N for a time of measuring equivalent to (15sec) in seven diverse locations from the surface of the composite samples to reach the average value of these readings. Figure 2 a and b illustrates the standard laminated composite and the specimens prepared according to ASTM (D-2240 standard) [20].

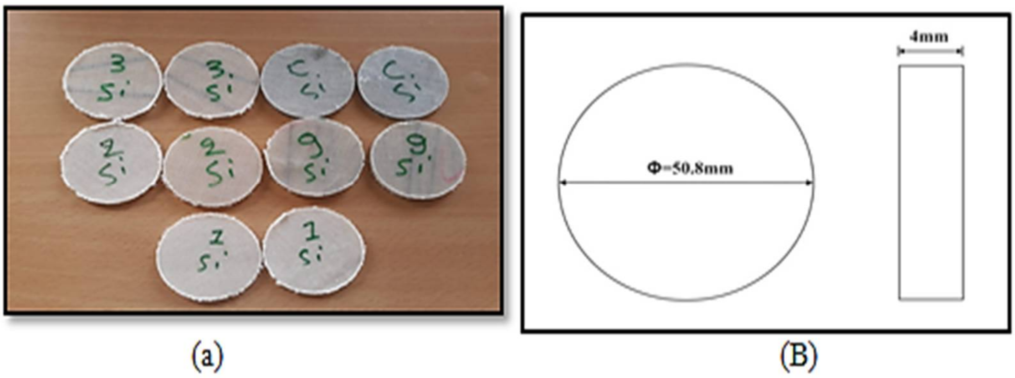

Figure 2: (A) Hardness Test Specimen, (B) Standard Specimen of Hardness Test

2.4.2 Surface Roughness Test

The surface roughness test was executed employing the profilometer device, prepared by (Maher Company), made in the USA that supplied a surface analyzer (sharp diamond stylus) and the supreme distance that can be move is (11mm).

Each specimen was verified seven times on the altered sites of each sample at a similar time and the average value was reserved.

2.5 Physical properties

Physical properties are those features that can be perceived without altering the individuality of the matter. The assets of the material such as (density and water absorption) are cases of physical characteristics.

2.5.1 Density Test

The density test is executed rendering to (ASTM D792) employing the displacement technique proved Archimedes theory. In this test, any convenient size of samples can be used, with a volume that cannot be less than ($1cm^3$). The test procedure was continued by weighing the samples in air and weighing them after immersing in distilled water, and density data can be achieved by applying the next equation.

As represented in the following equation:

$$\text{Specific Gravity (S.G)} = \frac{W_D}{W_D - W_i + 0.02} \quad (1)$$

Where:

W_D: Mass of dry sample (gm).

W_I: Mass of the sample after submersing and suspended in water (gm.).

0.02: Mass of engaging wire.

Specific gravity can be altered to density ($gm./cm^3$) by multiplying the specific gravity by D which signified the density of distilled water (gm/cm^3) that is equivalent to (0.9975) [21].

2.5.2 Water Absorption Test

The water absorption test is accomplished rendering to (ASTM D570). In this test, the sample was engrossed in distilled water underneath an exact temperature and time. By completely immersing the samples in a vessel of distilled water at room temperature (23 ± 2) ℃ and for (24hr), after that the samples were detached from distilled water. Then, surfaces were smeared off the water with a dry fabric and weighed by employing a digital balance device and water absorption was achieved by using the equation below. Figure 3 displays the standard sample used for this test [22].

$$\text{Water Absorption \%} = \frac{W_S - W_D}{W_D} \times 100 \quad (2)$$

Where:

W_D: Mass of the dry sample before immersion

W_S: Mass of the sample after immersion in distilled water for (24 hr.) at room temperature.

