Chapter One

Introduction

1-1 Amputation:

People who have had an amputation experience several issues, including decreased mobility, changing body perception, and lingering pain. Analysis to help comprehend these effects enables improved recovery and lengthy treatment plans, as well as the development of an information foundation from which we can more properly tell people about their predicted results. However, problems with community selection are common in amputation studies, limiting our capacity to derive precise conclusions [1].

The number of amputations in Iraq has steadily climbed. This is undoubtedly due to a massive number of terrorist attacks and a diminishment in the country's medical level, as well as nuclear radiation existing in our country due to consecutive wars, which led to an increase in the number of amputations [2].

Lower limb amputation accounts for (80 - 85 percent)of major limb amputations in the United States, but it has risen to 97 percent in Denmark [3, 4].In the last ten years, this number has risen from 80.7 percent to 89.3 percent in Iraq [2].

Amputation is a surgical operation that has been used for over a century. When a limb is declared non-salvageable after a serious injury (e.g., a war injury or a car accident), or when tissue loss is due to vascular occlusive disease, or infection, it is frequently performed. A prosthetic limb is commonly assumed to be able to substitute a missing limb both visually and functionally [5].

The optimal level for a below-knee amputation in the presence of adequate blood flow is at the intersection of the middle and lower thirds of the leg. Nevertheless, the level of amputation is frequently influenced by the basic pathology, such as infection, tissue scarring, and other variables. All effective lengths should be saved to the optimum level to provide a pleasant, non-tender stump [6].

Amputation necessitates a period of rehabilitation for the patient to address difficulties such as discomfort and loss of function, which may include several professions such as psychologists, physiatrists, physiotherapists, and prosthetics. Rehabilitation of individuals who have had their lower limbs amputated is a difficult task that must take into account a variety of circumstances [7, and 8].

1-2 Classification of Trans-Tibial Amputation:

Landmines or limb illnesses are the most common reasons for the amputation of a lower limb. The levels of typical amputation are depicted in figure (1.1). Transfemoral amputations are amputations of the lower limbs above the knee; the most frequent is at the mid-thigh (resection above the knee but below the hip).

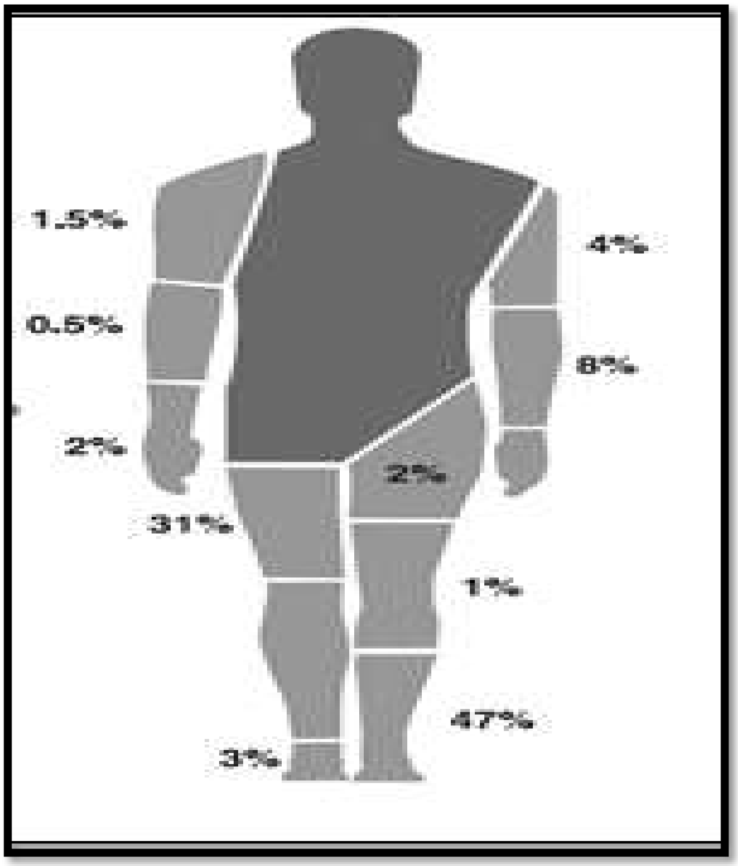


Figure (1.1): The percentage of limb amputation at all levels [1]

Transtibial (resection just above the foot but below the knee) amputations are those that keep the knee intact and can happen anyplace beneath the knee, comprising ankle and foot, as shown in figure (1.2) [9].

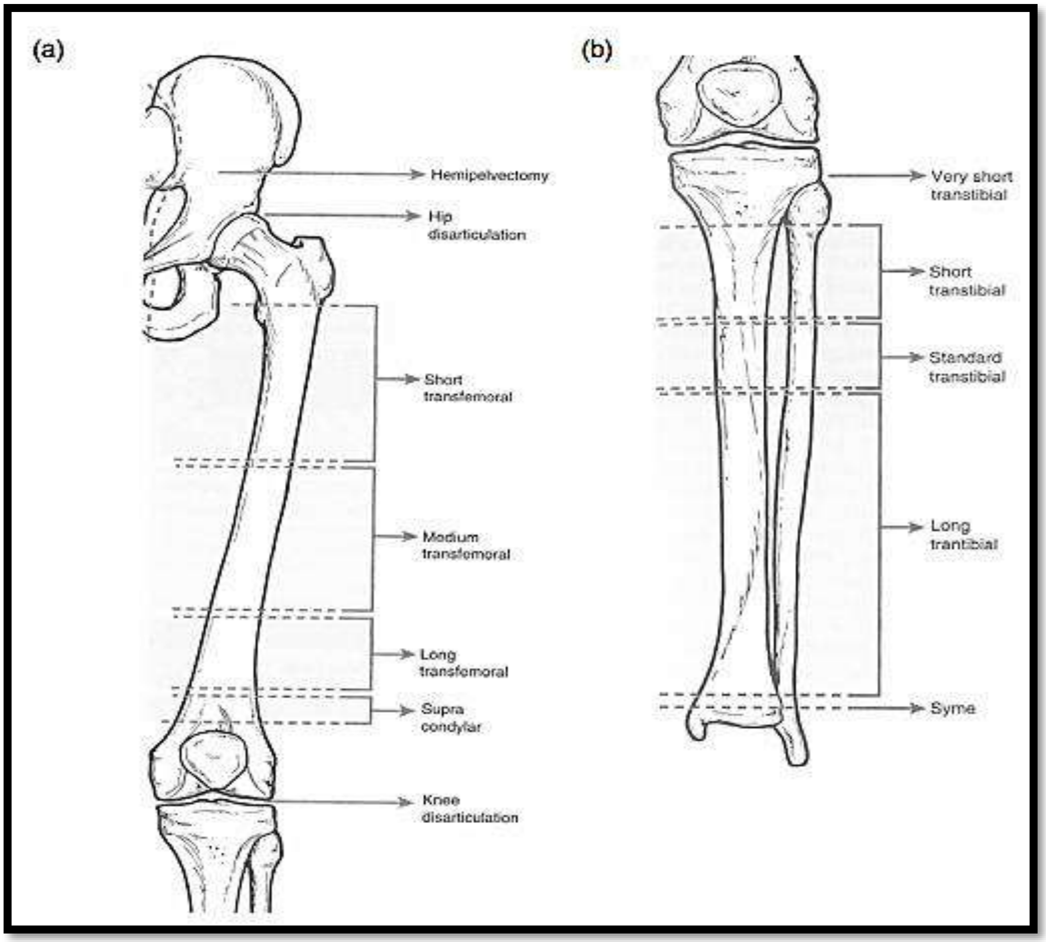


Figure (1.2): (a) Transfemoral or above-knee level and (b) Transtibial or Below-knee amputation level [10].

The most common major limb amputations are transtibial amputations, often identified as "below-the-knee" or "BK" amputations. Transtibial amputations account for more than half of all major lower-limb amputations, and the number of individuals with lower-limb amputations is anticipated to double by 2050, owing to dysvascular disease caused by an aging population and a rise in diabetes and heart disease [11].

The loss of the lower limb is exacerbated by the removal of the articulated ankle joint, foot joints (particularly the metatarsal-phalangeal joints), and muscles of the anterior and posterior compartments of the shank [12]. Figure (1.3), typically comprise four major components of BK prostheses:

1) Socket

2) Pylon (shank)

3) Foot prosthetic

4) Couplings [13].

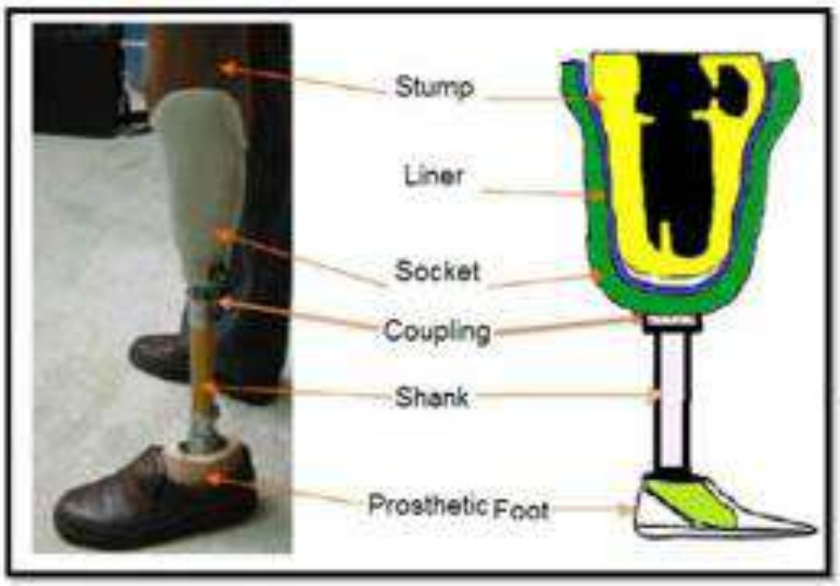


Figure (1.3): The Prosthesis Components [14].

The primary function of a prosthetic foot, shank, and socket are to replace the skeleton and muscles of the foot, ankle, and shank that have been lost [15].

The general comfort and role of a below-the-knee (BK) prosthesis are heavily influenced by the design of the prosthetic socket [10]. To amputate a limb and fashion the stump, good knowledge of the prosthetic process is required, as well as close collaboration as a team with the prosthetic specialist and the physiotherapist [16].

1-3 Prosthetic System:

Prosthetic systems must incorporate several components. Many items are easily available, but others must be produced to order for every patient. There are two types of transtibial prosthetic structures: endoskeletal and exoskeletal, as illustrated in figure (1.4). These structures have three basic constituents: a socket, a pylon, and a foot [7]. A pylon attaches the socket to the foot in an endoskeletal system. Figure (1.4a) displays a lightweight and adjustable arrangement. The system can also be enclosed with cosmetic skin if chosen [17]. While figure (1.4b) depicts an exoskeletal design that includes a rigid covering that attaches the socket to the foot. This structure has the advantage of being more durable, but it is also the heaviest of the pair [18].

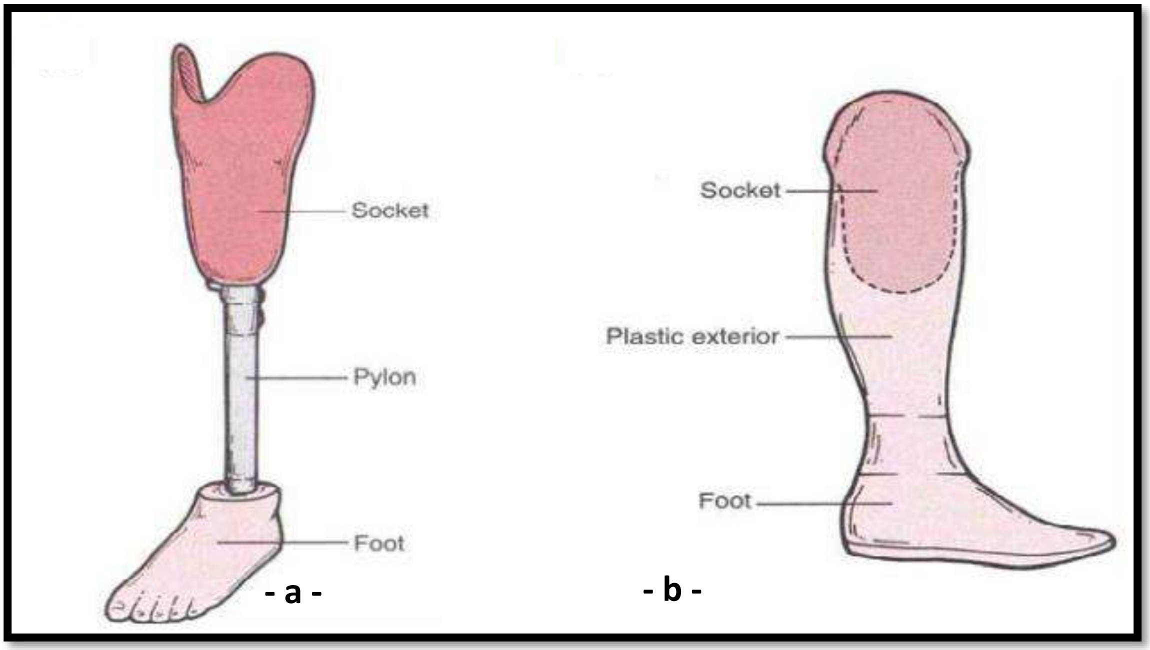


Figure (1.4): (a) Endoskeletal and (b) Exoskeletal transtibial prosthetic systems [17].

1-4 Socket:

The socket is the component of the prosthesis that links the remaining limb. It is the most important part of the prosthetic. If the prosthesis does not have a stable, strong, yet pleasant socket, it will not be deemed a success. If these requirements are not met, the patient will refuse to wear the prosthetic or be severely dissatisfied [19].

In today's prosthetics, a wide range of natural and man-made materials are utilized. They must, however, meet the requirements of the profession, whether natural or man-made, in biocompatibility, strength, longevity, lightness, and ease of production. Prosthetic materials must be nontoxic, physiologically and chemically stable, and have enough mechanical integrity and strength to bear the loads [20].

Previously, sockets were carved from wood or formed from aluminum. While both materials were capable of supporting weight, they were difficult to work with and time-consuming to produce [21]. However, manufacturing technology has advanced to the point where they can now be made from one of two materials: a thermoplastic sheet made of polypropylene developed by the ICRC (International Committee of the Red Cross) or a laminated composite, as shown in the figures (1.5 a, b) [19, and 22].

The number and type of reinforcement layers determine the mechanical features of a plastic laminate. It can be enriched by raising the number of high-tensile-strength layers [23].

Other user-based specifications comprise the provision of ease and effectual body movement. To accomplish the necessary comfort, the socket must be well fitted to the remaining limb; pressure amid both the remaining limb and the socket, as well as extreme tissue loading, can cause discomfort. Three conditions must be met to attain efficient locomotion: (1) a steady foot on the land; (2) a smooth rollover from the time the heel touches the land until the toe leaves; and (3) it should be able to move the limb onward efficiently after the toe quits the land [7].

The socket is the component of the prosthesis that grips the amputee's stump and is shaped so that forces are dispersed relatively evenly across the total surface area of the stump [23].

Lower-limb prostheses are frequently employed to reinstate the function and appearance of individuals who have had limbs amputated. Lower-limb prostheses are becoming more popular in the market, not only in quantity but also in quality. Because the socket offers a connection between the residual limb and the prosthesis, the design of the prosthetic socket is crucial in determining the quality of fitting. The socket's form is not a replica of a residual limb. To enable more efficient load transfer, a proper alteration of the residual limb is needed. The shape of the residual limb, tissue assets, and soft tissue load tolerance [24] may determine the alteration.

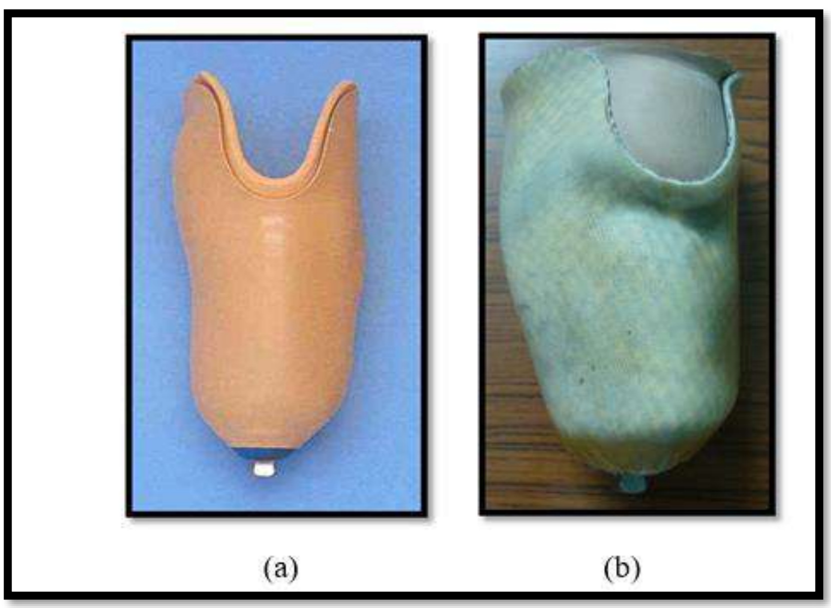


Figure (1.5): (a) Polypropylene Socket and (b) Laminated Socket [25]

1-5 Gait Cycle:

Walking is referred to as "a form of mobility involving the alternate use of the two legs to provide both help and propulsion". Proper walking is characterized by a repetitive order of limb motions that propel the figure onward whereas preserving a consistent posture. The term “gait” refers to a person's walking style rather than the walking process itself [26, 27]. Gait entails putting one foot onward, then the other, outputting the same foot onward once more, and reiterating the sequence of occurrences. Taking each limb one at a time, each gait cycle has two major phases: the stance phase and the swing phase. The stance phase is the interval between the heel striking the floor and the toe leaving the floor, and it accounts for approximately 62 percent of the overall gait cycle period. The swing phase is designated as the period amid when the toe drops the floor and when the heel of the similar foot strikes the floor, and it regards for around 38% of the entire gait cycle period. [28]. The gait cycle of an individual is generally involved in the following steps [29], as shown in figures (1.6).

- Initial contact in the stance phase
- Loading response
- Mid stance.
- Terminal stance
- Toe-off
- Initial swing
- Mid swing
- Terminal swing in swing phase.

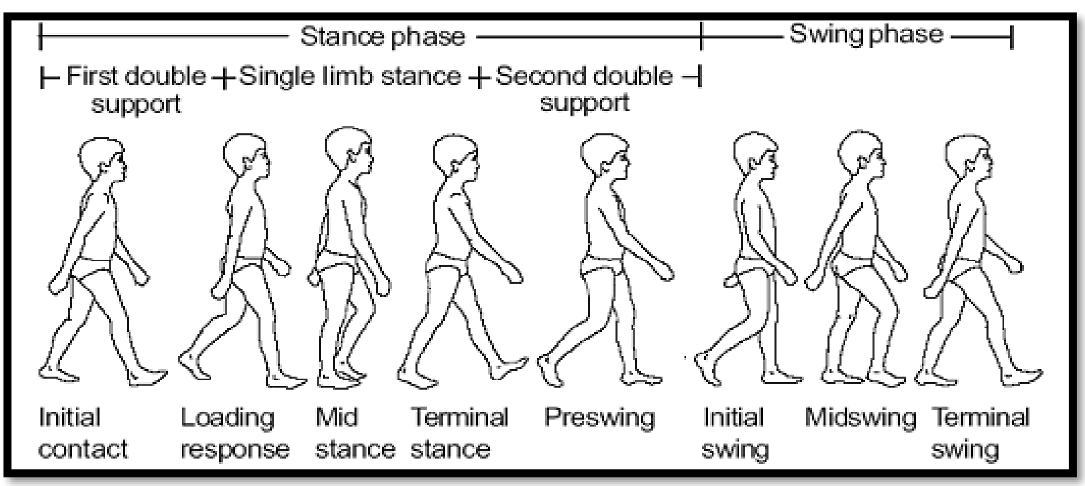


Figure (1.6): The general steps of the human gait cycle [29]

1-6 Problem of the work

Thousands of Iraqi war victims have suffered because of three wars, resulting in thousands of amputees and increased demand for artificial limbs, particularly lower-limb prostheses, due to injuries caused by landmines. Even though numerous studies have been conducted in Iraq over the years to analyze the mechanical properties of materials used in lower-limb prostheses as well as the static strength of lower-limb prostheses, the novel proposed fiber-reinforced employed in prosthesis manufacture has not been evaluated. The goal is to prove that prosthetic limb sockets can be built from renewable, safe resources without conceding the strength of these composite materials.