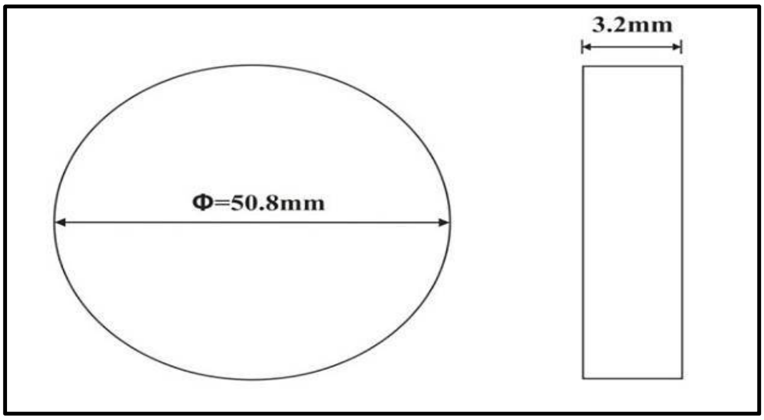

Figure 3: Graphic Sample for Standard Specimen of Water Absorption Test

3. Experimental results

3.1 Physical Features of Samples

Figures 4 show the effect of reinforcing material used in the composite prosthetic socket on the average thickness of the composite specimens. There were no significant differences across all reinforcement. Matrix material seemed to bond better with specific materials than others based on thickness comparison. In addition, the absorbing ability in the lamination is increased slightly when cotton fibers are used leading to increase thickness and hybrid (Cotton Glass) reinforcement having the highest thickness [23].

Figure 5 illustrates the variation of volume fraction of composite specimens with changing the type of reinforcing material, which was calculated theoretically by the Rule of mixture [24, 25]. It can be seen from this figure that the specimens with hybrid (Cotton Glass) reinforcement have the highest volume fraction [26].

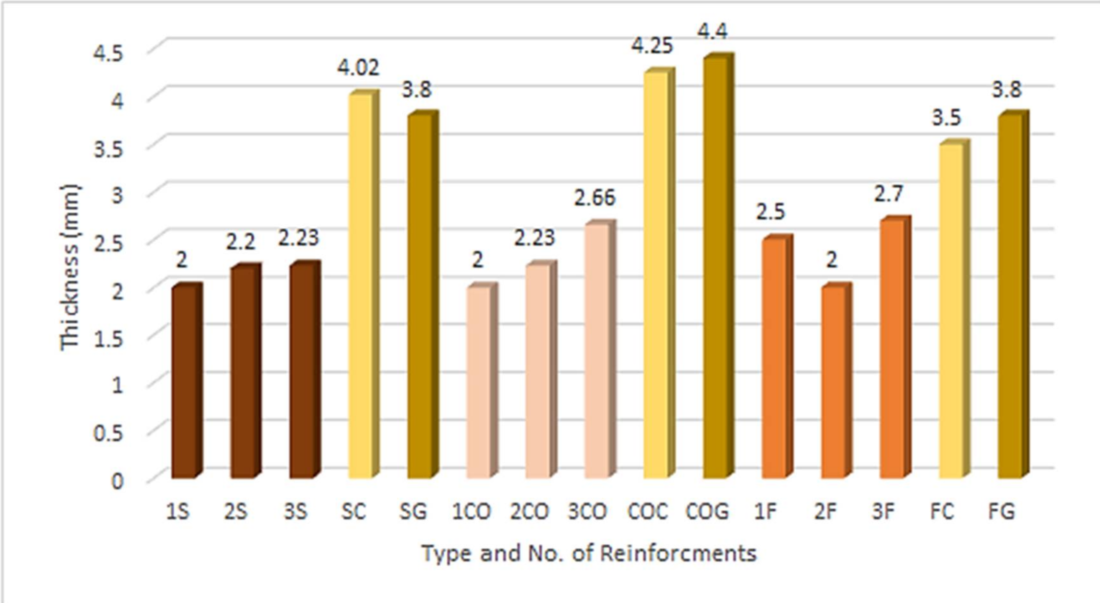

Figure 4: Effect of Reinforcing Material on the Thickness of the Composite Specimens