1-7 Motivation

Natural fiber-based composites are less harmful to the environment and are utilized in a wide range of applications such as prostheses, transport, and construction. The results were presented as a survey of the possibility of creating a lower prosthetic limb socket made from renewable resources. This study suggests that combining natural and synthetic hybrid reinforcements allows for the creation of bio-composites with improved performance.

The hybrid fiber reinforcements in the composites can withstand a higher load than single-fiber reinforcements in a variety of paths proven on the reinforcement, and the matrix retains them in the favored position and orientation, acting as a greater load transfer medium between them.

This study revealed the advantages of flax, sisal, and cotton fiber hybrid reinforced Poly Methyl Methacrylate (PMMA) resin composites (hybridized at various volume percentages and lamination layup) which had not previously been investigated.

1-7 Objective of the Work:

The following goals were planned to achieve during the present work:

1. Suggest new natural fiber-based composites (NFCS) for designing and manufacturing below-knee prosthetic sockets, as well as being able to choose the applicable layups with the best mechanical characteristics.
2. Experimentally improving the material used in the manufacture of the below-knee socket by laying up several laminations and analyzing the composites and their constituents over a series of experimental tests, to study their mechanical and physical properties and designate natural materials as a probable choice for the fabrication of the prosthesis.

3. Simulate the experimental results numerically by the using finite element method (FEM) - Ansys workbench program to associate the outcomes attained experimentally with an appropriate numerical model that should be capable to offer a virtuous agreement in relations of ultimate load, over-all behavior, and failure approach of the samples fabricated and established in the laboratory.
4. Theoretically by calculating: The factor of Safety, Poisson Ratio, Volume Fraction, and Failure Index.

1-8 Thesis Layout

Seven detailed chapters cover the general theme of this thesis:

Chapter One: This chapter provides an overview of the prosthetic socket, the materials used to make it, and the purpose of this research

Chapter Two: Explains the historical features of the prosthetic with the review and presents the literature review, which will give a general idea of the investigations.

Chapter Three: Includes the theoretical part that involves an introduction, prosthetic socket materials, bio composite materials, reinforcing materials, the matrix materials, the rule of mixture, mechanical, physical, and miscibility properties required for prosthetic sockets in this study.

Chapter Four: Offerings experimental effort providing details of the materials used in a prosthetic socket, followed by the fabrication of specimens prerequisite in this study. In addition, the experimental work comprises executing tests for estimation of the diverse features of the socket.

Chapter Five: Describes the steps involved in performing a numerical inquiry of a prosthetic socket by utilizing the finite element technique.

Chapter Six: Presents the results and discusses the experimental and numerical parts obtained.

Chapter Seven: The final chapter presents the main conclusions and commendations that can be haggard from this work for future inquiry.

Chapter Two

Literature Review

2-1 Historical Review for Prosthetic Limbs

Amputation is a Latin word derived from the verb amputate, which means "to chop off or cutaway" and is derived from an amp, about, and putare, meaning “to prune, or to lop”. It was rarely used in Roman texts and was never thought to denote a surgical amputation. However, the verb amputate was used when criminals' hands were severed [30].

Prosthetics have a distinguished history, beginning with their primeval early stages, to their advanced present, and thrilling future revelations. Some concepts and inventions, such as the fixed-position foot, have operated and have been developed upon, while others, like the use of the iron, have fallen by the wayside or become outdated.

The Egyptians were among the first to develop prostheses. These prostheses were constructed of fiber and were supposed to be worn as a sensation of "wholeness" rather than an occupation. Researchers believe they have uncovered the first prosthetic toe in an Egyptian corpse, and it seems to be functional [31].

Amid 484 B.C. and 1800 A.D., a metallic prosthesis prepared of static and preset constituents was utilized as a means of shield and aided visual aims [32]. But the oldest known application of a prosthesis is that of Hegesistratus, a Persian soldier who was said by Herodotus to have fled from prison by chopping off one of his feet and substituting it with a wooden one around 484 B.C. [20].

In the 15th century, "Ambroise Paré," a French military barber/surgeon, presented advanced amputation treatments (1529) to the medical world and created prostheses (1536) for amputees of both the upper and lower extremities. He also designed a kneeling pin limb and foot prosthesis with an immobile posture, variable attach, knee padlock governor, and additional engineering characteristics that are still utilized in today's equipment. [33].

In 1690, "Pieter Verduyn" created a below-knee prosthesis featuring special joints and a leather collar for a better fit on the body [34].

In 1769, Louis observed that, regardless of the method used to remove over the thigh, comprising the circular method, difficulties of an uncured stump with shaft protuberance (sugarloaf deformity) sometimes demanded an additional wounding, that is, a higher-level bone segment [30].

Discrete assistances by individuals like Lames Potts (1816), Antenreith (1818), and Verdayen (1826) led to major advances in prosthetics [32].

"Sir James Syme" invented an innovative technique of ankle subtraction in 1843 that did not require a thigh amputation. This was well received by the amputee community because it means that they may walk again and, rather than a leg prosthetic, a foot prosthetic is employed. [35].

According to Benjamin Palmer in 1846, there is no need for leg prosthetics to have unattractive spaces among separate elements, so he enhanced the leg by incorporating an anterior spiral, a flat form, and concealed tendons to emulate natural-looking movement [31].

Doctor Bly's anatomical leg was designed and patented by Douglas Bly in 1858, and he called it "the most comprehensive and successful invention ever obtained in artificial limbs" [31].

In 1863, “Dubois Parmelee” incorporated a socket, knees, and a multi-articulated foot into the advanced prosthesis.

In 1868, "Gustav Hermann" proposed that artificial limbs be made of aluminum rather than steel to make them lighter and more effective. The first important advancement of the twentieth century occurred in 1912 when "Marcel and Charles Desoutter" produced an aluminum prosthetic leg after Marcel lost a leg in an aviation accident [36].

For decades, the only materials accessible for prostheses were wood and leather, but today's physical therapist has a considerably larger range of possibilities, such as modern plastics and carbon fiber, which are stronger, lighter, and more resilient [37]. New plastics, better colors, and more advanced methods are behind the creation of skin that appears to be realistic [38].

2-2 Review of Literature On Prosthetic Below Knee Socket:

One of the most significant obstacles in the field of prosthetics is still the human-machine interface, more specifically, the socket. Historically, the current list of accepted prosthetic socket materials has been adopted without extensive description and/or evaluation. This is particularly true when it comes to the impact of commonly used manufacturing techniques on these materials. This absence of material knowledge becomes noticeable when one considers that the mechanical properties of prosthetic socket materials play a critical role in limiting the possible properties of the resulting prosthetic sockets [49, and 40].

2-2-1 Literature Review of Materials Used in Artificial Lower Limb:

Phillips S.L. and Craelius W. (2005) studied the mechanical characteristics of eight different lay-ups under tensile and bending loads. Multiple fibers were bonded with three resins to create 24 unique laminates. All laminations were executed in a vacuum. The results revealed that mixtures were classified into different types centered on mechanical characteristics: the lowest was strengthened with Perlon, nylon, cotton, nyglass, and spectralon, with mechanical strengths varying between 18 and 42 (MPa); the middle range was fiberglass, with mechanical strengths varying amid 67 and 109 MPa; and the uppermost was reported in carbon fiber, with mechanical strengths varying between 236 and 249 MPa [41].

Muhsin J. J. et al. (2007), experimented with analyzing the stiffness of five prosthetic sockets composed of different materials. The testometric machine performs compression, three-point flexural, and tensile tests. Polypropylene (5mm), polypropylene (2mm), Perlon (10 layers) with orthocryl resin, Nyglass (8 layers) with orthocryl resin, and polyester resin (12 layers of Perlon, nyglass, and fiberglass fiber reinforcements).In all mechanical properties, the results showed that laminated sockets are stronger than polypropylene. According to the results of the tests, the compressive stiffness of lamination is significantly higher than that of polypropylene [42].

Muhsin J.J. et al. (2009) considered the impact of raising and reducing perlon and fiberglass layers on physical and mechanical characteristics by tensile and flexural testing of fourteen lamination groups. According to the findings of their study, the lamination made from six perlon and two fiberglass layers with lamination resin matrix 80:20 polyurethane provides the best mechanical assets while lowering the cost of socket lamination to a reasonable level. It was also discovered that increasing the number of fiberglass layers from zero to two with fixed perlon layers leads to greater mechanical properties [43]

Shayma H. M. and Oliewi J. K. (2010) used vacuum molding to create trans-tibial prosthetic sockets. The matrix materials of the composites were polyester, and (PMMA). The composites were strengthened with reinforcement fibers (perlon, glass) to determine various tensile and fatigue characteristics. Material testing and FEM (Ansys11) findings demonstrate that both the polyester matrix material and the PMMA matrix composites have a high fatigue life, but the polyester composites have better tensile and fatigue characteristics than the PMMA matrix and composite [44].

Kahtan Al-Khazraji et al. (2012) showed that altering the form of strengthening used in socket materials has a significant impact on the measured characteristics. Using a vacuum molding methodology, they created five laminated composite materials needed to create lower limb prosthetic sockets. The researchers investigated the tensile and fatigue characteristics of prosthetic sockets made of composite materials like epoxy, PMMA, and blends, carbon, glass, hybrids, and nano and micro precipitated silica particles with a median particle size of 15 m) [45].

Mustafa T. I. et al. (2012) investigated the effect of heat and creep-fatigue on the socket. It is obvious that as temperature increases. It is obvious that as temperature increases, mechanical features decline with time because of creep, resulting in failure owing to the association between fatigue and creep. The fatigue test determines failure at ambient temperature to produce an S-N curve. At 60, the stress dispersion on the socket is also being investigated. They discovered that as the temperature rises, the fatigue safety factor drops, but that stress numbers in the lateral and medial regions do not change. [11]

Adawiya A. H. et al. (2014) used a vacuum to create prosthetic sockets made of different laminations of perlon/fiberglass/perlon with Lamination resin (80:20) polyurethane. Mechanical and thermal properties (σy, σult, andσ) were tested at temperatures ranging from 20 to 60 degrees Celsius using tensile and rotational bending fatigue devices. When the temperatures are raised, the young modulus, yield strength, ultimate strength, stiffness, coefficient of thermal expansion, and S-N curve values are all predicted to drop [46].

Jumaa S. C. (2014) investigated the impact issue in below-knee prosthetic sockets using three distinct composites: (eight perlon / two carbon fiber layers), (six perlon / two carbon fiber layers), and (six perlon/1 carbon fiber layer) with Lamination resin 80:20 polyurethane. A piezoelectric sensor was used to monitor the pressure at the interface amid the remaining limb and the prosthetic socket. The absorbent energy percent in below-knee prosthetic socket lamination (6 perlon/1 carbon fiber layers) with the highest absorbent energy percent is 89.4% [47]

Shireen H. C. et al. (2015) explored the materials used in the fabrication of below-knee sockets and performed tensile tests on these materials. Material sockets (perlon, NY-glass, polypropylene with PMMA) were exposed to creep tests at 50°C by utilizing a (creep/stress relaxation) device and analysis of creep test data for each material to obtain stress relaxation coefficient by utilizing a burger model was investigated and included using a numerical method to find deflection distribution areas in the socket (AUTOCAD 2014 and ANSYS 2015). Materials with 12 reinforcements offer the best mechanical characteristics and deflection resistance due to a lower stress relaxation coefficient over time [48].

According to **Falah H. A. et al. (2019),** material testing is crucial in the construction of prosthetic sockets. Polyethylene has been largely employed in the manufacture of prosthetic sockets owing to its inexpensive price and mold ability; however, it has a high weight-to-strength ratio. The carbon fiber composite was examined with polyethylene in this investigation. The mechanical characteristics of the lamination, which consisted of (6 perlon+2 carbon fiber), were assessed. Carbon fiber had 20.4 percent higher yield stress and 18.5 percent higher ultimate stress than PE, according to the findings. Carbon fiber was believed to be mechanically better than PE in prosthetic sockets. Additionally, from the perspective of strength-to-weight ratio, carbon fiber composites beat polyethylene [49].

Ehab N. Abbas et al. (2020) studied toughness and the impact energy of several kinds of fibers and polymers to determine their success in surviving impact piling. Carbon, Kevlar, and glass fibers were used with various kinds of resins as per the ASTM specifications. To attain this purpose, tensile, bending, and impact analyses were carried out. The findings revealed that combining Kevlar with further fibers alters the strength and toughness of the material. This demonstrates that Kevlar fibers absorb energy more efficiently than other fibers utilized in laminates and prosthesis sockets. [50]

Sumeia A M. et al. (2021) A.enhanced and improved the mechanical qualities of socket materials used in a below-knee prosthesis. Various fibers (Kevlar, perlon, carbon, natural kenaf) were utilized with resin 80:20 to achieve optimum performance that may be utilized to create a good layout and adequate mechanical qualities with a longer lifespan. The samples were examined using tensile, bending, and impact tests throughout the experimental stage. Any use of natural fibers improved the highest tensile strength by 39.35 percent and the modulus of elasticity by 4.23 percent, resistance to impact by 8.8 percent according to theoretical and experimental results [51].

2-2-2 Review of Literature on Natural Fiber Materials:

Natural fiber-reinforced polymer composite materials are becoming increasingly popular. Natural fibers, on the other hand, were first used in composite systems in ancient Egypt, where straw and clay were used to build walls [52]. Material technology has progressed over the previous decade to biomaterials based on natural fiber composites, which are more ecologically friendly, economical, abundant, and recyclable, making them vital for our future generation. Because natural fiber composites have a high strength-to-density ratio, they are lighter than synthetic and metal matrix composites [53].

Soemardi et al. (2011) aspired to create a socket prosthesis comprised of natural fibers, particularly ramie fiber reinforced epoxy composites (RE) and ramie polyester composites (RP). Following that, the findings of the tests were compared to those of fiberglass polyester composites (FGP). The filament winding method was used in the manufacture of socket prostheses. The mechanical properties of RE, RP, and FGP composite materials for socket prosthesis materials are discussed in this work, with a focus on tensile and flexural properties. The present study's findings indicate that RE composite material has the possibility of being further established as a substitute material for socket prostheses with fiberglass polyester composites (FGP) [54].

Irawan A.P. and Sukania I. W. (2011) presented an overview of woven bamboo fiber reinforced epoxy composite (BRECO), which is expected to be a potential material for developing above-knee prosthetic sockets. The test specimens were produced in a hand process with fiber volume fractions of 10%, 20%, 30%, 40%, and 50%. The strength of the material was tested in tensile, impact, and compressive tests. The tensile, compressive, and impact characteristics of BRECO are superior to those of common materials, according to the results of standard tests. BRECO has the potential to grow further as an above-knee prosthetic socket material [55].

Sexton S. et al. (2012) developed a socket prosthesis composed of a variety of natural fibers and copolymer as a replacement for available composites to improve the maintenance and convenience of prosthetic fabrication. The vacuum bagging method was utilized in the fabrication of socket prostheses. A specimen was subjected to tensile tests. It was established that ramie fiber composites have the potential to substitute the typical lay-up and have the potential to be utilized as a substitute material for socket prostheses, particularly for tensile properties that are readily accessible, biomechanically suitable, and can be intended to be as lightweight and comfortable as possible [56].

Rosalam C. M. et al. (2012) investigated the use of kenaf fibers in prosthetic sockets. Natural fibers are being utilized to lower the cost of manufacturing lower limbs while also offering sustainable materials. Their utilization is required since the body keeps changing with time because of growth or weight loss. In this research, kenaf fibers are used in one or two layers in lamination groups to replace glass fibers with copolymer (propylene and ethylene). Tensile, flexural, impact, density, and moisture content tests were conducted [57].

Sukania I. W. and Irawana A. P. (2015) created a prototype of lower limb prosthesis sockets using rattan fiber-reinforced epoxy composites (RFREC) materials. Through compressive failure tests and gait analysis, the attributes of the prosthesis socket were determined. Based on the outcomes, a prosthesis socket prototype created of RFREC materials could be an effective alternative that the participant could utilize with comfort and safety, as well as a beneficial effect on using natural materials that are environmentally friendly and biodegradable [58].

Odusote J. K. et al. (2016) aimed to see how effectively pineapple fiber-strengthened composites worked as an above-knee prosthetic socket. Glass fiber polyester composite mechanical characteristics were compared to those of pineapple fiber polyester composites and pineapple fiber epoxy composites. Hand lay-up procedures were utilized with fiber percentages ranging from 0% to 20%, 30%, 40%, and 50%. Flexural, impact, and tensile testing were performed on the composites. The analysis indicated that pineapple fiber epoxy composites had superior characteristics to fiberglass and pineapple fiber polyester composites [59].

Tahir M. S. and Chiad J. S. (2017) investigated whether fiberglass could be replaced with monofilament fiber to ensure the safety of the socket's developers and users. In the case of mechanical and fatigue characteristics, the two models of vacuum-bagged lamination were evaluated. The first is accessible and comprises eight perlon and two fiberglass layers, while the second is projected and comprises eight perlon one cotton, and one monofilament layer. When compared to existing materials, the proposed material reduced yield stress and ultimate stress by 45.4 and 10.6 percent, respectively, while increasing the modulus of elasticity by 42.6 percent [60].

Nurhanisah M. H. et al. (2017) designed a below-knee prosthetic socket composed of kenaf-glass fiber composite as a replacement for fiberglass-polyester composite prosthetic sockets. Kenaf, glass-silk, and nylon fibers are all used in the laminates. The prosthetic socket was manufactured using the vacuum lamination process. Flexural and impact tests were used to assess the effects of the kenaf fiber arrangement on mechanical and volumetric characteristics. Based on volumetric results, the introduction of a double layer of woven kenaf fiber has superior mechanical characteristics to single-layer kenaf fabric-based composites, with a flexural of 7.11 MPa and an impact of 16.7 kJ/m^2, which is greater than a layer of kenaf-strengthened composites [61].

Kadhim K. R. et al. (2019) evaluated three kinds of composites with the optimum one chosen to replace polypropylene in the fabrication of sockets. Groups (A) (eight bamboo/two fiberglass layers), (B) (six perlon/two fiberglass layers), and (C) (eight bamboo/ three carbon fiber layers) were proposed for the fabrication of the socket for BK amputation. The study involves tensile and fatigue tests to establish the mechanical qualities of the recommended materials as well as observe the interface pressure between both the socket and the amputation's residual portion. The test results revealed that all of the proposed materials had been successful in mechanical testing and outperformed the available material's mechanical qualities (polypropylene). It had been successful in mechanical testing and outperformed the available material's mechanical qualities (polypropylene). The optimum material to be chosen came from the third proposed group, and the mechanical characteristics were improved by modifying the types of composite materials rather than the number of layers that compose the composite material. Because of its strong mechanical qualities and strength, it can support large weights for patients without falling [62].