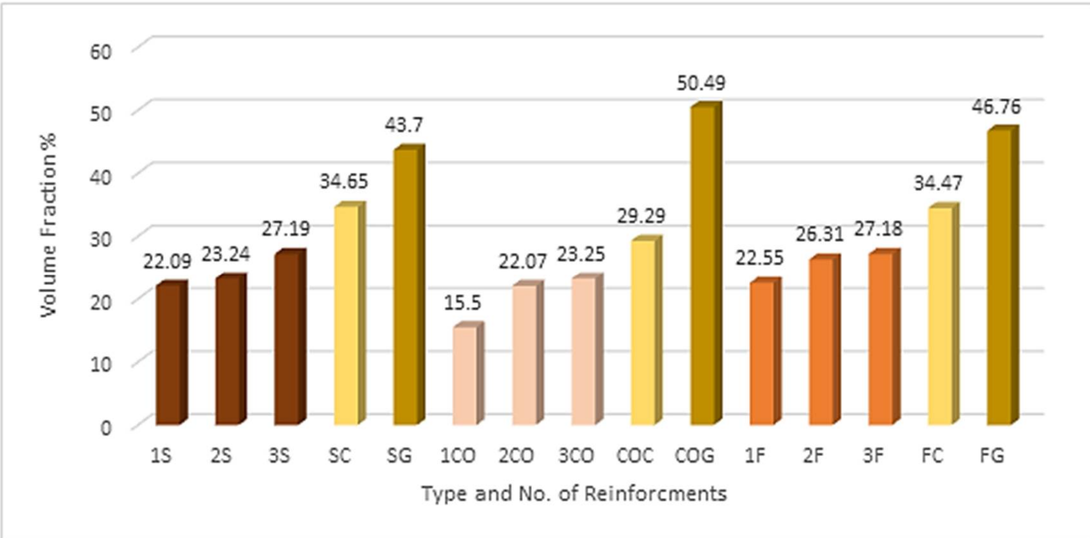

Figure 5: Variation of Volume Fraction of Laminations

3.2 Mechanical Tests Results

3.2.1 Results and Discussions of Hardness Test

From Figures 6, 7, 8, it can be perceived that the values of hardness property rise by growing the number of flax, sisal, and cotton layers. Where fiber layers increases, the hardness property was improved as the fiber volume fraction is amplified [27, 28]. However, for these specimens, the variance in hardness is due to the variance in the properties of flax, sisal, cotton, glass, and carbon fibers. Therefore, by comparing the fifteen laminations, the three layers of flax fiber with carbon fiber consume the uppermost values of hardness. This can be subsidized to the existence of carbon fibers with thus confirming the transmission of loads from matrix to fiber [29].

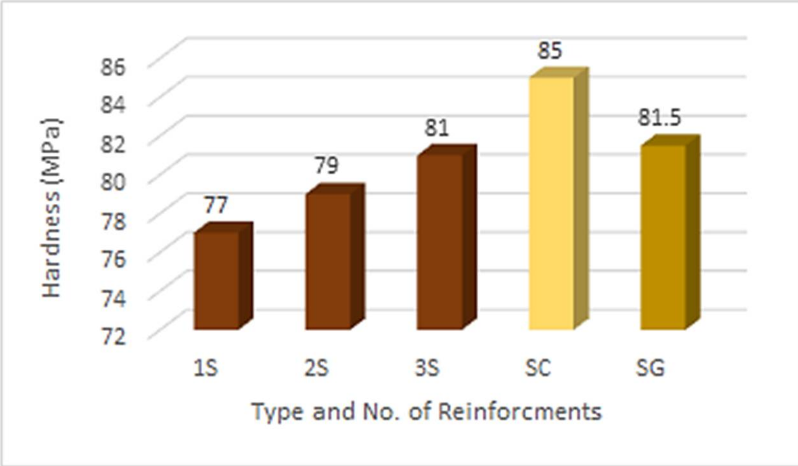

Figure 6: Hardness (Shore-D) of Laminated Composite Materials and Woven sisal Fibers