Widhata D. et. al. (2019) attempted to construct composites of MMA resin and fibers of water hyacinth as strengthened constituents, assess mechanical performance, and evaluate suitability for fabricating trans-femoral socket prosthesis applications. A methyl methacrylate-based resin was used as efficient matrix material. Tensile and flexural tests were chosen to evaluate this proposed material. The results showed that flexural and tensile strength tests designated that water hyacinth fibers can yield a resilient composite that can replace the conventional layup. [63].

Agustinus P. I et al. (2020), prepared composites of prosthetic sockets made from epoxy as a matrix and reinforced with bamboo fiber. The compressive failure test and morphological analysis using SEM were studied. The compressive strength achieved (87.1 4.3 KN) outpaces the compressive strength required of the socket, according to the findings of the compressive test of socket built from epoxy bamboo fiber composites, and the findings of the SEM demonstrated that the bamboo strengthened epoxy composites have an exceptional bond between fibers and the matrix, with no cavities. This improves epoxy's strength with bamboo fiber composite as a socket prosthesis material [64].

Dominic M. P. et al. (2020), developed sockets that are normally prepared from glass or carbon fiber by using flax that has exceptional vibration damping features, which provide a benefit natural, and cost-effective. The vibrations that are transmitted to the body during movement are reduced by flax fibers due to their lightweight. The results showed that flax fibers performed best damping vibrations than carbon fiber and fiberglass when testing flat plate samples. However, young modulus, flexural stiffness, and strength, of flax strengthened sockets were contrived by the customary engineering procedure were originated to be ten times lesser than the theoretical data of flax composites which are instituted in the works. Flax fiber improves the damping properties of prosthetic sockets; but, it has limited stiffness and strength when compared with carbon (similar to fiberglass) [65].

Santosh K. et al. (2020), created a suitable bio-composite material for orthopedic implants and bone grafting that is reinforced with natural fiber. The compression hand layup technique was used to test the mechanical characteristics of the ramie and flax fibers bio-composite reinforced the bio-epoxy resin matrix with various weight fractions (10%, 20%, and 30%). The results showed that the tensile strength was 102 MPa, compressive strength was 130 MPa, and flexural strength was 138 MPa of a hybrid composite material made up of 15 % ramie and 15 % flax. The bonding behavior of the microstructure between matrix and fiber at the surfaces of fracture is studied using a scanning electron microscope (SEM) [66].

2-2-3 Numerical research of prosthetic socket:

Algbory et al. (2005) investigated the stress placed on the trans-tibial socket to counter its lack of structural stability. The research was carried out both numerically and experimentally. The numerical analysis employed the finite element methodology to determine the forces acting on the socket due to varied participant weights of (25, 70, and 110) kg. The numerical findings confirmed that the socket grew larger and that the link between both the socket and the shank in the prosthesis could break due to generated shearing stresses [67].

Kumar R. et al. (2014) fabricated sockets for trans-tibial reconstructions to compare various tensile and fatigue parameters of the composite. The Epoxy was strengthened with several forms of reinforcement utilizing vacuum molding technology. The fatigue and tensile characteristics of the socket were anticipated by utilizing the ANSYS workbench. It is projected that epoxy with carbon-strengthened composite provides the best experimental data, with the maximum fatigue limit, safety factor, and strain energy of 45 MPa, 6, and 50 J/mm3, respectively [68].

Composites were suggested in this paper by **Al- shammari M. A. et al. (2017**) to change the prosthetic socket and lengthen its life while also increasing the person's comfort. This research was divided into three sections: experimental, numerical, and theoretical. The F-socket method was utilized to assess the interface pressure between the stump and the socket, and it was estimated mathematically in the theory section. The experimental and theoretical sections' interface pressures, as well as the design, were entered into ANSYS for simulation analysis to derive the equivalent Von-Mises stresses and safety factors. As can be noted, deformations are at their lowest for the suggested design. This is supported by the fact that the proposed design has exceptional mechanical qualities in comparison to the materials available [69].

This research by **Nazik A. J. et al. (2018)** was divided into two sections, the first of which began with the creation of a prosthesis. Lamination resin 80:20 polyurethanes strengthened with perlon and carbon fibers were used to produce below-knee sockets. To determine how much ground reaction load is exerted on the participant's foot, ground reaction force testing is needed. The tensile test was also performed. The second stage of this study consists of finite element analysis performed with the Ansys program. The yield stress for this lamination was 34 MPa, the elasticity modulus was 1.109 GPa, and the ultimate stress was 38 MPa. According to the results. equivalent (Von-Mises) stresses and deflections were calculated employing ANSYS software [70]

Hammoudi Z. S.et al. (2018) have conducted tensile, bending, and fatigue analyses were carried out on composites made with acrylic as the matrix and perlon and carbon fibers as reinforcement. The interface pressure between the remaining limb and the socket was measured using F-socket equipment. The Workbench software was utilized to produce the results for maximum primary stress, total deformation, and safety factor. The analysis indicated that laminations made up of (eight perlon / four carbon fiber layers) had the best mechanical qualities and that the lamination was stable in this configuration with no failures [71].

Ahumdany A. A. et al. (2019) conducted a study that was divided into two sections: experimental and numerical. When compared to exciting material, the recommended laminations included 5 perlon and 2 kevlar fiber layers. The recommended martial tensile characteristics and dynamic load factor were calculated. These properties were entered into the ANSYS simulation program. The CT-scan approach will be utilized to build the socket. When compared to the usual geometry portrayal of the socket, the CT-scan approach proved to be very effective in FEL modeling geometry [72].

In addition to finite element simulation, **Muhannad Al-Waily et al. (2020)** conducted a full program of fatigue testing was completed to determine the best kind of laminate for socket production that can withstand dynamic fatigue throughout the gait cycle. (Eight perlon+4 glass), (eight perlon+4 carbon), (8 perlon+2 kevlar+2 carbon), (eight perlon+2 kevlar+2 carbon), and (seven perlon+2 kevlar+3 carbon) were stacked. The Ortocryl matrix has been proven successful. The experimental data are in good accord with the Finite Element Analysis results. The findings of the constant amplitude with cycle number for all samples are quite comparable to those found numerically utilizing the finite element approach. [73].

2-3 Concluding Remarks:

The above literature survey's research can be classified into two parts based on our scope of attention, as follows:

The first part: Include the currently available synthetic materials utilized to manufacture prosthetic sockets, as well as the various mechanical, physical, and morphological tests used to estimate their characteristics.

The second part: Include the designing and manufacturing of prosthetic sockets using new natural reinforcement and matrix materials, as well as testing to determine their general characteristics and bearing weight abilities.

In general, extensive work has been done on the prosthetic foot, pylon, and prosthetic socket. However, minimal research has been conducted on the modification and testing of new novel socket materials. This study aims to combine natural and synthetic reinforcement (hybridized prosthetic sockets at various volume percentages and lamination layup) as alternative prosthetic socket materials that have not yet been presented.

Various laminations were utilized in this work to obtain the optimal lamination that can be employed in the construction of a prosthetic socket to meet the necessity of a practical design with acceptable mechanical characteristics while reducing the cost. In addition, the three new natural fiber materials proposed for prosthesis socket manufacturing achieve the main goal of suitable accuracy at a suitable cost.

In addition, the results are supported by using an advanced version Ansys program to simulate the prosthetic socket prepared from laminated composite materials.

Chapter Three

Theoretical Analysis

3-1 Introduction:

In this chapter, various materials were used in the fabrication of socket laminations for below-knee amputees. The fifteen laminations laid up were created specifically for this purpose. Given their inherent potential uses, such as their natural profusion of sustainable resources, low price, easy manufacture, accessibility, and, importantly, environmental affability, new natural fiber materials were suggested as a promising alternative to fiberglass and carbon fiber currently used in the manufacturing of sockets. These new materials were sisal, flax, and cotton. Furthermore, it describes the details of the testing procedure utilized in the current study.

3-2 Prosthetic Socket Materials:

The material on the prosthetic socket is critical for meeting the needs for effective functionality. Before the development of composites and thermoplastics, prosthetic sockets were previously constructed of metal, leather, and wood.

In the past, prosthetics were made up of several different forms of leather or wood that were strained, immersed, engraved, and sewed together. It was proven more durable after being dried, lacquered, or sealed. However, in developing countries, where a large percentage of amputees are influenced by the impact of war and landmines, carbon fiber reinforced prosthetics (CFRP) have proven to be extremely costly [74].

Polyethylene, high-density polyethylene (HDPE), polypropylene, and acrylic are the most common polymers utilized in production. Because of their higher characteristics, carbon and glass fiber with acrylics are widely used. Regrettably, these are costly and release damaging gases during production [75]. Although fiberglass/HDPE composite and polypropylene composites are the least costly prostheses for profitable use, they are getting a lot of attention for fabricating durability, mechanical performance, and cost of comfort [76].

Material selection for prosthetic devices is critical because the material greatly influences socket comfort and movement for the infected. The material's strength and weight add to the patient's comfort while walking. There must be an equilibration between providing enough strength and not applying too much weight for the individual to walk. In an ideal world, the material should be chosen based on the patient's needs and capabilities. The socket material influences the cost of the limb, and deciding on a lower-cost material can end up making the prosthetic available to a greater number of people around the world. For prosthetics, a variety of materials are used, ranging from advanced carbon fiber materials to simpler co-polymers that are easily manipulated and involve less technology to mold. As a result, material selection is considered one of the most serious aspects of prosthetic design [77].

In prosthetics and orthotics, lamination is a composite made up of filler material retained together by a resin matrix. A layup can be made up of various materials, such as layers of perlon stockinet and layers of glass stockinet. Acrylic and polyester are the two most common types of resin used in prosthetics and orthotics [78].

3-3 Biocomposite Materials in Prosthetic Socket:

Researchers have increasingly turned to composite materials rather than monolithic materials in recent decades, combining the assets of their components into one. Polymer composite materials are widely utilized in high-tech applications such as aerospace engineering, prosthetic manufacturing, automobiles, and sports devices. As reinforcements in these composites, aramid, carbon and glass fiber are commonly employed. Glass fibers are the most commonly utilized conventional fiber reinforcement owing to their low price and worthy mechanical characteristics. Conversely, these fibers have limitations, including health risks when inhaled and difficulties with reprocessing and disposal of modern composites [79].

Environmentally friendly composites made from renewable materials can be reprocessed or biodegraded, making them a viable alternative to (reinforced) plastic materials [80].

The concepts of bio-composites and eco-composites all refer to materials that take up this space in general. They are all-inclusive: they can refer to any mixture of these materials, such as natural fibers in a synthetic matrix, natural fibers in a renewable synthetic matrix, synthetic fibers in a biodegradable matrix, synthetic fibers in a renewable synthetic matrix, natural fibers in a natural matrix, and so on [81].

Green composites are biocomposites prepared from natural fibers and biodegradable polymers. The term "green" is associated with materials that are both "biodegradable" and "renewable". They are commonly stated as biomedical materials [82].

Bio-based composites can be characterized as partly eco-friendly or green, depending on the nature of the components, as indicated in figure (3.1). All of the components of a green composite are derived from renewable resources, possibly reducing carbon dioxide releases and the reliance on petroleum-based products. Whereas partially environmentally responsive, one of the elements, whichever fiber or matrix, is not derived from renewable resources [83].

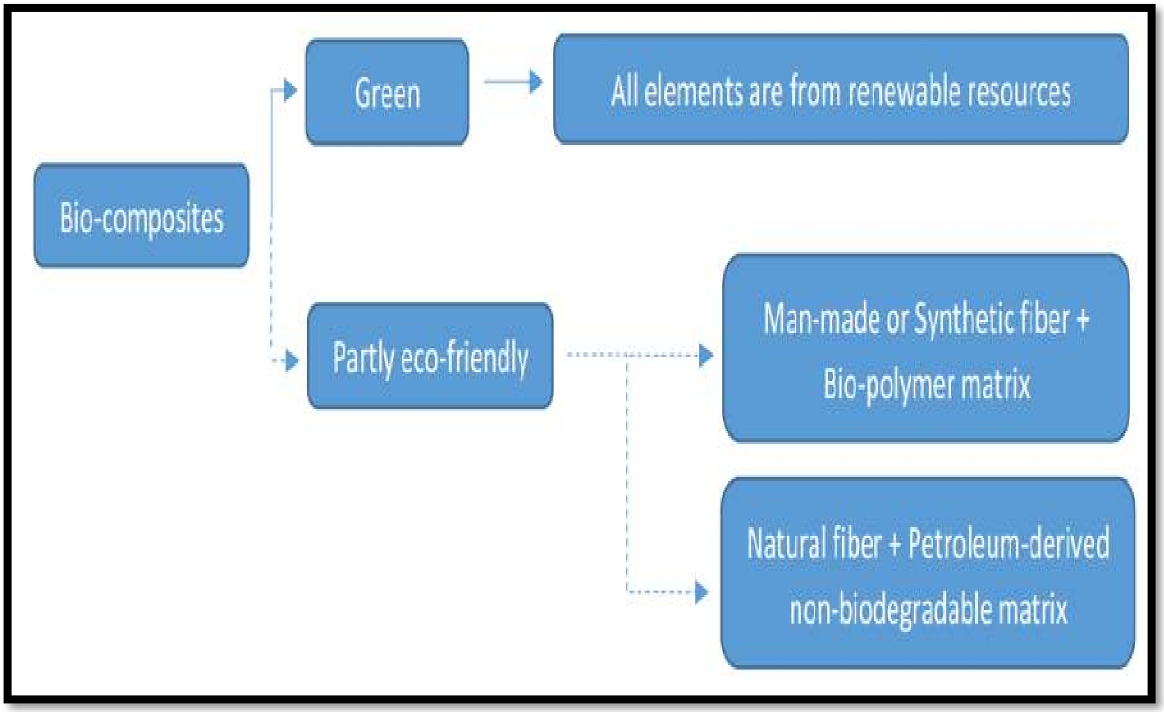


Figure (3.1): Classification of bio-composites [83].

Wood is a great example of a bio-composite material because it has long-oriented cellulose fibers that are aligned in the matrix, and biodegradable materials are used in both constituents. Tensile strength is offered by cellulose, while compressive strength and hydrophobicity are given by lignin [81].

3-4 Reinforcing Materials:

As the name implies, reinforcing components in composites offer the strength that makes the composite. They do, however, work with additional functions such as heat resistance or transfer, corrosion resistance, and rigidity. As needed, reinforcement can be prepared to execute all or some of these functions. A reinforcement that augments matrix strength must be stronger and stiffer than the matrix, and able to change the failure mechanism to the composite's advantage [84].

Composite materials are divided into laminate composites, particle composites, and fiber-reinforced composites based on the kind of reinforcement [85]. Each of them has its own set of qualities that may be added to composites and, hence each has its own set of applications [86].

3-4-1 Laminate Composite Materials:

The most popular form of fiber-strengthened composite for utilization in structural uses is laminate. It is formed by assembling several thin layers of fibers and matrix and combining them to the preferred thickness. An arrangement for every layer, in addition to the assembling arrangement of different layers in a composite, must be governed to produce a wider variety of physical and mechanical characteristics [87].

These materials provide a distinct advantage over more traditional materials due to their high specific modulus, high specific strength, and ability to be tailored for a specific application [88].

3-4-2 Particulate Composites Materials:

The reinforcement is particle-based, as the name suggests. It can be sphere-shaped, cubic, platelet-shaped, or any even or uneven form, but it is roughly equiaxed. Particles are not considered effective in enhancing fracture resistance but are broadly utilized to enhance the characteristics of the matrix, for instance, enhancing conductivities, successful behavior at high temperatures, rising wear, and abrasion resistance as well as increasing surface hardness [85].

Ceramics and glasses, for instance, microscopic mineral and metal particles like aluminum, and amorphous resources, such as polymers and carbon black, are all employed as reinforcing particles. High strength, melting temperatures, stiffness, wear, corrosion resistance, and low density are only a few of the features of ceramics and glasses that are beneficial [89].

3-4-3 Fibrous - Reinforced Composite Materials:

They are comprised of high-strength, modulus fibers placed in a matrix with different interfaces (boundaries). Fibers and matrix maintain their physical and chemical characteristics in this state, but they provide a unique combination of qualities that neither of the constituents could attain on their own. The surrounding matrix preserves fibers in the proper placement and orientation, functions as a load transfer medium between them, and protects them from environmental damage due to increased temperatures and humidity [87].

Fibers are the most frequently utilized reinforcing form in composite applications, and they have the greatest impact on composite material characteristics. The high aspect ratio between the length and diameter of the fibers is one of the reasons behind this [86].

Fiber-reinforced composites can be categorized according to fiber length. Composites with long fiber reinforcements are designated continuous fiber reinforcement composites [85].

A mixture of two or more kinds of fibers in a distinct polymeric matrix produces superior stiffness and strength than the discrete consistent polymer composites. Diverse fibers can be used in such a way that their characteristics superpose to achieve optimal performance when imperiled to a specific mechanical loading as an entire [91]. As a result, the hybridization of composites can enhance resistance to impact and fatigue, offer high toughness, and reduce total bulk and price [92].

3-5 Fibers Classified According to their Nature:

3-5-1 Synthetic fiber:

To strengthen polymer matrix composites, many types of fibers have been used. Carbon fibers, glass fibers (E-glass, S-glass, and so on), aramid fibers (Kevlar and Twaron), and boron fibers are the most frequent [86].

They have benefits such as high strength, stiffness, fatigue life, and wear resistance, but they also have drawbacks such as high density, expensive, poor reprocessing, and biodegradability. Natural fibers derived from plants and animals have recently been utilized as reinforcements as a substitute for synthetic fibers to overcome these drawbacks [92].

When compared to traditional materials, composites have various benefits, but they also have significant drawbacks that cannot be avoided. These materials not only pollute the environment during production, but they also consume a lot of energy, which is required to dispose of them at the expiration of their lifetime [80].

A- Carbon Fiber:

Carbon fibers with tensile moduli varying from (207 GPa) to (1035 GPa) are widely viable. In comparison to high-modulus fibers, low-modulus fibers have a lower density, price, tensile and compressive strengths, and tensile strains-to-failure.

Carbon fibers have exceptional tensile strength to weight and tensile modulus to weight ratios, but also a low linear thermal expansion coefficient which offers dimensional stabilization in uses like space antennae, excellent thermal conductivity, and fatigue strengths.

Low strain-to failure, impact resistance, and high electric conductivity are drawbacks. Because of their exorbitant cost, they have yet to find widespread commercial use. They're typically used in the space business, where weight savings are more important than price, as well as in the automobile, sporting goods, and consumer goods industries [80, 87].

B- Glass Fiber:

The most prevalent reinforcing fiber in polymeric matrix composites (PMC),is glass fiber. G lass fibers possess pronounced tensile strength, strong chemical resistance, and superior insulating characteristics. These are the primary advantages of glass fibers. The drawbacks include low tensile modulus and fatigue resistance, but high density, and hardness. E-glass and S-glass are the two most well-known categories of glass utilized. Because E-glass has the cheapest option of any obtainable reinforcing fiber, it is widely used in the fiber-reinforced polymer industry [87].

Glass fibers were prominent materials that were utilized for various applications until carbon fibers became available on the market, which is why they are more expensive. Because of their superior fire resistance, tensile strength, and chemical resistance, glass fibers are a highly advanced technical material. This material is being employed in aircraft parking, runways, architectural panels, septic tanks, walls, pavements, thin shells, slope stabilization, tunnel linings, and pipes [93and 94].

C- Perlon Fibers:

Perlon fibers, also known as polyamide (nylon 6) fibers, are utilized as stockinets in orthopedic technology [95]. It is a thermoplastic material with unique mechanical properties, toughness, good water absorption, high abrasion resistance, as well as elasticity, and high melting points. Because nylon 6 has low biodegradability, it could be recycled to be reused in a variety of applications [96]. The chemical structure of polyamide fiber is depicted in Figure (3.2).