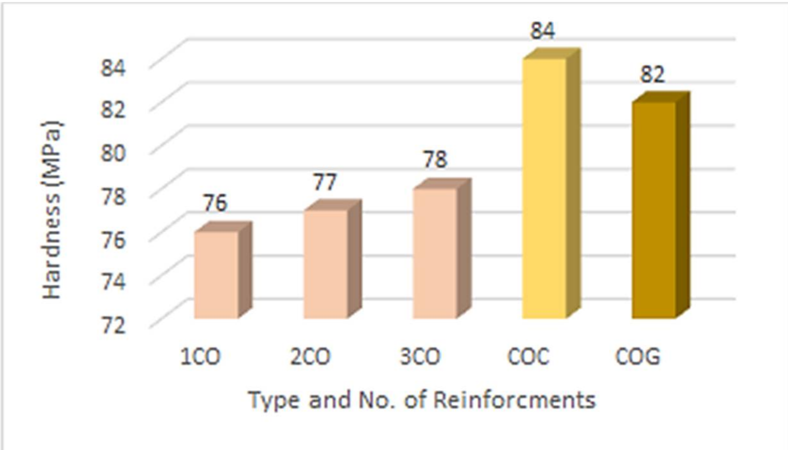

Figure 7: Hardness (Shore-D) of Laminated Composite Materials and Woven Cotton Fibers

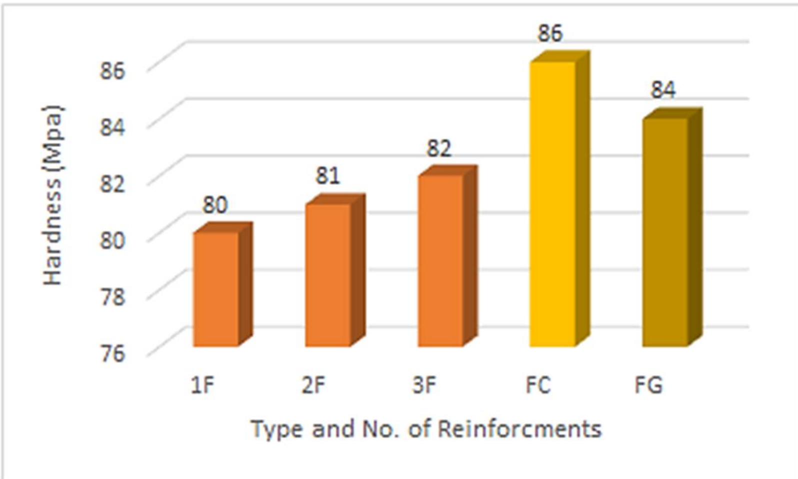

Figure 8: Hardness (Shore-D) of Laminated Composite Materials and Woven flax Fibers

3.2.2 Results and Discussions of Surface Roughness Test

Figures 9, 10, and 11 shows the affiliation amid the form and no. of layers of altered kinds of natural fibers reinforced PMMA polymer resin and surface roughness property of the samples for all lamination groups.

The values of surface roughness feature rose with the growth of the layer numbers of flax, sisal, and cotton fibers for all groups [30]. Therefore, by relating the fifteen laminations, the three layers of cotton fiber with carbon fiber spent the maximum values of surface roughness for composites. In addition, it can be perceived that when with the addition of a woven mat of glass fiber or natural fiber in PMMA composite, the surface roughness decreases as associated with paring the natural fibers with carbon fibers.

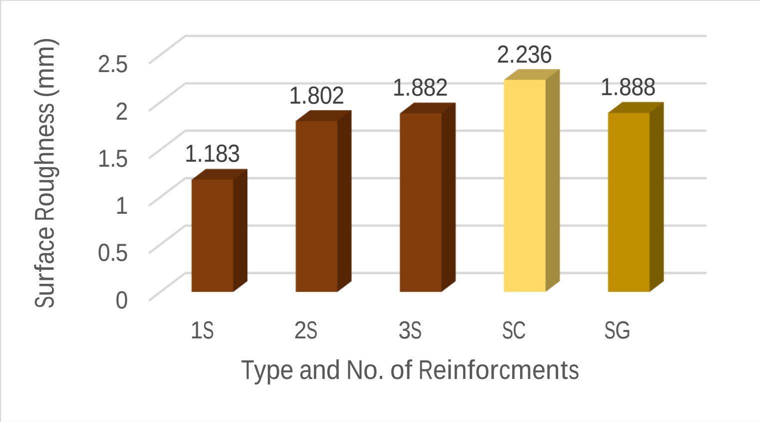

Figure 9: Surface Roughness of Laminated Composite Materials and Woven Sisal Fibers