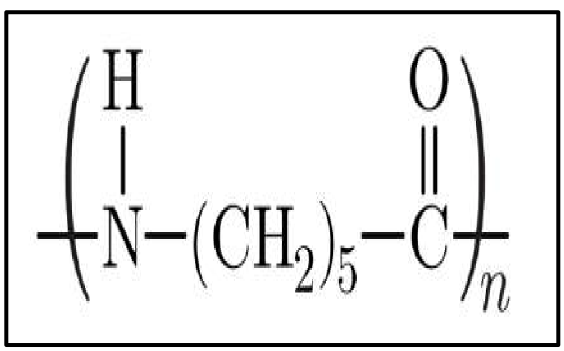


Figure 3.2: The repeat unit in nylon 6 [97]

In terms of properties, nylon 6 and nylon 6, 6 seem to be similar, though nylon 6 has greater toughness and process ability. Nylon 6, 6, on the other hand, has better mechanical qualities and is more heat resistant. Both nylon 6 and nylon 6, 6 are engineering plastics that may be utilized in a variety of industries, including automotive, consumer, industrial, electrical, and electronic segments [97]. The general properties of perlon fibers are shown in Table (3-1).

Table (3-1): The general properties of perlon fibers [95]

Property	Density ($g.\ cm^{-3}$)	Coefficient of thermal expansion (K^{-1})	Tensile modulus (GPa)	Tensile strength (MPa)	Flexural modulus (GPa)	Impact strength j/m	Tensile elongation %
Perlon	1.14	9.5×10^{-5}	2.6-3.0	45-85	1.2-2.7	25-90	100-150

3-5-2 Natural fiber:

Natural fibers are materials that are sustainable and come from natural sources. They are obtained from plants, animals, and minerals, although plants are the most commonly employed because of their great availability and renewability in a short period [98]. Natural fibers are composites made up of cellulose fibers bound together by a lignin and hemicellulose matrix [99].

Natural fibers are attractive to scientists because of their low price, high strength-to-weight ratio, low density per unit volume, non-corrosive quality, and adequate specific strength, as well as their renewable and degradable properties [100].

Natural fibers, on the other hand, have some limits. Natural fibers have low tensile strength. Other limitations include a low melting point and moisture absorption. Natural fibers begin to degrade at temperatures above 200 ℃, first through hemicellulose degradation and then through lignin degradation. Degradation causes odor, discoloration, volatile release, and mechanical property deterioration [87]. While moisture absorption causes fiber swelling, mechanical and physical properties degrade, resulting in significant dimensional changes in the composites [101]

Natural fibers' above-mentioned drawbacks can be overcome using various approaches and techniques. Natural fiber pretreatments can clean the surface, chemically improve the surface (to have an efficient hydrophobic barrier), halt moisture absorption, and improve adhesion with various matrices. Among some of the various pretreatment techniques, ideal fiber separation techniques, accurate fiber sizing and coating, and chemical alteration (alkaline, benzoylation, acetylation, silane, acylation, and isocyanate treatment) are the most common. In addition to chemical treatments, physical modifications such as corona and plasma treatment can alter the surface and structural characteristics, affecting the mechanical bonding of polymers [102 and 103]. Even though the thermal instability of fibers restricts the choice of suitable matrix materials, thermoplastics and thermosets are utilized. The most common thermoplastic matrix is polypropylene. Similarly, thermoset polymers like epoxies, vinyl esters, and polyesters are utilized [88]. Compounding, mixing, extrusion, injection molding, compression molding, and resin transfer molding are common techniques for producing natural fiber-reinforced plastic composites [83].

Natural fibers, on the other hand, have a strong potential in a variety of commercial and industrial applications, such as internal applications of passenger cars, panels for partition and false ceilings, partition boards, roof tiles, coir fibers in packaging, furniture usage, as insulation material in low-energy houses, geotextiles for soil protection and erosion control, improving barrier function, composites, and so on [104].

3-5-2-1 Classification of Natural fiber:

Natural fibers are divided into three classes founded on their source: plants or vegetables, animals, and minerals, as shown in figure (3.3).

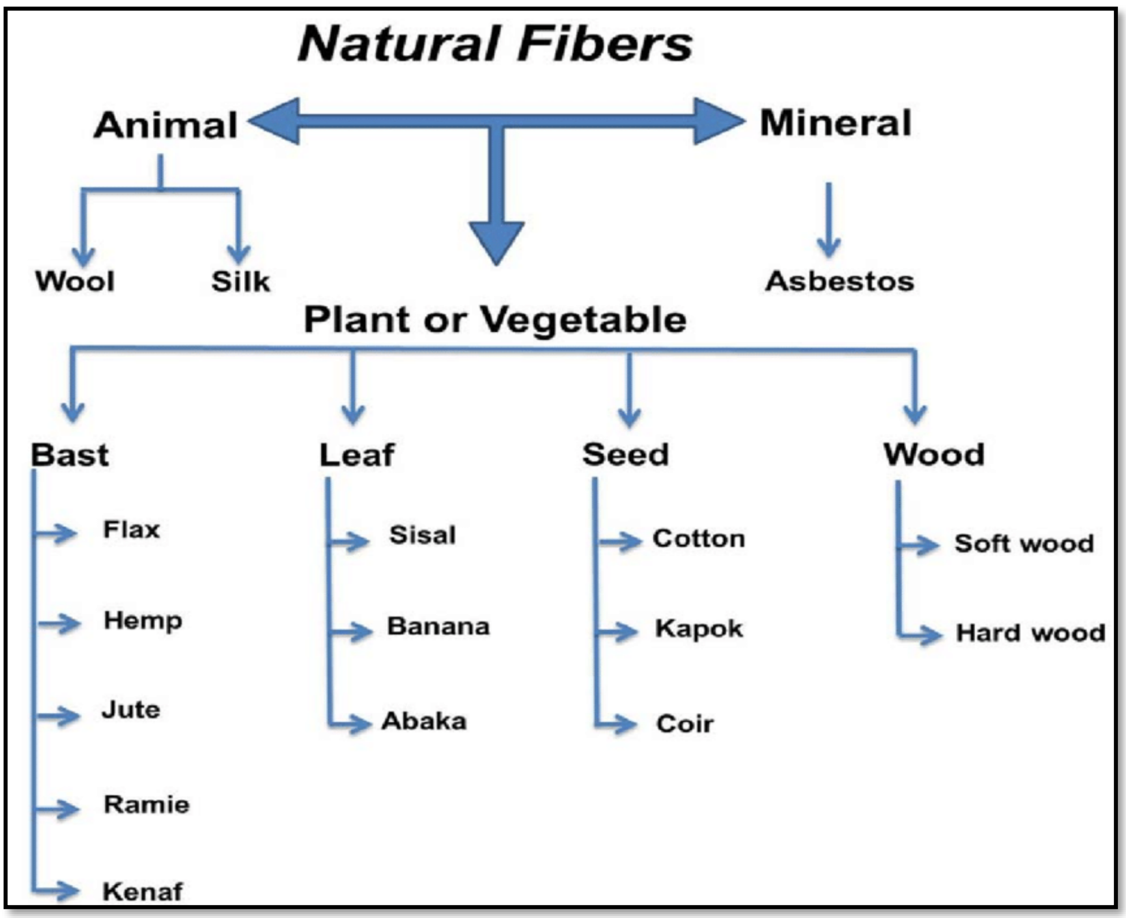


Figure (3.3): Classification of Natural Fibers [105]

Natural fibers originating from plants are denoted as cellulose or lignocellulose fibers, with cellulose, hemicelluloses, and lignin as the primary components. Natural fibers' hydrophilic characteristics are sourced from lignocelluloses, which mainly contain large hydroxyl groups. Pectin and waxes are the other ingredients [106]. Each of these vegetable fibers has a cellulose component that provides the majority of their strength [81].

Natural fiber-producing plants are categorized as primary or secondary, depending on how they are used. Primary plants are developed for their fiber content, whereas secondary plants are those that generate fiber as a by-product [107].

Animal fibers have many advantages: they are strong, thin, do not absorb odors, and are effective at controlling temperature. Animal fibers have received less investigation into composites than vegetable fibers, owing to their higher price and thus limited application potential. However, the incredible strength and mechanical characteristics of various silks have piqued academic interest for quite some time [81].

Mineral fibers are fibers derived from minerals that are naturally occurring or have been slightly improved. They are classified into three types: Asbestos is the one mineral fiber that occurs naturally. Glass fibers, aluminum oxide, silicon, and boron carbide are examples of ceramic fibers. Metal fibers are used to make aluminum fibers [89]. Further Table (3.2) presents a summary of the physical and mechanical properties (strength and modulus) of various natural fibers, in comparison with the advanced (synthetic) fibers.

Table (3.2): Mechanical Properties of Natural and Synthetic Fibers [108]

Fiber	Density (gcm^{-3})	Diameter (μm)	Tensile strength (MPa)	Young's modulus (GPa)	Elongation at Break %
Flax	1.5	40-600	345-1500	27.6	2.7-3.2
Ramie	1.55		400-938	53	1.2-3.8
Cotton	1.5-1.6	12-38	287-800	5.5-12.6	7-8
Jute	1.3-1.49	25-200	393-800	13-26.5	1.16-1.5
Sisal	1.45	50-200	468-700	38	3-7
Hemp	1.47	25-500	690	70	1.6
Coir	1.15-1.46	100-460	131-220	4-6	15-40
E-glass	2.55	17	3400	73	2.5
Kevlar	1.44		3000	60	2.5-3.7
Carbon	1.78	5-7	3400-4800	240-425	1.4-1.8

3-6 Natural Fiber Composite:

Natural fiber composites are growing increasingly popular as people become more environmentally conscious. Furthermore, the materials' low cost and density, as well as their satisfactory specific characteristics, ease of parting, improved energy regeneration, CO_2 balance, and biodegradability, have sparked renewed interest in natural fiber composites [83].

All-natural fibers are composed of the following basic chemical ingredients: cellulose, hemicellulose, lignin, and pectin. Whereas cellulose is primarily accountable for strength, the lignin, as well as other components, acts as a binder to the cellulose, Natural fibers vary in chemical and physical structural characteristics, which contribute to their distinctness.

Cellulose is resilient to strong alkalis, acid hydrolysis, and oxidizing agents. Hemicellulose can be found in fiber cells. It's very hydrophilic, alkali-soluble, and acid-hydrolyzable. Lignin provides the rigidity of the fiber cell wall. Pectin gives plant fibers flexibility. Wax is the final component of natural fibers, and they are made up of various kinds of alcohol [109 and 110].

The impact of fiber volume on the mechanical characteristics of natural fiber-strengthened composites is especially noteworthy. In general, growing the fiber content in a composite improves the strength and modulus until the fiber loading becomes too high for the resin to completely saturate the fibers. Natural fibers have lower mechanical characteristics than synthetic fibers, with lower densities that offer them specific strength and stiffness characteristics that are comparable to synthetic fibers [111 and112].

The chemical composition of fibers, crystalline cell diameters, micro-fibrillar angles, flaws, physical qualities, and mechanical characteristics, as well as a fiber's interplay with a polymer, all influence the performance as well as the mechanical, physical, and geometric qualities of natural fiber reinforced polymer composites [83].

In terms of natural fiber drawbacks, reinforced composites are linked to the incompatibility of hydrophilic natural fibers and moisture absorption. As a result, Natural fibers are unsuitable for high-performance military and aerospace applications owing to their low strength, sensitivity to the environment, and poor moisture resistance, which causes degradation in the strength and stiffness of natural fiber-reinforced composites [113].

Natural fibers are typically treated before they can be utilized as reinforcement in composites. This is done primarily to enhance the compatibility of the fiber and matrix, eliminate impurities, and minimize the hydrophilicity of the fibers [114].

Bio fibers act as reinforcement in bio composites, increasing the strength and stiffness of the resultant composite structures. The mechanical qualities of a bio-composite are similarly affected by the characteristics of the polymer, which could be bio-based (plant or animal) or man-made (an oil by-product) [115].

3-7 Natural Fiber in this study:

3-7-1 Flax Fiber:

The most vital and eldest member of the bast family for composite reinforcement is flax fiber (Linum usitatissimum) [111]. Bast fibers are extracted from the fibrous bundles institute in the inner bark of a plant stem that has developed in temperate climates [117].

Flax fiber-reinforced plastic composites have attracted increasing interest because of the advantages of flax fibers, for example, high toughness, strength and stiffness, biodegradability, and low density [105].

Flax fibers are especially suited to be utilized as reinforcement in composite materials owing to their elevated stiffness and low price, but the downsides are their rather elevated moisture sensitivity and wide variation of dimensions, which can be credited to the fiber's molecular fine structure, which is influenced by growth conditions and the fiber treating methods utilized. However, the extra procedures needed to minimize the moisture sensitivity increase their price. They may be affordable and cost-effective items. Fiber issues can be overcome by employing a hybrid reinforcement, i.e., one centered on environmentally friendly glass fiber and natural fiber with low moisture sensitivity [118].

Natural fiber composites based on flax fibers can strive with E-glass-based materials in stiffness-critical structures, but these materials will have to be enhanced further for strength and impact critical applications. As a result, flax fibers have the greatest ability to replace glass in polymer composites [119].

3-7-2 Cotton Fiber:

Cotton is a widely utilized natural and cellulosic textile fiber, and it is utilized to make clothing, home furnishings, and industrial products [120].

Cotton fibers are the world's longest single cells. Single epidermal cells on the exterior integument of the cotton fruit's ovules produce the fibers, which are single-celled outgrowths. Cotton fibers are the richest type of cellulose, which is the most common polymer in nature. Cotton fibers are almost entirely made up of cellulose [121].

Cotton fiber is composed of 85-90 percent cellulose, 0.1 percent pectin, 5.7 percent hemicelluloses, and 0.6 percent waxes [109]. Chemical compositions differ depending on variety, growing conditions (soil, water, temperature, pests, and so on), and maturity. Cotton fibers are strong due to the stiffness of the cellulose chains, their strongly fibrillar and crystalline composition, and the considerable intermolecular and intramolecular hydrogen bonding [121].

3-7-3 Sisal fiber:

Sisal fiber is a fiber derived from the sisal plant's leaves (Agava sisalana). It is a natural fiber with high specific strength and modulus, low cost, recyclability, ease of accessibility, and low moisture absorption. Materials scientists and engineers around the world are fascinated by the use of sisal fiber as reinforcement in sisal fiber-reinforced composites [122]. Sisal fiber is composed of 66–78% cellulose, 10–14% lignin, 10–14% hemicelluloses, 2% waxes, and approximately 1% ash [113].

Sisal-reinforced composites are regarded as excellent environmentally when likened to other composites because, when combusted, they create fewer CO2, CO, and toxic gases than their un-reinforced matrices and are degradable, in addition to having better electro- transmittance than other natural fibers [90].

Sisal is used in a variety of products today, including specialty paper, filters, geotextiles, mattresses, carpets, and wall coverings. It's utilized as a reinforcement in plastic composite materials, especially automotive components, but also in furniture. Another interesting application is as a brake pad replacement for asbestos [123].

3-8 Polymers Matrix:

The matrix controls the composites' form, surface appearances, environmental lenience, and permanency, while the fiber reinforcement bears the majority of the loads, offering macroscopic stiffness and strength [124].

According to their source, the polymer matrix can be classified as biopolymers or synthetic polymers. Biopolymers can be referred to as substitutes for synthetic polymers derived from petrochemical-based materials such as polypropylene (PP), polyethylene (PE), polystyrene (PS), polyester, and epoxy resin, etc. [125]. Biopolymers resulting from recyclable or natural materials can be biodegradable or non-biodegradable [126]. Sustainable, suitable for all types of fibers, devoid of odor, minimal shrinkage, non-toxic, and non-flammable are the key advantages of bio-based polymers. They also reduce reliance on limited petrochemical resources. [127].

3-8-1 Poly Methyl Methacrylate (PMMA):

Polymethylmethacrylate (PMMA) resin, with its chemical formulation (C5H8O2), is one of the most generally utilized acrylic polymers [128]. It is a linear thermoplastic polymer that is among the hardest polymers. PMMA has good mechanical and young's modulus, low elongation at break and moisture, impact resistance, good optical transparency, excellent outdoor weather resistance, and water absorption, exceptional dimensional stability, and excellent UV radiation and weathering resistance [129 and 130]. The polymerization of methylmethacrylate (MMA) to make PMMA is depicted in figure (3.4).

It is accessible in sheets, tubes, or rods that can be machined, attached, and shaped into a wide range of different parts, as well as beads that can be handled conventionally via extrusion or injection molding [96]. Table (3-3) shows the general properties of PMMA.

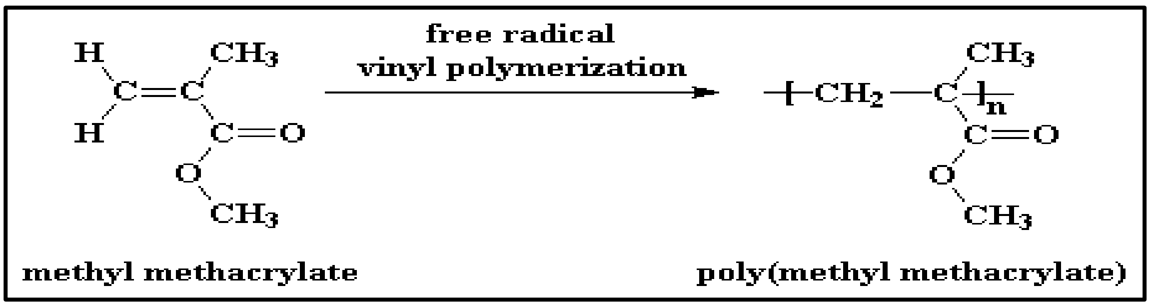


Figure (3.4): Chemical structure of PMMA [131]

Table (3-3): Some Mechanical and Physical Properties of PMMA Polymer [96 and 99]

Tensile strength, (MPa)	Young Modulus (GPa)	Density (g/cm³)	Yield strength (MPa)	Compressive strength (MPa)	Impact strength, J/m
72.4	2.24–3.24	1.19	53.8–73.1	10-15	21

3-9 Rule of Mixtures:

The rule of mixtures can be used to evaluate the properties of the composites. It can be utilized to obtain composite physical and mechanical characteristics, as well as diverse directions that may be affected by volume fraction or weight fraction [132].

The volume fraction of the composite material can be obtained using the steps listed below:

$$\rho_c = \sum \rho_i V_i \qquad (3.1)$$

$$\upsilon_c = \sum \upsilon_i V_i \qquad (3.2)$$

$$V_F = \frac{v_f}{v_C} \Longrightarrow v_f = \frac{m_f}{\rho_F} \quad (3.3)$$

$$V_m = \frac{v_m}{v_c} \Longrightarrow v_m = \frac{m_m}{\rho_m} \quad (3.4)$$

Where:

ρ_i: Density of constituent's composite material.

v_i: Poisson's ratio of constituent's composite material.

m_f, m_m: Mass of fibers and matrix respectively (gm).

v_f, v_m, v_C: Volume of fibers, matrix, and composite materials respectively(cm^3).

ρ_f, ρ_m: Density of fibers and matrix respectively(gm/cm^3).

V_F, V_m: Volume fraction of fibers and matrix respectively.

V_i: Volume fraction of constituent's composite material.

The major Poisson's ratio of the composite can be estimated from the following equation [133]:-

$$\upsilon_{12} = V_f \upsilon_f + V_m \upsilon_m = V_f \upsilon_f + (1 - V_f)\upsilon_m \quad (3.5)$$

Where:

υ f, υ m: the Poisson's ratios of each constituent.

3-10 Mechanical Properties for Socket Materials:

3-10-1 Tensile Properties:

This test determines a material's resistance to a static or gradually applied force. A tensile test can provide information about a material's strength, Young's modulus, and ductility. [128]

Tensile test data can be used to assist in determining the best materials, designing components that can withstand applied stresses, and providing crucial material quality control tests. [134].

Tensile stress: is referring to the maximum force that can be applied to materials without fracture. Tensile strength is calculated by dividing the force by the area:

$$\boldsymbol{\sigma} = \frac{\boldsymbol{F}}{\boldsymbol{A}} \quad (3.6)$$

Where:

σ = Tensile stress (MPa).

F= Applied load (N).

A= Original cross sectional area (mm2) [128].

Young's modulus is derived from the initial slope of the stress-strain curve, where the stress is instantly proportional to the strain. For instance, understanding that a material offers high tensile strength but low elongation indicates that it is strong but brittle, this is typical of thermosetting elastomers. Whereas understanding that material possesses low tensile strength but high elongation indicates that it is weak and ductile, this is typical of thermoplastic elastomers [135].

In addition, the expression for calculating Young's Modulus is:

$$\boldsymbol{E} = \frac{\boldsymbol{\sigma}}{\varepsilon} \tag{3.7}$$

Where:

E= Young's Modulus (GPa). [128]

Elongation is the increment in length created in the gauge length of the sample by a tensile load [129]. The percentage of elongation can be expressed by the following equation [128]:

$$\text{Percentage Elongation } (\boldsymbol{\varepsilon}) = \frac{\boldsymbol{L} - \boldsymbol{L_0}}{\boldsymbol{L_0}} \tag{3.8}$$

Where:

ε= Engineering strain (%).

L= Length of the specimen after the test (mm).

L_0= specimen original gage length (mm).

3-10-2 Flexural Test:

The bending test is utilized to determine how much force is needed to bend a beam under three-point loading conditions [136]. These tests' results on flexural properties are especially helpful for the quality controller and specification [137]. In this procedure, a rectangular-shaped specimen is placed amid two fixed supports, and a load is applied at its centroid. In this configuration, it is known as a "three-point bending test" [138].

As a result of the flexural test, the flexural modulus of elasticity can be utilized as a sign of a material's stiffness when bent and determined from a sketch (load-deflection) curve by utilizing the following equation: [139]

$$\boldsymbol{EF} = \frac{\boldsymbol{L^3 P}}{\boldsymbol{4b\delta d^3}} \tag{3.9}$$

Where EF represents Flexural Modulus, P represents Load Applied, L represents Support spam length, b represents Specimen's width, d represents Specimen's depth, and δ represents Specimen's deflection (mm).

In addition, from the flexural test, can we obtain flexural strength that is measured in the Mega Pascal unit. Many aspects influence the flexural strength of polymer composites, including strain rate, temperature, moisture, and residual monomer. Furthermore, for a rectangular cross-section, the following equation can be calculated the flexural strength: [140]

$$\boldsymbol{\sigma_F = \frac{3FL}{2wh^2}} \tag{3.10}$$

Where F represents the rupture load, L represents the distance between the two sites, w represents the specimen's width, and h represents the sample's height, Flexural strength is measured in stress units. The bend test yields identical results to the stress-strain curves except that the stress has schemed relative deflection rather than strain. The following equation can be used to determine flexural strain: [139]

$$\boldsymbol{\epsilon_{\mathrm{f}} = \frac{6\mathrm{Dd}}{L^2}} \tag{3.11}$$

Where:

ϵ_f: Flexural Strain (%).

D: Maximum Deflection of Specimen (mm).

3-10-3 Max Shear Strength Test:

Maximum shear stress relies on the maximum load attained from the bending device. It can be expressed by the following equation [141]:

$$\boldsymbol{\tau_{max} = \frac{3P}{4bd}} \tag{3.12}$$

Where:

τ_{max}: Maximum Shear Stress (MPa)

P= Rupture load (N)

Rather than fiber characteristics, the max shear is determined by matrix properties and fiber-matrix interfacial strengths. By increasing matrix tensile strength and matrix volume fraction, as well as decreasing fiber diameter, the max shear is improved [87].

3-10- 4 Impact Test:

Generally, impact surroundings can vary from unintentional dropping of hand tools to high-speed accidents, and a structure's reaction can range from localized impairment to complete collapse [142].

The Charpy test and the Izod test are two examples of test procedures that have been developed. The biomaterials are frequently subjected to the Izod test in the study. A heavy pendulum starts the test at an elevation of h_0, swings along its arc, hits and fractures the specimen, and ends at a lower final elevation of hf. We could determine the difference in potential energy if we knew the pendulum's initial and final heights. The impact energy absorbed by the specimen during a failure is the source of this difference [136].

The impact strength is expressed in KJ/m^2 and calculated by dividing the impact energy by the cross-section area at fracture and expressing it in the following equation: [87].

$$G_c = \frac{U_c}{A_c} \tag{3.13}$$

Where:

G_c : Impact Strength of Material (KJ/m^2).

U_c : Impact Energy (KJ).

A_c : Cross-Sectional Area of Specimen (m^2).

Fracture toughness defines a material's capacity to overcome fracture in the presence of a crack and can be determined by calculating using the following equation [142]:

$$\boldsymbol{K_c = \sqrt{G_c E_F}} \tag{3.14}$$

Where:

K_c: Fracture Toughness of Material $\left(MPa.m^{\frac{1}{2}}\right)$ or $\left(N/m\, m^{\frac{3}{2}}\right)$.

The determination of fracture toughness in this test was dependent on the calculation of fracture energy [138].

3-10-5 Compression Test:

Compression tests offer information about the compressive characteristics of plastics and composites when performed under conditions similar to those used in the tests [144].

A compression test is comparable to a tensile test, only the force is compressive and the sample compresses along the stress direction. When a material's behavior underneath big, everlasting strains is needed, such as in industrial uses, or when the material is brittle in tension, compressive tests are utilized [145].

Compressive strength is a measure of resistance to rupture under a compression load. Equations (3.15) are utilized to compute compressive stress [146].

$$\boldsymbol{\sigma = \frac{F}{A_0}} \qquad (3.15)$$

where F is the instant load smeared perpendicular to the sample cross-section, in newtons (N) or pounds-force (lbf), and A_0 is the initial cross-sectional area before any load is applied (m^2 or $in.^2$).

Compression tests are frequently performed with specific grips and gears. It is critical to verify that the specimen cannot rotate during some compression tests of composites and that the failure does not occur due to buckling [144 and 145].

3-10-6 Hardness Test:

A material's hardness is determined by its resistance to permanent indentation. Because they are convenient and easy, hardness tests are often used to analyze material qualities. [147]

Hardness is a complicated character that is linked to materials' mechanical qualities, including modulus, strength, elasticity, and plasticity, though the relationship isn't always clear. As a result, increased modulus and strength in a particular type of plastic and rubber material usually imply greater hardness [148].

Plastic hardness is most generally assessed using the Shore (Durometer) test or the Rockwell hardness test [149].

A durometer is utilized to determine the indentation hardness of various materials, including soft rubber, hard rubber, and plastics. When a hardened steel indenter is enforced into a sample using a calibrated spring, this device reads the depth of indentation under load [150].

3-10-7 Weathering test:

Despite the benefits of fiber-reinforced composites, one of the most serious challenges restraining their adaptability in real-world applications is the durability of natural fiber-reinforced composites, especially in continuous hot and humid climates [151]. After weathering cycles, biocomposites are prone to discoloration, and a decline in mechanical and thermal stability [152].

The natural fiber is degraded by exposure to the environment, sunshine, and moisture uptake during service, especially in the exposed portion. Furthermore, it destroys polymer matrices, which may decrease NFPC's mechanical qualities or, worse, contribute to parts failure in service [153].

When it comes to UV radiation, the deterioration begins on the polymeric materials' outer surface, which is susceptible to UV. If light diffusion is confined to the surface alone, surface discoloration may occur, but if the degradation extends to the majority of the material, the mechanical characteristics of the polymer materials may be affected [154 and 155]. The degree to which a material degrades when exposed to UV radiation is determined by the kind of polymer and the length of exposure [156 and 157].

Water, on the other hand, has a less severe influence on polymer composites than UV-induced deterioration, even at high temperatures. According to research, water's main function in joined UV/water condensation conditions is to remove UV-generated particles from surfaces and reveal the underlying virgin polymer for the next UV cycle [158].

3-11 Morphological Properties:

3-11-1 Surface Roughness Test:

The surface roughness of a part is critical for a variety of reasons and considerations, including [159]:

1. Corrosion resistance.
2. Cost consideration.
3. Fatigue and notch sensitivity.
4. Subsequent processing such as painting and coating appearance.

Surface roughness assessment and composite material damage description are required to determine surface quality. However, due to the non-homogeneous structure of composites and the diversity of damage, precise and consistent surface roughness measurement of composite materials might be difficult [160].

The mechanical performance of a fiber composite was demonstrated to be strongly influenced by surface roughness. Inter-laminar shear strength and compressive strength can be reduced as the average surface roughness rises [161].

3-12 Physical Properties:

The physical properties of a substance are those that can be identified without changing its identity. Which include:

3-12-1 Density test:

A material's density is referred to as its mass per unit volume. The mass of a specified volume of material at 23°C divided by the identical volume of deionized water can be referred to as specific gravity [162].

Archimedes' base, which indicates that the evident loss in weight of a material dipped in a liquid is equivalent to the weight of the liquid displaced, is yielded by specific gravity determination when the weight of the material and the weight of an equal volume of water are determined [163].

The specific gravity and density can be concluding from equation (3.16) & (3.17) correspondingly [157]:

$$\text{Specific gravity} = m_1 / (m_1 + w - m_2) \quad (3.16)$$

$$\text{Density} = (\text{Specific gravity}) * (997.5) \quad (3.17)$$

Where:

m_1= Specimen's mass in the air.

m_2= Specimen's mass and sinker (if utilized) in water.

w = Mass of completely engrossed sinker if employed and dipped wire.

3-12-2 Water absorption:

The water absorption test is utilized to assess how much water is absorbed in a given situation [164]. Natural fibers have been restricted in their use as reinforcement because of their susceptibility to water absorption, which is owing to their chemical composition, which is high in cellulose and hydrophilic in nature. Water absorption causes the fiber to swell, which can affect the composites' mechanical and dimensional stability qualities [165 and 166]. Due to microcracks appearing in the fiber-matrix space, it separates the reinforcing phase from the matrix by breaking interface bonds or causing the matrix to swell and perhaps separate the matrix material. As a result, the load transmission from the matrix to the reinforcing phase will be reduced [167].

When polymers are alternately soaked and dried, they can expand and contract. This parameter is critical for the clinical application of polymer composite materials because water absorption can affect dimensional stability and other physical and mechanical properties [163, 168].

The rate of water absorption test serves two purposes: first, as a guide to the quantity of water absorbed by the material, and second, as a control test on the homogeneity of a product [169].

The following equation can be utilized to calculate water absorption:

$$\text{Water Absorption } \% = \frac{W_S - W_D}{W_D} \times 100 \qquad (3.18)$$

Where:

W_D: Mass of the dry specimen before immersion

W_S: Mass of the specimen after immersion in distilled water for (24 hr.) at room temperature [170].

3-13 Miscibility Tests

3-13-1 Fourier Transform Infrared Spectrometers (FTIR) Analysis:

FTIR spectrometers are being utilized to explore the interaction of many materials (polymers and additives) with electromagnetic radiation in the infrared region of the spectrum. This method helps determine a compound's chemical composition and functional groups by recognizing the rotational, vibrational, and stretching of chemical bonds as fingerprints for these materials [171 and 172].

Figure (3.5) displays a schematic illustration of the fundamental elements of an FTIR spectrometer. Before reaching the detector, the radiation passes via an interferometer and is sent to the sample. An analog-to-digital converter changes the data into a digital formula, which is then sent to the computer for Fourier processing after the signal has been amplified and filtered to remove high-frequency contributions [171]

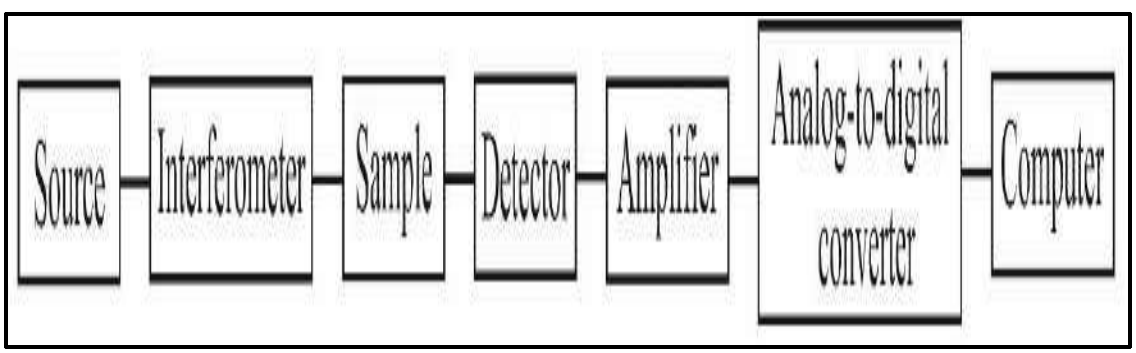


Figure (3.5): Basic Constituents of FTIR Spectrometer [130].

3-14 Theoretical Analysis:

3-14-1 Factor of Safety (SF):

In Ansys, the highest value of the safety factor shown is 15, but when the stress in a precise location develops greater than the strength of the material, the safety factor ratio develops inferior to 1, and with this, there is a risk, which is mainly that in an exact part of the model, the stress is greater than the strength the material can stand and failure is projected earlier in the design life [173].

3-14-2 Failure Index (K):

The failure index is the ratio of von Mises stress to exploratory failure strength, and it can be determined using the equation below [174]:

$$\boldsymbol{Failure\ Index(k)} = \frac{\boldsymbol{Von\ Mises\ Stress}}{\boldsymbol{Experimental\ Failure\ strength}} \qquad (3.24)$$

Chapter Four

Experimental Part

4-1 Introduction:

The materials and tests employed are the subjects of this chapter. It also describes how to manufacture laminated samples with PMMA acrylic resin and other reinforcement components in various layouts (Carbon, Glass, Sisal, Flax, Cotton, And Perlon). Mechanical properties were assessed using (tensile, flexural, impact, compression, max. shear stress, hardness, and weathering tests); physical properties using (water absorption and density tests), morphological (surface roughness), and miscibility (FTIR) test. The technological path map of the experimental part that was accomplished in the current work can be seen in Figure (4-1).

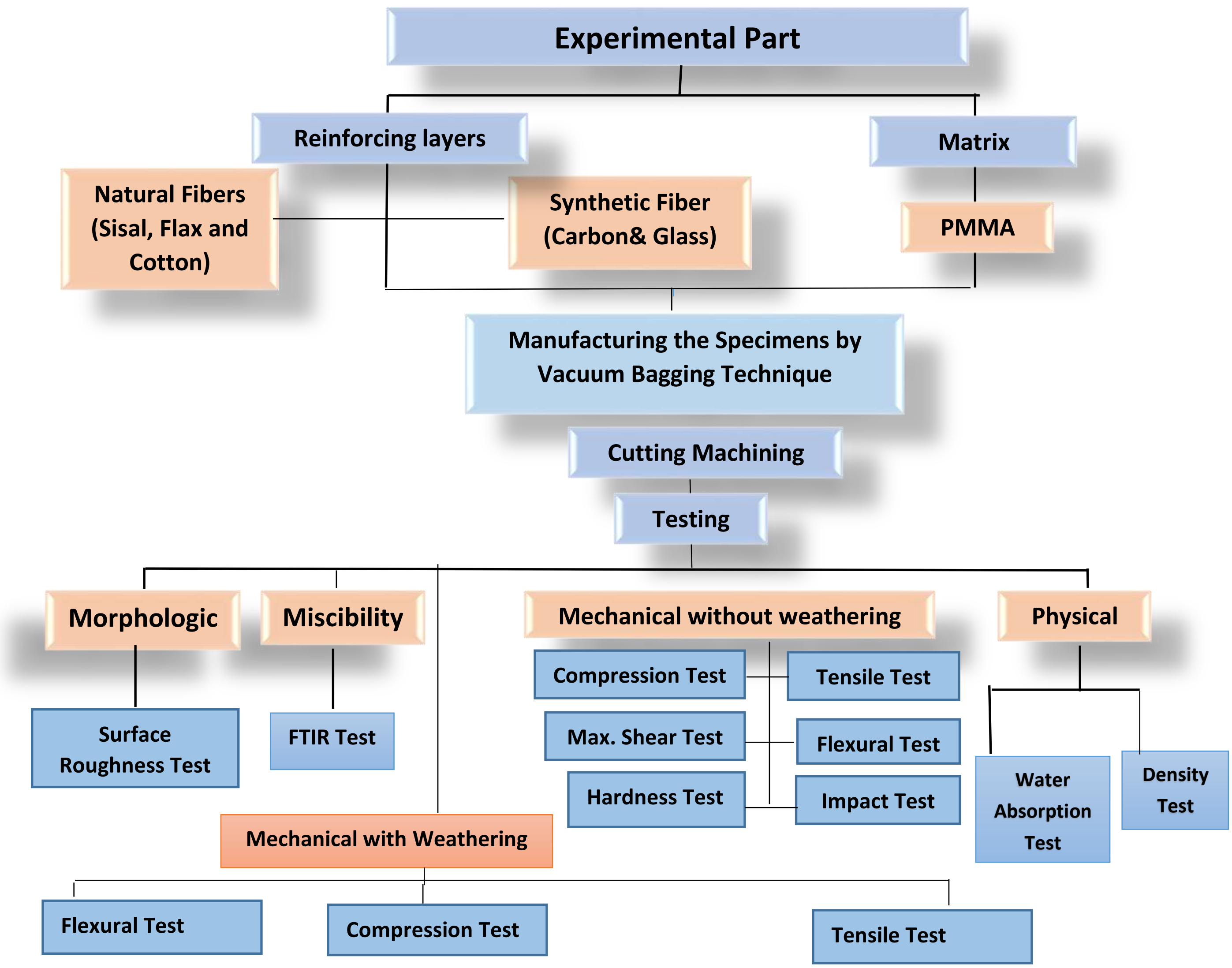


Figure (4-1): Diagram of the Technical path of this study

4-2 Materials utilized in Laminated Composites Prosthetic Socket:

The following materials were utilized to manufacture test specimens of the below-knee prosthetic socket in this study:

- White perlon stockinet (otto Bock health care 623T3)
- Fiberglass stockinet (Otto Bock Health Care 616G3).
- PMMA (Polymethyl methacrylate resin) lamination resins.
- Hardening powder.
- Polyvinylalcohol PVA bag
- Materials for the Gypsum mold
- Carbon fiber is a woven mat
- Sisal fiber woven mat
- Flax fiber woven mat
- Cotton fiber woven mat

4-2-1 Matrix Material:

In this study, a fluid resin matrix made by (Ottobock SE & Co. KGaA Company, Germany, was utilized to prepare specimens as a below-knee prosthetic socket where liquid MMA and solid hardener are mixed and then applied to the vacuum bagging technique. This laminating resin is widely utilized in humans and does not irritate the skin.

PMMA resin is becoming popular for prosthetic laminations for its high strength, allowing for a thinner, lighter-weight lamination, and its thermoplastic qualities, which allow for faster prosthesis adjustments by reheating the plastic and reshaping it [175]. The reinforcements can be permeated more efficiently due to their low viscosity, allowing air to be forced out and therefore rising to exit from the resin during lamination. By using Orthocryl Lamination resin, the reinforcement soaks up the resin more quickly; this improves the quality and the consistency of the results. The characteristics of PMMA are seen in Table (4-1).