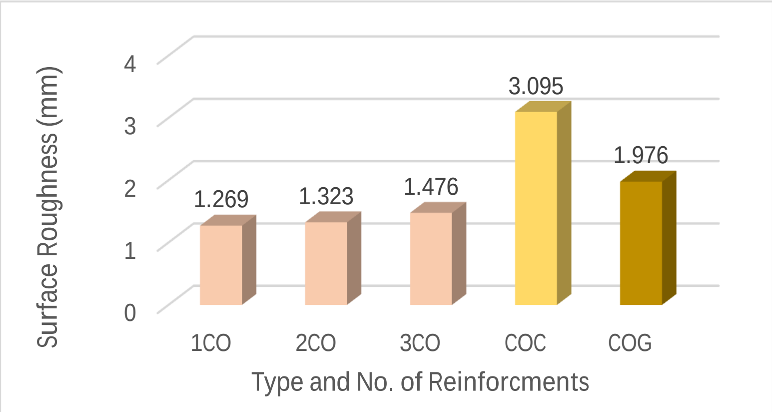

Figure 10: Surface Roughness of Laminated Composite Materials and Woven Cotton Fibers

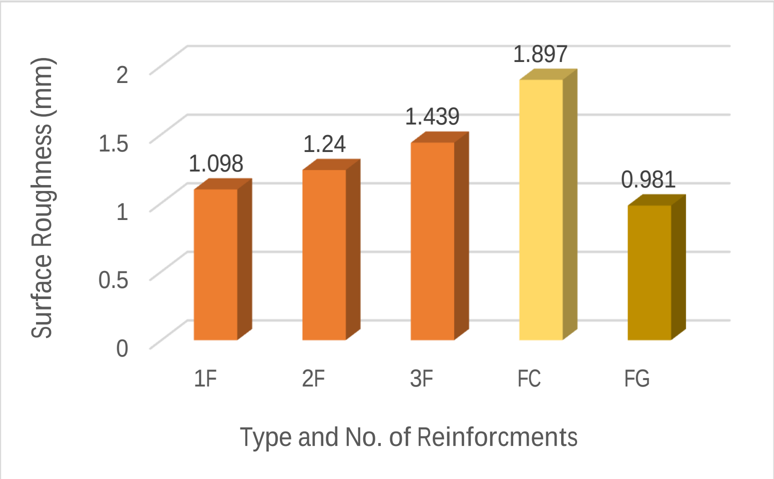

Figure 11: Surface Roughness of Laminated Composite Materials and Woven Flax Fibers

3.3 Physical tests

3.3.1 Results and Discussions of Density Test

In this test, the density for all groups can be premeditated by using the Archimedes method. Figures 12, 13, and 14 express the relationship between the number of reinforcing fibers and density for all the lamination composites. It can be perceived from the data that the values of density property enlarged with the rising of the volume fraction [27]. It can be perceived that with the accumulation of a woven mat of glass and flax fibers in PMMA polymer resin, the density surges. This could be credited to the detail that the fiberglass is categorized by their upper density than the PMMA matrix, consequently upsurge the density of the hybrid laminated composite specimen [19].