Table (4-1): The Properties of PMMA as Obtained from the Company.

Tensile Strength (MPa)	Young's Modulus (GPa)	Percent Elongation (%)	Density (g/cm^3)	Thermal Conductivity (W/m.k)	Poisson's Ratio
48.3-72.4	2.24-3.24	2-5.5	1.19	0.17-0.25	0.35

4-2-2 Fibers Reinforcement:

Six types of fibers were utilized in this study, which includes:

A. Glass Fiber:

Ottobock SE & Co. KGaA Company, Germany, produced the E-glass fiber utilized in this investigation as a knitted fabric with fibers oriented in direction (0/90). Many polymer products incorporate glass fibers as a reinforcing material; the resultant composite materials are called fiber-reinforced polymers. It has excellent absorption of all Otto Bock lamination resins, as well as high strength and elasticity. The woven glass fiber employed in this study is shown in figure (4.2).

B. Carbon fiber:

The Otto Bock SE & Co. KGaA Company, Germany, produced the carbon fiber utilized in this study as a woven mat. Carbon fiber reinforced composites rely on carbon fiber for stiffness and strength, only with polymer serving as a supportive matrix to bind the fibers intact as well as provide some toughness. They have good absorption of all Otto Bock lamination resins and very high torsional strength in laminates, in addition to their extensive application as high-strength laminate reinforcements. The amount of woven carbon fibers employed in this investigation is shown in Figure (4.2).

C. Sisal Fiber:

The sisal fiber utilized in this study was manufactured by Guangzhou Boya Feather Accouterment Limited Company in Guangzhou City, China, and is in the form of a knitted mat. The fiber was harvested from the leaves of the sisal plant and is light yellow. They were dipped in a 5% NaOH solution at room temperature for approximately two hours. Sisal fibers were extensively washed with running water after the alkaline treatment, resulting in a fiber that is tougher and more resilient, as well as improved bonded with the matrix. It is utilized to create a composite with other polymers to enhance the strength of the polymers due to their high tensile strength. It is inexpensive, biodegradable, and environmentally friendly. (Figure 4-2) shows the sisal fiber utilized in this study.

D. Flax Fibers:

The Changzhou Doris textile company in Changzhou City, China produced the flax fiber utilized in this investigation as a woven mat. The color of this fiber is white. They were immersed in a solution of 5% NaOH at room temperature for approximately two hours. Flax fibers were completely washed with running water after the alkaline treatment to make them more durable and create a stronger bond with matrix materials. It is soft, smooth, flexible, does not cause allergies, and enables the skin to breathe, making it ideal for prosthetic socket manufacturing. It is more durable than cotton fiber, although it is less elastic. The woven flax fiber utilized in this investigation is shown in Figure (4.2).

E. Cotton Fiber:

As a knitted mat, cotton fibers, which are fabricated at the general company for cotton industries, spinning, and weaving factories in Baghdad-Kadhimiyia, were utilized as reinforcement. The fabric is soft, smooth, absorbent, and flexible. Cotton is considered environmentally friendly because it is a natural and biodegradable fabric. The woven carbon fibers employed in this work are shown in Figure (4.2).

F. Perlon Fibers:

The Otto Bock SE & Co. KGaA Company, Germany, manufactured the white knitted perlon elastic stockinette utilized in this study. It has good stretching capabilities, can be shaped well, and has a very smooth finish. It works well with a wide range of resins and is suitable for ordinary socket laminations due to its ease of saturation. The woven perlon fiber utilized in this experiment is shown in Figure (4.2). The mechanical and physical parameters of the perlon fiber employed in this experiment are registered in Table (4-2).

Table (4-2): The Features of Perlon Fibers as Obtained from the Company

Tensile Strength (GPa)	Young's Modulus (GPa)	Percent Elongation (%)	Density (g/cm3)	Thermal Conductivity (W/m.k)	Poisons Ratio
78	2.6-3	1-30	1.13	0.24-0.28	0.39

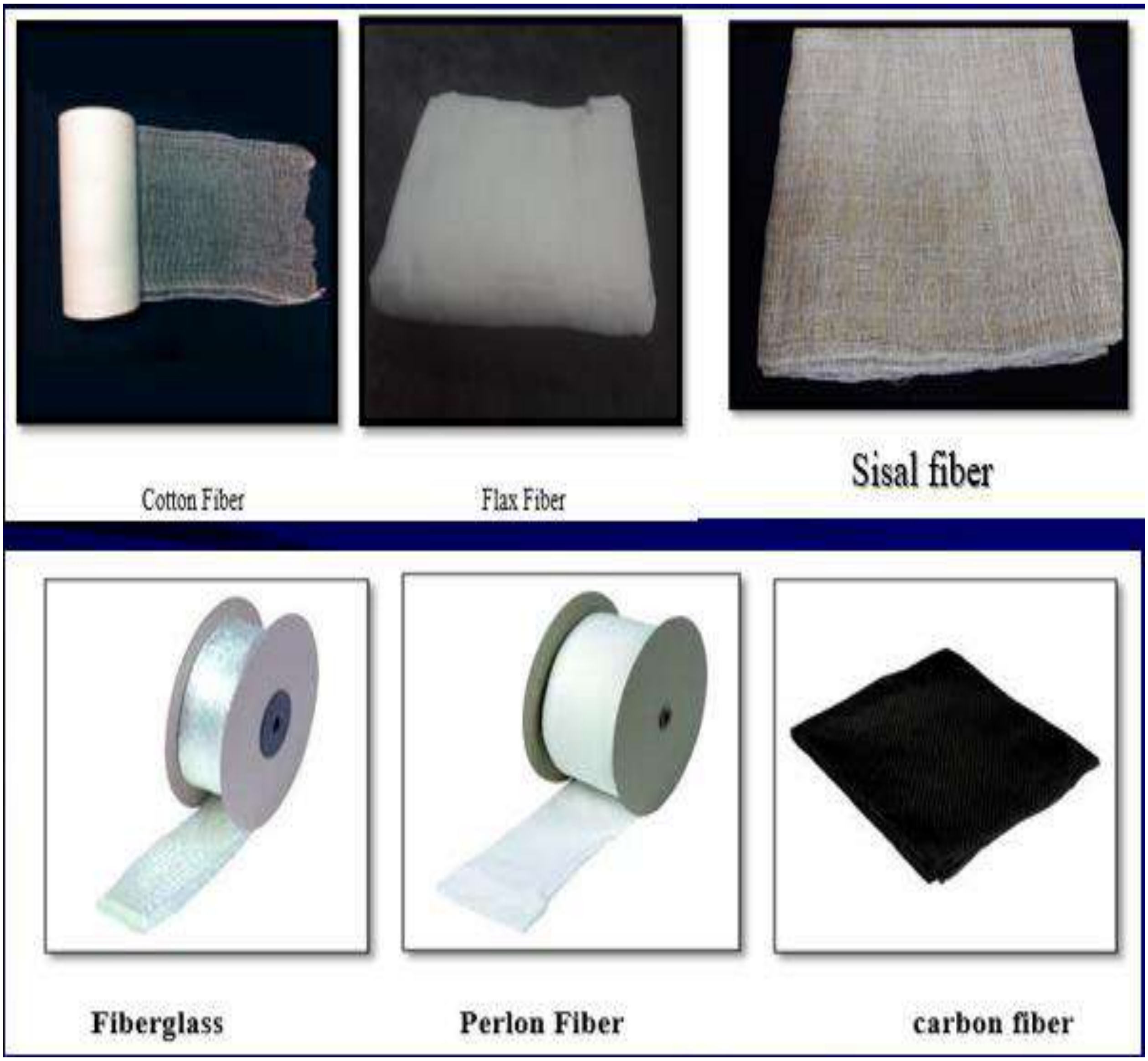


Figure (4-2): Reinforcing Materials utilized in this Study

4-3 Equipment in this study:

The following equipment was utilized: -

- A vacuum forming arrangement entails a vacuum pump and several kinds of stands, pipes, and tubes. (Obtainable at the Al Ibtisaam Prosthetic Limbs Center).
- A digital vernier and sensitive weighing three-digit (0.003) equipment for assessing the dimension and weight of a sample (obtainable in the materials science department's laboratories at the University of Technology).

4-4 General Preparation of Test Specimens:

4-4-1 Mould Preparation:

The vacuum molding technique is utilized to fabricate defect-free samples with a smooth finish. The mold is made of gypsum and has dimensions of 20 cm x 26 cm x 5 cm.

4-4-2 Procedure:

The following procedures were utilized to perform all laminations under a vacuum:

1. A digital sensitive weighing device was utilized to estimate the mass of the fiber reinforcing materials for composite testing samples according to the specified volume fractions.
2. Install the fabricated mold on the laminating podium. At ambient temperature, connect the vacuum forming device via the pressure pipes, revoke the interior (PVA) bag onto the mold, and turn on the pressure controllers to roughly 0.06 MPa or 30 mm Hg, as indicated in figure (4-3 A).
3. Figure (4-3 B) shows the first group's reinforcement fibers with other groups of laminated composite specimens being placed according to the lamination order stated in the table (4-3) and the outer polyvinyl alcohol (PV) being pulled.
4. As seen in figure (4-3 C), mix matrix resin and hardener in the ratio of 1:3 for every 100 portions of resin blended with (2-3) portions of hardener. Then slowly pour the combination into the outer PVA bag and evenly disperse it across the entire area of the mold
5. A Cuboid composite material is produced by maintaining a steady vacuum until the composite material mold cools down, as illustrated in figure (4-3 D), which will be cut to the desired dimensions of specimens.
6. A digital sensitive weighting device was utilized to determine the mass of composite testing samples. For the remaining laminations and lay-ups, the production procedures are repeated for the other types of reinforcement fibers.

Table (4-3): The Laminations Manufactured with different lay-up Methods

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+2 sisal (2S)	(2P +2S+2P) layers
Lamination 13	7	4perlon+3 sisal (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

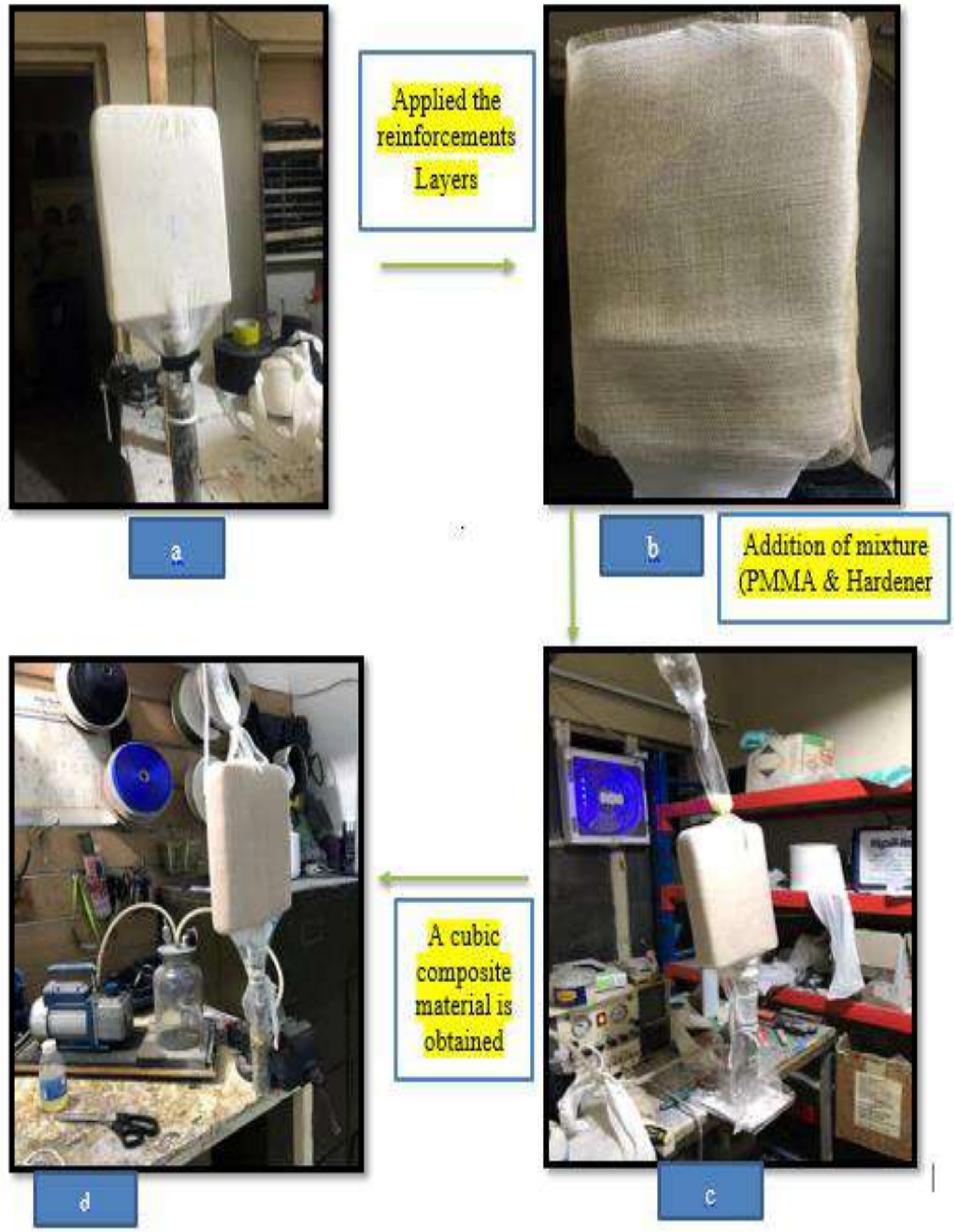


Figure (4-3): The Steps of Test Specimens' Preparation for prosthetic socket.

4-5 Cutting the Specimens:

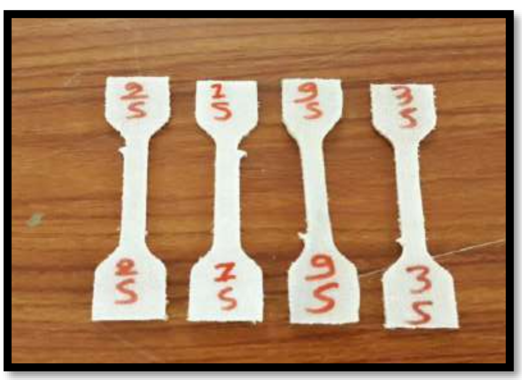
The cutting process for the specimen is carried out at the University of Technology using a computer numerical control (CNC) machine (Rapimill 70). To acquire the standard specimens required for this thesis, the mold is cut.

4-6 Mechanical Tests:

This study utilized a variety of mechanical tests to evaluate the mechanical characteristics of hybrid laminated composite materials for the prosthetic sockets, including the following:

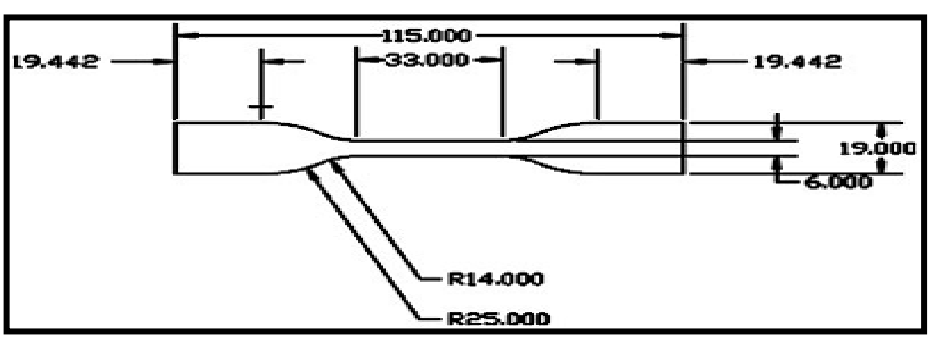
4-6-1 Tensile Test:

A stress-strain curve was obtained for each specimen by utilizing the tensile test. It is utilized to estimate tensile characteristics, for instance, ultimate tensile strength (UTS), elastic modulus (E), and elongation percentage at the break for these specimens. [134]. The tensile test is performed per the (D638-03 ASTM), kind IV standard. Tensile tests were performed at ambient temperature utilizing an Instron tensile machine (universal testing machine) in the Materials Department/ University of technology with a crosshead speed of (5 mm/min), and the load was subjected to this till the sample was broken. Forty-five standard tensile specimens prepared in this study and the device utilized in this investigation are presented in Figure (4-4).



(A)

(B)



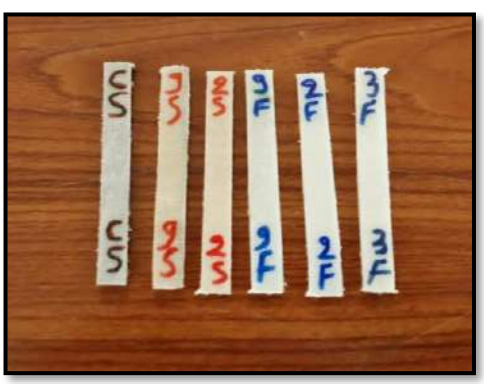
(C)

(D)

Figure (4-4): (A) Samples before the test, (B) Samples after the test, (C) Standard Sample dimensions by (mm), and (D) The tensile test device.

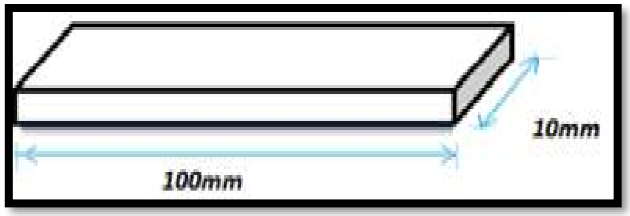
4-6-2 Flexural Test:

Three-point bending test machines (Lybold Harris No.36110) performed a three-point flexural test in the Materials Department/ University of technology with a strain rate of (5 mm/min) and a load of 5 kN till the specimen was bent. A perpendicular force was smeared to the midpoint of the sample to attain the curve that signifies the association between force (N) and displacement (mm). Flexural modulus and strength were determined for every forty-five samples prepared under the standard (ASTM D-790) [137], as displayed in Figure (4-5).

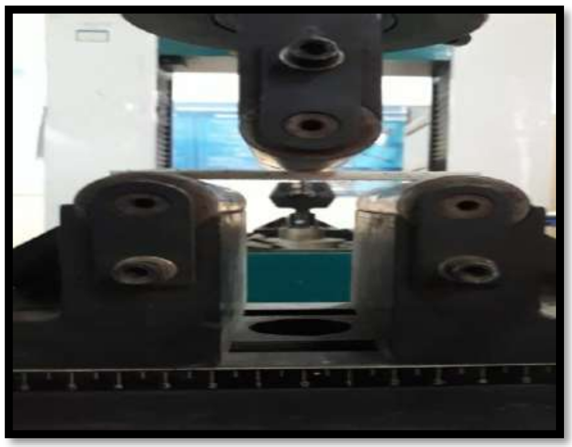


(A)

(B)



(C)

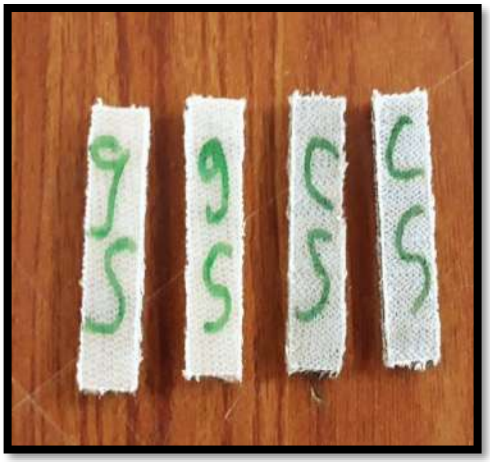


(D)

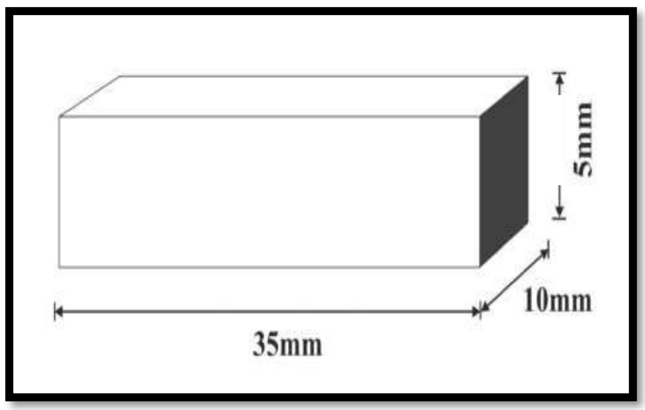
Figure (4-5): (A) Sample before the test, (B) Sample after test, (C) Standard sample dimensions, and (D) The bending test apparatus.

4-6-3 Maximum Shear Strength Test:

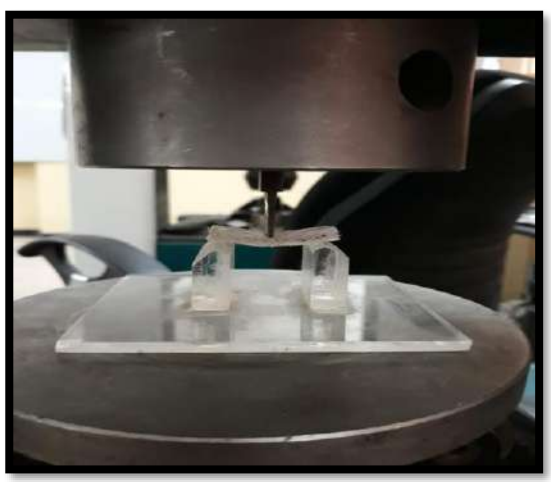
These laminated composite specimens are designed following the ASTM (D-2344 standard) [176]. The Forty-five standard specimen for this test is illustrated in figure (4-6). All data was gathered from a three-point bending test machine equipped with the same Instron tensile machine in the Materials Department/ University of technology with a short beam and a gradually applied load. However, max. shear stress is determined by the max. load acquired from the apparatus and then stratified in equation (3.12).



(A) (B)



(C)



(D)

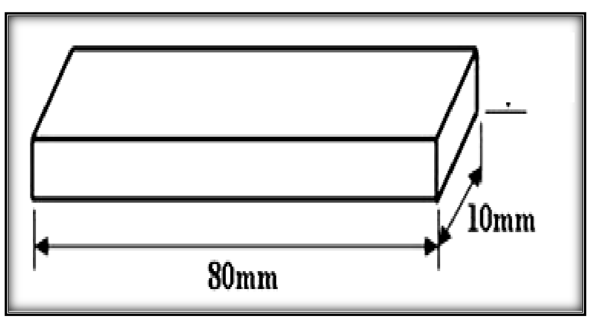
Figure (4-6): (A) Sample before test, (B) Sample after test, (C) Standard sample dimensions, (D) The bending device

4-6-4 Impact Test:

The impact test is executed at ambient temperature, employing an Izod impact test instrument (XJU series pendulum equipment) following the ISO (180) in the Materials Department/ University of technology.

The specimen was fastened at one side and detained perpendicularly by a cantilevered beam and it broke at a pendulum impact energy of (5.5 Joul) and a velocity of (3.5 m/s). The kinetic energy needed to initiate a fracture and maintain it until the specimen is fragmented is referred to as an Izod impact. The Forty-five standard specimen for the impact test and the apparatus utilized in this study [177] are presented in figure (4-7)

(A) **(B)**



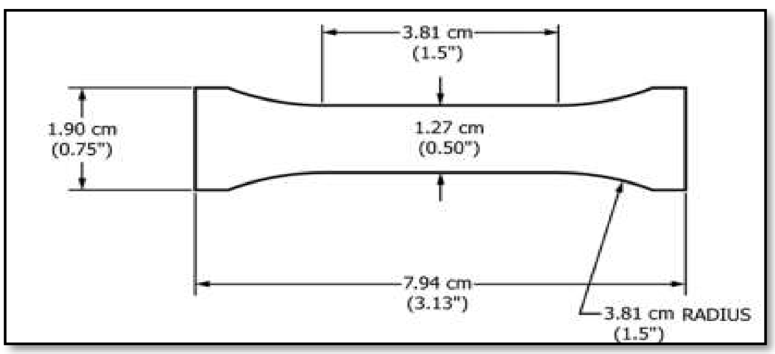
(C)

Figure (4-7): (A) Sample before the test, (B) Sample after the test, and (C) Sample dimensions

4-6-5 Compression Test:

Compressive (stress-strain) curves were plotted for every sample, and the compressive strength is determined using this test. The compression test was executed following the standard (ASTM D695) by utilizing a universal test machine (Materials Department/Technology University) at a strain rate of (5 mm/min) and a load of (25 kN) until the specimen was broken [145]. The Forty-five standard laminated composite specimens and the device utilized in this study are depicted in Figure (4-8).

(A)

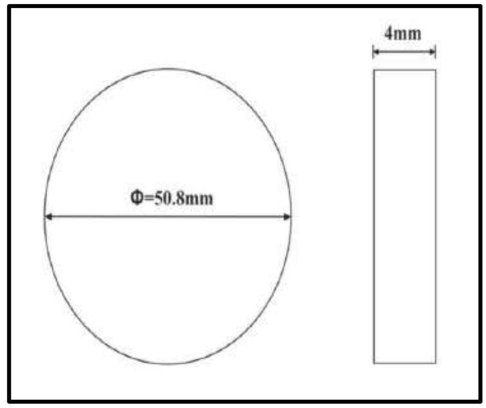


(B)

Figure (4-8): (A) Sample before the test, and (B) Sample dimensions

4-6-6 Hardness Test:

The hardness test of polymer materials was conducted following ASTM D2240 utilizing a Dorumeter hardness test, kind (Shore D), at a load of 50 N and a depressing period of measuring equivalent to (15 s) in the Materials Department/ University of technology. In zone testing, the surface of the specimens must be smooth. Each sample was tested by interring the device's indenter in seven positions on the surface and calculating the average value of the readings [151]. Thirty standard laminated composite specimens and the Shore-D device utilized in this study are depicted in Figure (4.-9).



(A) (B)

Figure (4-9): (A) hardness test specimen, and (B) Standard Hardness Tests Sample

4-6-7 Weathering Testing:

A weathering test was utilized in this study to assess the compressive, tensile, and flexural characteristics of all fifteen lamination groups under the influence of accelerated weathering (water spray, temperature, and UV radiation). The QUV accelerated weathering test device in the Materials Department/ University of technology was employed to conduct the accelerated weathering test following ISO (4892-3) [178]. The device is (UV-A340 lamps), and the model is (QUV/spray) from Qlabs in Australia.

The ninety test sample is subjected to heated, saturated moisture of the air and water vapor since the fluorescent UV apparatus offers a condensation sequence throughout the power-off period to produce moisture [179]. The temperature was 50 °C, and the incidence of UV radiation on the samples was 0.58 (W/m^2). The overall testing time was 100 hours, with 8 hours of UV exposure and 4 hours of moisture exposure [176].

4-7 Morphological tests:

4-7-1 Surface Roughness Test:

The surface roughness test is carried out using a profilometer device (surface roughness) manufactured by (Mahr Company) in the Materials Department/ University of technology. The type is the Pocket Surf, manufactured in the United States, and equipped with a sensor that keeps moving linearly alongside the measured length. The probe begins to move following the surface profile, and these movements are transformed into electric signals, which are magnified and converted to digital signals by a converter. Thirty samples were verified seven times in various locations, and the average value was calculated [177].

A profilometer was utilized to assess the effect of reinforcements on the surface micrometry of the specimens under test. This device seems to be a great tool for estimating surface roughness and providing quantitative measurements that can be evaluated.

4-8 Physical tests:

4-8-1 Density Test:

In this study, the density of laminated specimens is being employed as an indicator for the strength-density ratio and modulus-density ratio.

The composite specimens in this test were fabricated following ASTM (D 792 standard), and their weights were obtained following the Archimedes method utilizing Precision Balances device type: PS 360/C/1, in the Materials Department/ University of technology. Any suitable size of the specimen can be utilized in this test, but the volume must not be less than 1 cm3, the specimens' surfaces and grease, oil, and other undesirable things must be removed from the edges. The thirty items that were analyzed had to be weighed in air and distilled water, and the density could be calculated using equation (3.17) [162].

4-8-2 Water Absorption Test

ASTM D570 is the most extensively utilized standard for measuring water absorption in polymer materials in the Materials Department/ University of technology. The thirty samples were dipped completely in distilled water at an ambient temperature of 23 ± 2 °C and remained on an edge for 24 hours, after which they were taken away from the distilled water. After that, all surfaces were wiped down with a dry cloth, weighed the specimens were with a digital balance, before and after immersion in distilled water and water absorption was calculated using equation (3.18) [170]. The standard specimen for this test can be seen in Figure (4-10).

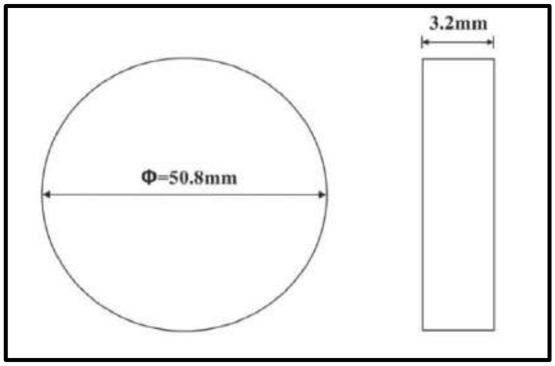


Figure (4-10): The water absorbtion test standard specimens utilized

4-9 Miscibility Tests:

4-9-1 Fourier Transform Infrared Spectrometry (FTIR) Analysis

The (FTIR) test was executed using a (Bruker Optics Company FTIR spectrometer) following (ASTM E1252) standards (TENSOR-27) in the Materials Department/ University of technology. After putting the sample into the device, Fourier transform analyses were executed on a spectrum for PMMA composites strengthened by synthetic and natural fibers [182].

Chapter Five
Numerical Analysis

5-1 Introduction:

The lower limb prosthesis, as structural support for the participant's instance and motion, can lead to injuries to the user if it collapses due to the loss of load-bearing capacity or ruptures of the material caused by extreme stresses. As a result, a key standard in the design of a lower limb prosthesis is to protect against an unplanned collapse of the structure by analyzing the stresses to which the device will be exposed during service and ensuring that the stress limits of the construction material are not surpassed [172].

The finite element (FE) methodology can be useful in determining mechanical contact between the stump and socket, as well as in the design and manufacture of sockets using computer-aided design and development [183]

Geometry is the initial criterion of the FE model. The properties of the material for the individual parts that make up the geometry are then presented. The geometry is then subjected to loads and boundary conditions. The geometry is then discretized into elements, which are characterized in terms of nodes and connections between elements. The element type represents the type of problem that needs to be solved. The model is then solved. Finally, the computed and visualized results are obtained [184].

ANSYS is a commercial finite element technique capable of performing simple linear static analyses as well as complex nonlinear and dynamic analyses [185 and 186]. The analyses are described in detail in the following sections.

5-2 Theory of Finite Element Method (FEM):

The F.E.M. is a numerical process that may be utilized to resolve a varied range of engineering complications such as stress analysis, heat transmission, fluid flux, and electromagnetic.

Nowadays, FEM is among the most widely known and practical tools for computing complicated difficulties in a variety of fields, such as (civil, biomedical, and mechanical) engineering, heat flow, geomechanics, and so on. On the other hand, FEM might be viewed as a useful tool for solving differential equations that describe various physical processes. [187]

For the study of stress and strain in composites, the ANSYS program is utilized, which is based on the numerical simulation equations constructed using the finite element technique [188].

The structure to be evaluated is provided as a collection of subdivided elements. To form a solid mesh, nodes or nodal points are joined at certain joints to provide a resolution to the stresses in the system when it is subjected to a load. When adjacent elements are regarded to be connected, the nodes are frequently found on element boundaries [189].

These components may have varied outlines and characteristics depending on their use. Among the most prevalent kinds of three-dimensional components utilized in the analysis of engineering, complications are those presented in figure (5-1). The number, kind, size, and organization of the components have a major effect on how accurate the solution is [190].

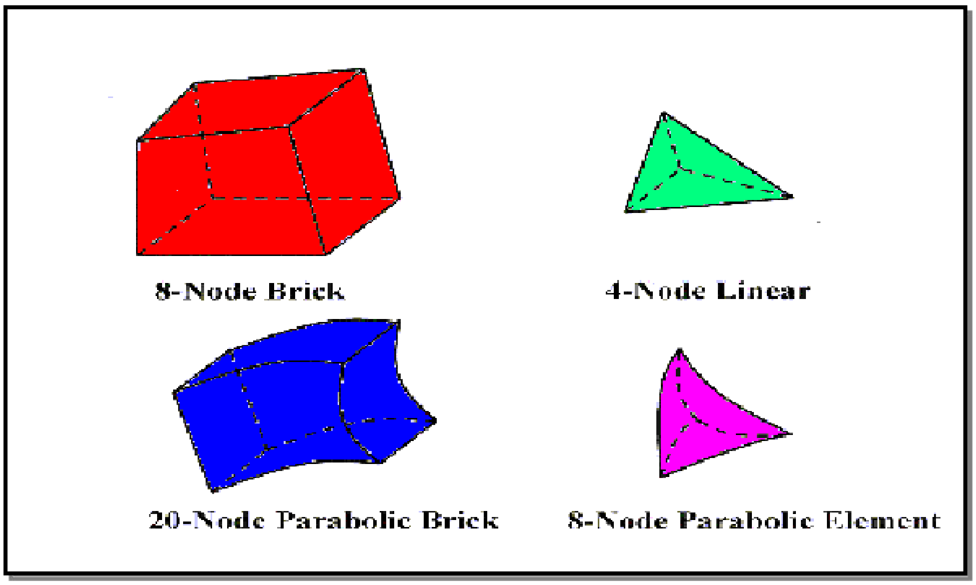


Figure 5.1: Common forms of three-dimensional components [191].

5-3 The FEM Process:

The overall approach of finite element analysis can be divided into three phases: preprocessing for data analysis, processing for equation formulation and solution, and post-processing for analysis presentation.

5-3-1 Preprocessing:

It is identifying the problems and their major components. It begins with the user creating a model of the object to be analyzed where the structure is separated into several separate sub-regions, or "elements," that are attached at discrete points known as "nodes." Some of these preprocessors can combine a mesh with an existing CAD file, permitting the analysis to be executed conveniently as a section of the computerized design and drafting procedure [11]. This phase consists of the following steps:

A- Modeling:

This technique offers numerical solutions to difficult problems such as complex geometrical boundaries and non-linear material properties.

In the ANSYS workbench, a three-dimensional model of the socket was created to determine the stress dispersal and deformation outline under acceptable loading conditions during the standard gait cycle, as well as to evaluate the pressure amid both the stump and socket to achieve good prosthetic socket fitting. A below-knee amputee is a young subject. He was around 23 years old, stood 169 cm tall, and weighed 58 kg. For his right lower leg, the individual wore a socket below the knee. A 3-D finite element model of the socket was created based on the true geometrical dimensions of the amputee stump [172].

After creating a positive mold of a trans-tibial amputee out of gypsum and measuring and documenting the (x, y, z) measurements, the model was plotted in the AutoCAD program (version 2014). The socket was drawn by inserting the dimensions and sketching the actual shape of the below-knee socket after taking the dimensions of the socket. To measure the socket's dimensions, Cartesian coordinates were utilized. For every ten degrees at every level, a measurement was made beginning at the knee adaptor joint and continuing to rise with the height of the socket for each 2 cm. Because of minor changes in the angle between the measured points, this is precise enough. Eventually, the geometry of the socket is imported to the Ansys-15 workbench.

B- Selected Element:

There are many different element types in the ANSYS element library. The element category is identified by a unique number for each element type [133].

The element type selected in this study is solid-185, as presented in Figure (5.2), and is utilized for the 3-dimension modeling of solid systems. It is referred to by eight nodes with three degrees of freedom at every node. Some abilities characterize the element which has no specific orientation, such as plasticity, stress, creep, and strain. Modeling is possible with SOLID185 Structural Solid. When employed in unbalanced locations, it permits prism and tetrahedral degenerations. Several element tools, for example, B-bar, are supported, resulting in significantly reduced integration and increased strains [192]. All of the materials utilized in the socket lamination recommended were analyzed using the final model.

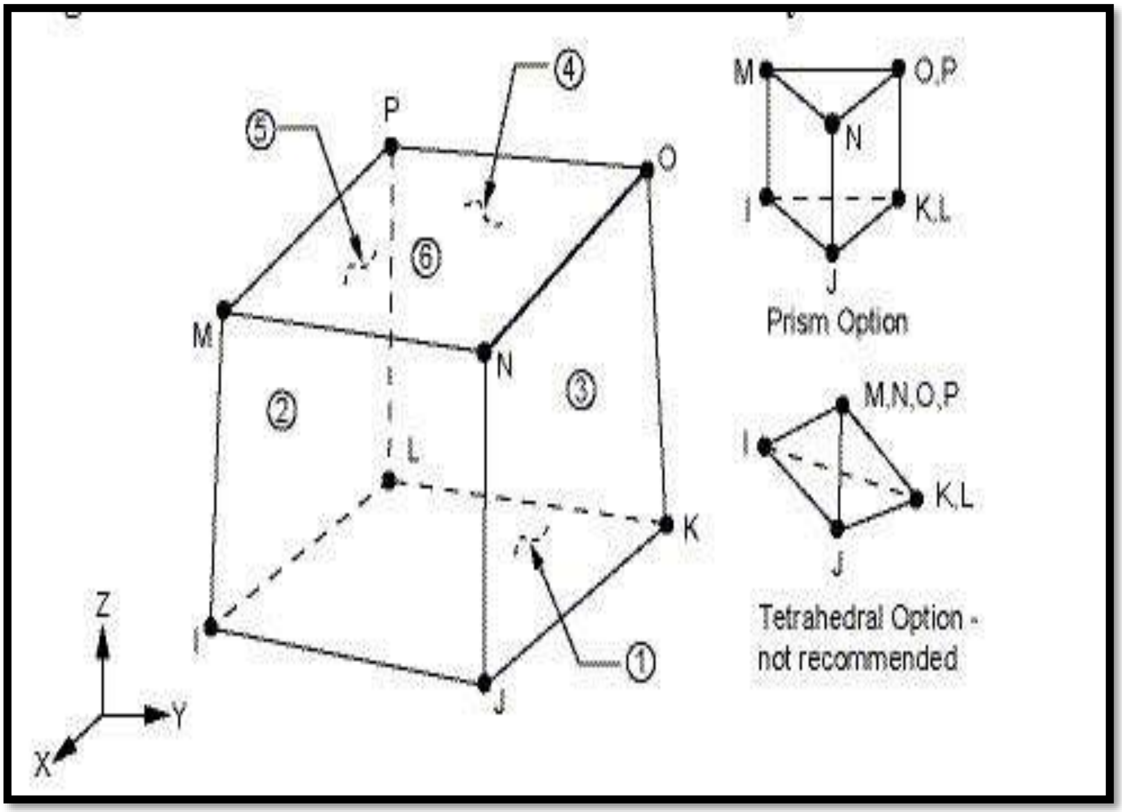


Figure (5.2): Solid -185 [192].

C- Element Real Constant:

In this option, the only model average thickness is entered.