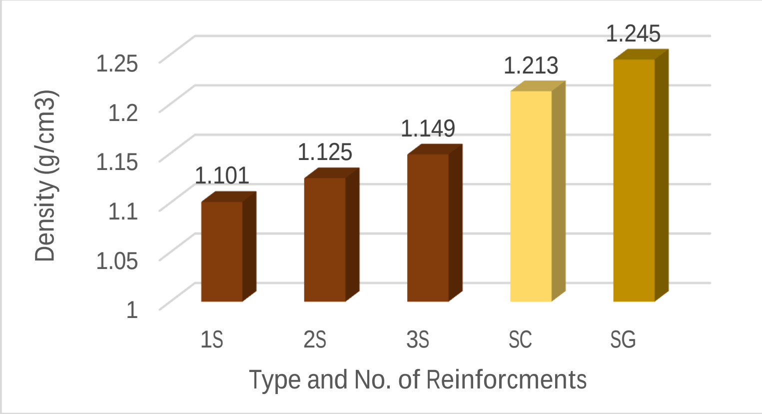

Figure 12: Density of Laminated Composite Materials and Woven Sisal Fibers

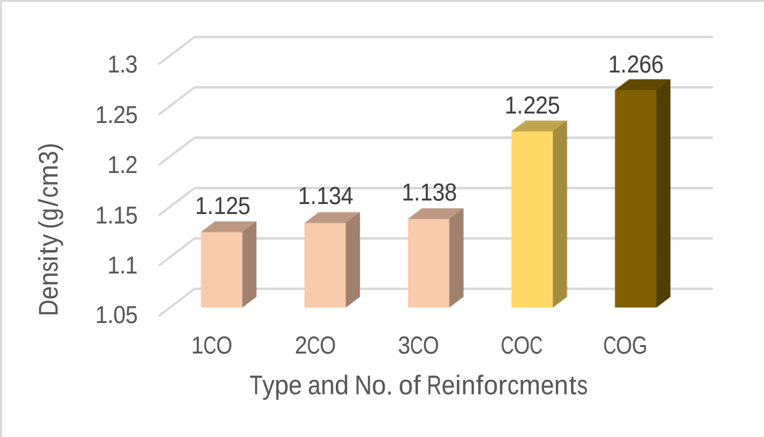

Figure 13: Density of Laminated Composite Materials and Woven Cotton Fibers

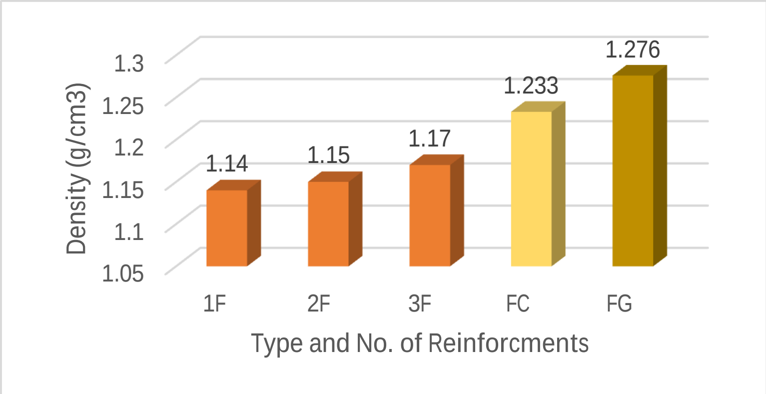

Figure 14: Density of Laminated Composite Materials and Woven Flax Fibers

3.3.2 Results and Discussions of Water Absorption Test

With intermingling with water throughout their facility life, polymeric materials are vulnerable to degradation. The existence of moisture in the composite result in enlargement, hydrolysis, and plasticization of the polymer matrix [31].

From the data obtained, it can be perceived that the values of water absorption percentage were reduced with the growth of the volume fraction of all lamination groups as shown in Figures 15, 16, and 17. This can be contributed to the fact that with the growing number of reinforcing layers, all the spaces, and cavities, which were inside the PMMA matrix, will be lessened or occupied by these reinforcements. Consequently, in the outcome, the water absorption percentage will be reduced of prepared composite specimens [32].

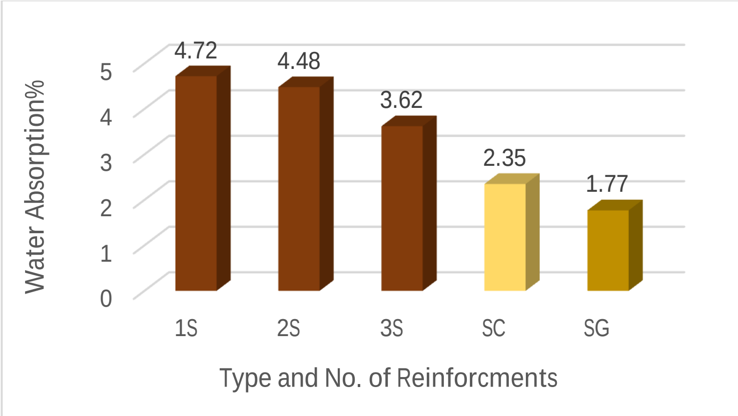

Figure 15: Water Absorption (percentage) of Laminated Composite Materials and Woven Sisal Fibers

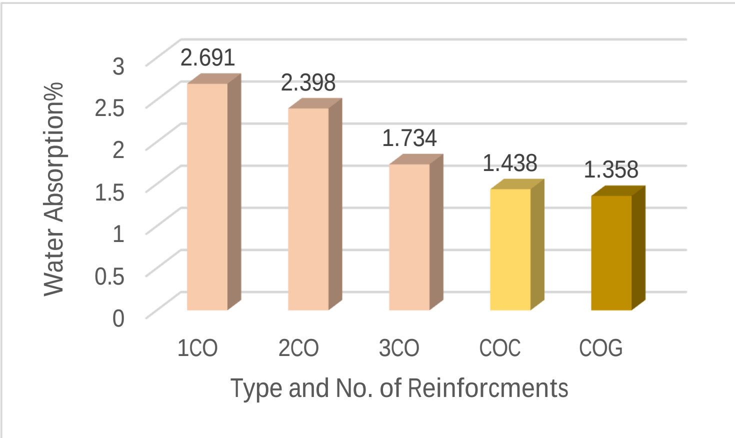

Figure 16: Water Absorption (percentage) of Laminated Composite Materials and Woven Cotton Fibers

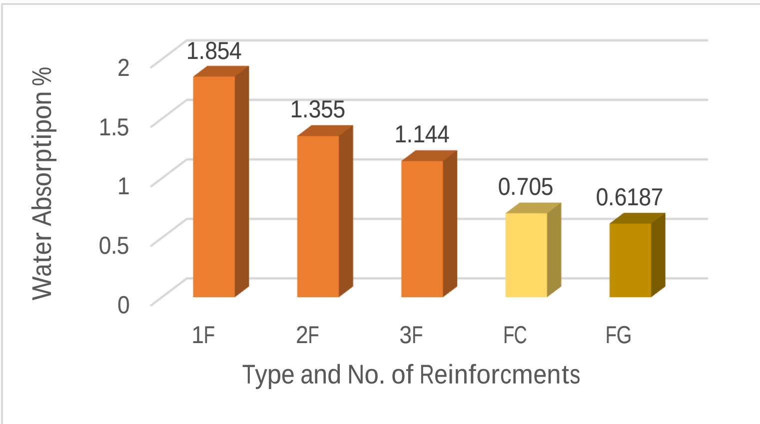

Figure 17: Water Absorption (percentage) of Laminated Composite Materials and Woven Flax Fibers

4. Conclusions

In this work, fifteen types of composite materials were proposed for comparison between them and choice of the best to be an alternative to the material currently available in the manufacturing of the socket. The purpose of selecting a composite material to be a suitable alternative and obtaining a more strong and lightweight material to bear the high weights of the patients when used in the manufacturing of the socket. The main findings of this study are as follows:

1) Hybrid (cotton glass) reinforcement had the uppermost thickness and volume fraction.
2) There is a prodigious consequence in the hardness of the socket with varying its material, by using the stacking arrangement: 4perlon fiber –3flax-2-carbon fiber.
3) The surface roughness of hybrid laminated materials grasped its maximum value in lamination (4) with (3.095 mm) and its lowermost value in lamination 6 with (1.098 mm).

4) The maximum values for density were found in flax/carbon hybrid laminated composite materials with (1.276 gm. /cm^3).

5) The highest water absorption percentage values were reached with one sisal layer culminating at (4.72 %).

Author contribution

All authors contributed equally to this work.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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