D- Material Properties:

Material properties are needed for the majority of element types, dependent on their intended use. While the mechanical properties of the composite utilized in this investigation (tensile strength, yield strength, and Young's modulus) were ascertained through tensile tests and the Poisson's ratio, while density was calculated theoretically using the rule of mixture [60 and 193], Table (5-1) contains the tensile properties, Poisson's ratio, and density of the composite sockets utilized in this study.

Table (5-1): Tensile Properties and Density of The Composites of this work.

Lamination	Density (g/cm^3)	Young's Modulus (GPa)	Poisson's Ratio	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)
Lamination 1	1.14	1.67	0.355	32	37
Lamination 2	1.15	2	0.353	42	47
Lamination 3	1.17	2.2	0.356	51	56
Lamination 4	1.233	3.2	0.335	140	143
Lamination 5	1.276	2.4	0.272	83	86
Lamination 6	1.125	2.5	0.341	41	46
Lamination 7	1.134	3	0.332	60	65
Lamination 8	1.138	3.4	0.33	86	91
Lamination 9	1.225	5.6	0.321	420	423
Lamination 10	1.266	3.8	0.277	172	175
Lamination 11	1.101	2.1	0.43	36	41
Lamination 12	1.116	2.5	0.342	45	50
Lamination 13	1.125	3.1	0.334	60	65
Lamination 14	1.213	4.76	0.339	258	261
Lamination 15	1.245	3.65	0.283	151	154

E- Mesh Generation:

Following the completion of the model geometry, the next step is to generate a finite element mesh. Mesh generation is among the most important aspects of engineering simulation because it allows users to balance these specifications and get the right mesh for each simulation in the most automated conceivable way.

As seen in figure (5.3), the meshing begins with the volume selection, followed by the choice of the subject's outline as a tetrahedron (automatic meshing). Fixed support is subjected to the distal end of the mesh model, and the distal end is connected with the residual parts. This meshing has a total number of elements (8935) and a total number of nodes (18138), granting involuntary ANSYS features and a node counter

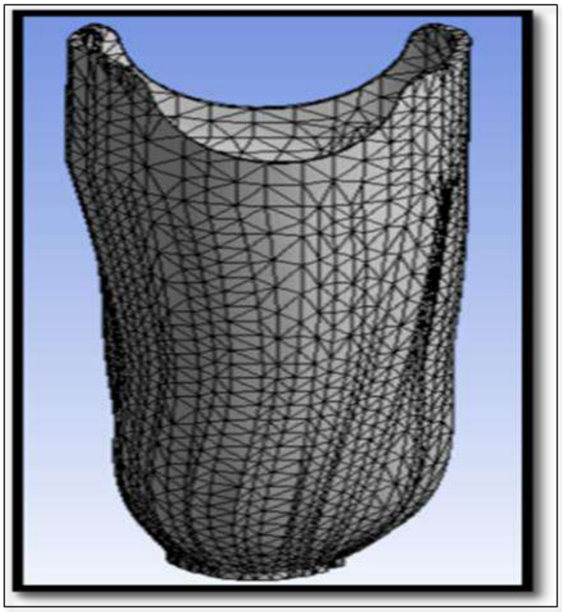


Figure (5.3): The model of the below-knee socket with meshing.

F- Loading and Boundary Conditions:

The term "loads" in ANSYS refers to boundary conditions as well as forcing functions that are applied externally or internally [displacements, forces, pressures, temperatures (for thermal strain), and gravity]. The load on the socket adapter will be the load in the ANSYS® Workbench program. The interface pressure is dispersed in various ways based on particular positions.

In this research, the load is delivered as varying pressures on the internal surface of the socket. The regions of the BK socket are associated with these pressures. The socket is examined under the most severe load circumstances, which occur during the gait cycle's heel strike. By applying for fixed support at a basal plane pressure values as listed in table (5-2) were applied to the plane of the socket shown in figure (5.4) [172].

Table (5-2): Site and Average Pressure Date of Heal Strike Created in Socket [11]

Site	Anterior	Medial	Posterior	Lateral	Basal
Average Pressure value (kPa)	100	80	90	65	288

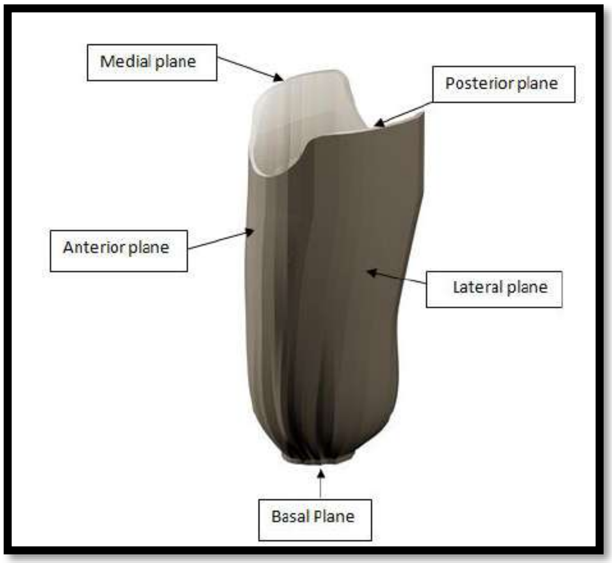


Figure (5.4): Planes of Socket [194].

5-3-2 Processing:

A- Solving Method:

The global governing equations are resolved in this phase to identify unknown field parameters. There are a variety of solution techniques based on the complexity of the problem (count of degrees of freedom), the amount of computer storage available, the kind of equations (symmetrical or not), etc. The Highline design, frontal solution mechanism, and iteration methods are the most popular solution strategies. It should be emphasized that the essential boundary conditions must be implemented to solve the system of equations. The kind of model and the approach used to formulate the FEM equations determine the boundary conditions. The mandated numbers of the displacement at defined nodes, for instance, are important boundary conditions for elasticity problems. Boundary conditions are normally applied to the global system of equations effectively, but they can also be applied during the creation of element feature matrices [195].

If the global system of equations is expressed as:

$$\begin{bmatrix} K_{uu} & K_{un} \\ K_{nu} & K_{nn} \end{bmatrix} \cdot \begin{Bmatrix} U_u \\ U_n \end{Bmatrix} = \begin{Bmatrix} F_n \\ F_u \end{Bmatrix} \quad . \quad . \quad . \quad . \qquad (5.1)$$

Where the subscripts:

u for unknown values,

n for known values.

Then, the reduced system of equations is:

$$K_{uu}\, U_u + K_{un}\, U_n = F_n$$

Or,

$$K_{un}\, U_u = F_n - K_{un}\, U_n$$

Which is equivalent to equation

Which is equivalent to the equation

$$[K]\ \{\ \varphi\ \} = \{f\}. \quad . \quad . \quad . \qquad (5.2)$$

Where:

[K] is the global characteristic matrix,

{f} is the global load vector,

{ φ } is the global field variable vector.

5-3-3 Post-processing:

Viewing of the results is represented by the total deformation, Von-Mises equivalent stress, and Von-Mises elastic strain about the solution of static analysis. The steps used to calculate the properties of the trans-tibial prosthetic socket are presented in the chart of the analysis process shown in figure (5.5).

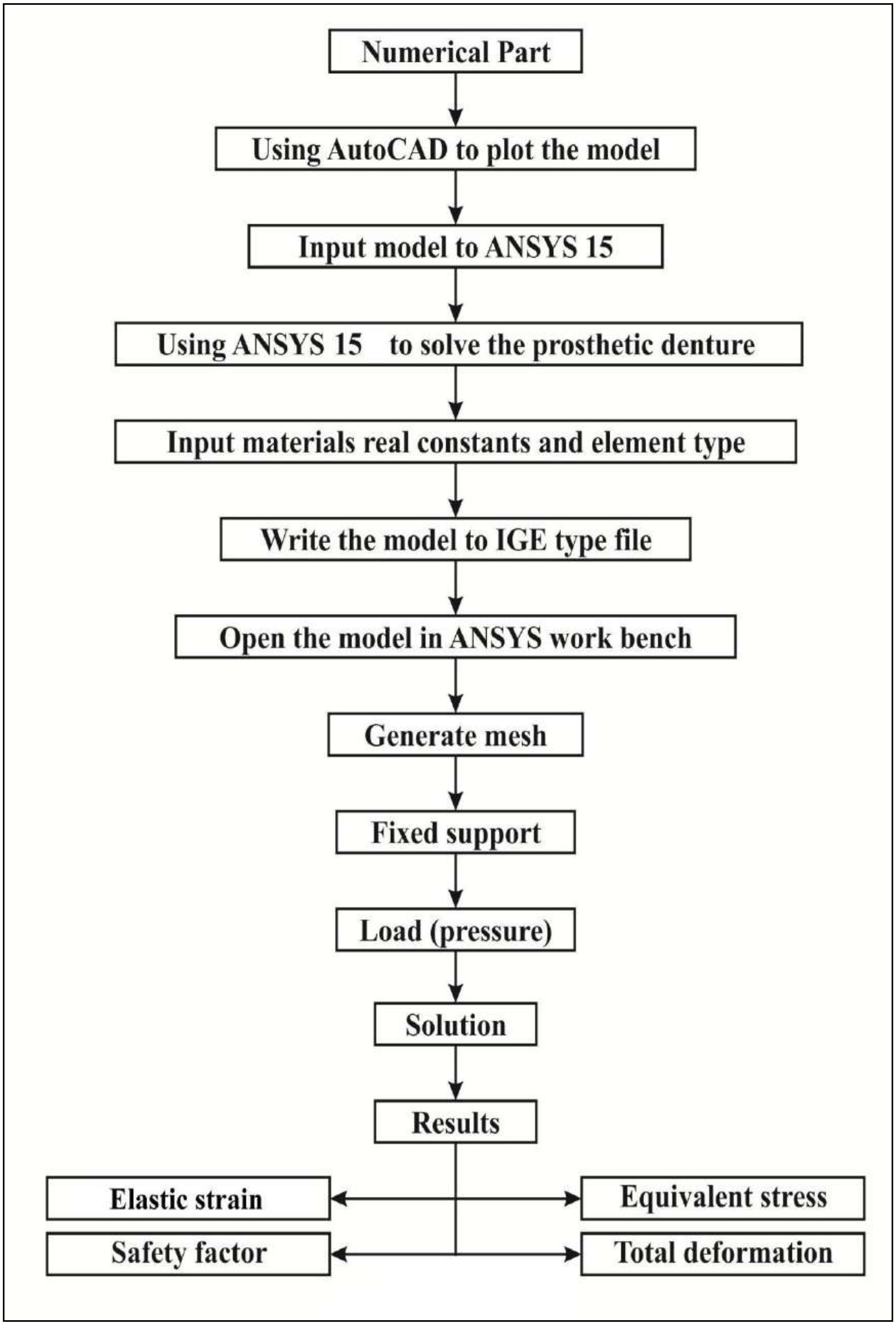


Figure (5.5): Flow-Chart of Analysis Procedure by FEM for prosthetic socket.

Chapter Six

Results and Discussion

6-1 Introduction:

The results and discussion of the experimental and numerical analysis for prosthetic socket laminated composite specimens of prosthetic are presented in this chapter. Experimental mechanical test results for various types of laminated composite materials used to make prosthetic sockets were presented, including: (tensile, flexural, impact, max shear, compression, hardness, and weathering), physical tests (water absorption and density); morphological test (surface roughness), and miscibility tests with Fourier transform infrared spectrometry (FTIR).

The results of the numerical analysis include safety factors, maximum deformation, equivalent von mises stress, and equivalent von mises strain.

6-2 Experimental Results:

6-2-1 Physical Features of Samples:

The sample set's average thickness and weight are measured with a digital vernier and a digital weighing device, respectively, and volume fractions are obtained [137].

Table (6-1) demonstrate how the reinforcing material utilized for the prosthetic socket affects the average thickness. Although there were no substantial variances throughout all the reinforcement, it was revealed that increasing the no. of fiber layers in the laminations tends to increase the thickness and weight. This increase in thickness was caused by the addition of fiber layers and acrylic resin, but a majority of it can be attributed to the matrix acrylic resin based on thickness comparison. The thickest reinforcement is a hybrid (Cotton Glass) reinforcement [196].

Table (6-1) demonstrates the contrast of volume fraction with altering the kind and number of reinforcing materials. It can be seen that the absorbing capacity is amplified by increasing the fiber layers. Fiber volume fraction results virtually supported this analysis. The cotton glass reinforcement samples have the utmost volume fraction [197].

The influence of reinforcements and matrix on the strength/density ratio can be seen in Table (6-1). The tensile strength/density ratio of the hybrid (Flax, Perlon, and Carbon) reinforcing composite is superior to other laminations with 345.3 MPa.cm^3/g [198], whereas lamination (1) has the lowest (strength/density) ratio in comparison to the other lamination groups with 32.8 MPa.cm^3/g.

The impact of reinforcing material and matrix on the modulus of elasticity/density ratio can be seen in Table (6-1). The tensile modulus/density ratio of the hybrid (Flax, Perlon, and Carbon) reinforcing composite is superior to other laminations with 4.6 GPa.cm^3/g [198], whereas lamination (1) has the lowest (modulus of elasticity/density) ratio in comparison to the other lamination groups with 1.48 GPa.cm^3/g.

Table (6-1): Physical and Mechanical Properties of the Composites of this work.

Lamination	**Thickness (mm)**	**Volume fraction %**	**Young's Modulus/ density (Gpa*cm^3/gm)**	**Ultimate Tensile Strength / density (MPa*cm^3/gm)**
Lamination 1	2	15.5	1.48	32.8
Lamination 2	2.23	22.07	1.76	41.4
Lamination 3	2.66	23.25	1.93	49.2
Lamination 4	4.25	29.29	2.61	116.7
Lamination 5	4.4	50.49	1.89	67.9
Lamination 6	2.5	22.55	2.19	40.8
Lamination 7	2	26.31	2.6	57.3
Lamination 8	2.7	27.18	2.9	79.9
Lamination 9	3.5	34.47	4.6	345.3
Lamination 10	3.8	46.76	3.1	138.2
Lamination 11	2	22.09	1.9	37.2
Lamination 12	2.2	23.24	2.22	44.4
Lamination 13	2.23	27.19	2.69	56.5
Lamination 14	4.02	34.65	3.9	215.1
Lamination 15	3.8	43.7	3	123.6

6-3 Mechanical Test Results:

6-3-1 Results and Discussion of Tensile Test:

The tensile properties (Young's modulus (E), ultimate tensile strength, and percentage of elongation at break) of trans-tibial sockets are compared in this study. Varying the kind of reinforcement has a significant influence on the tensile characteristics.

6-3-1-1 Results and Discussions of Tensile Strength:

From figures (6.1, 6.2, and 6.3), it is noted that tensile strength values were found to improve with increasing volume fraction for fiber layers. This improvement in the strength is due to the bonding nature and greater loads maintained by the fibers, because of upper load transmission from the matrix to them. [199].

It can also be noticed that the incorporation of carbon and glass fibers has an evident influence on the tensile strength more than the use of natural fiber alone. Therefore, the values of tensile strength for these lamination groups are found to be greater than for those reinforced with only natural reinforcements with higher results found when reinforcing with carbon fibers than with glass fibers. This is owing to the enhancement of mechanical characteristics affiliated with the introduction of these types of reinforcements, which have higher strength compared with sisal fibers [196].

Figure (6.3) also shows that the tensile strength values for flax hybrid laminations rise significantly more than those for sisal and cotton hybrid laminations as the volume fraction increases. This is dependent on the characteristics that distinguish flax fiber from sisal and cotton fibers, with the former having a higher tensile strength than the latter, particularly the fibers that carry the majority of the externally applied stress to the composite material specimen [200 and 201]. While reinforcing with cotton fibers resulted in the lowest tensile properties of any other lamination. Figure (6.3) further shows that laminated composite specimens with three layers of flax and carbon reinforcements have higher tensile strength than samples with one, two, or three layers with(423 MPa.), since fibers are stronger than the matrix, as shown by composite mechanical theories. While the least tensile strength values were observed in lamination (1) with (37 MPa.).

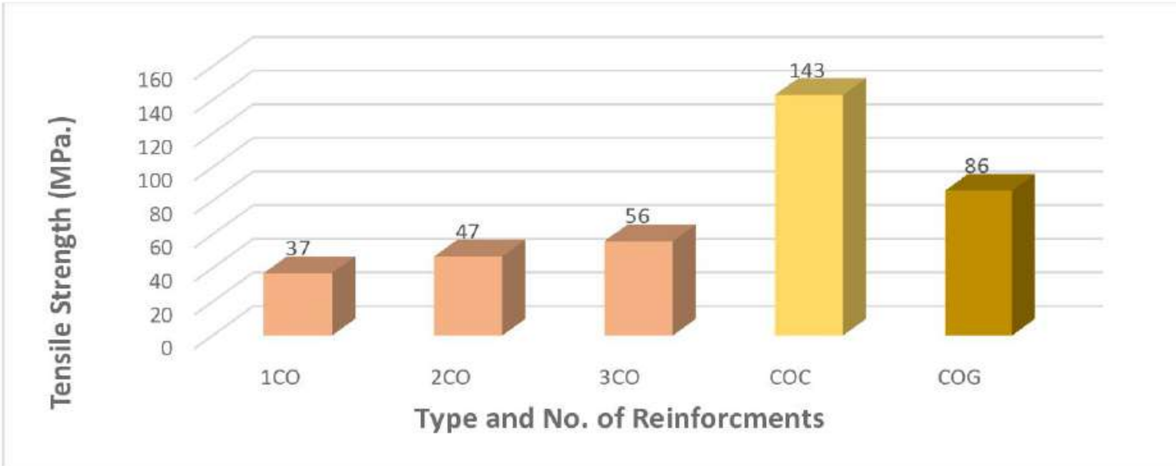
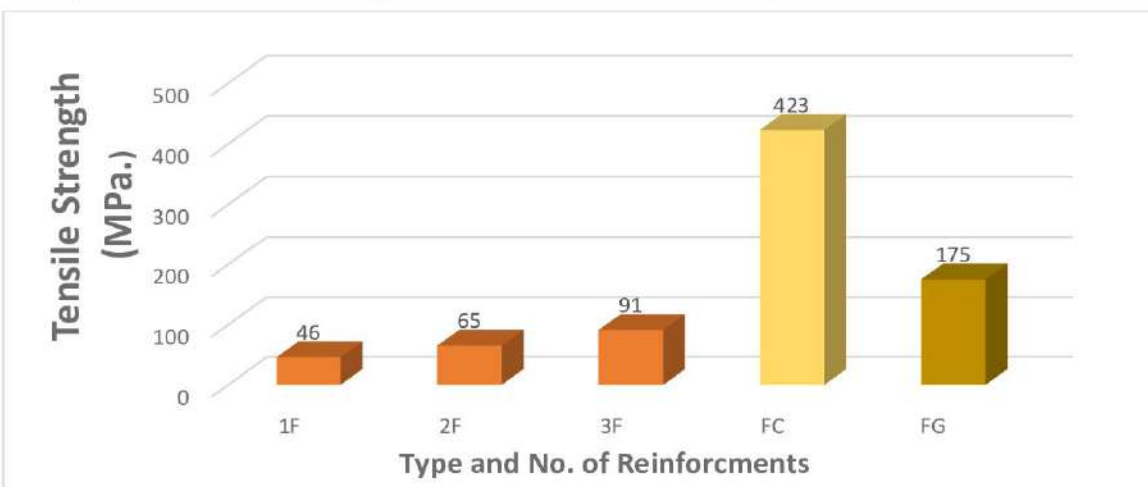


Figure (6.1): Tensile strength and number of cotton fiber layers for prosthetic specimens.

Figure (6.2): Tensile strength and number of sisal fiber layers for prosthetic specimens.



ζure (6.3): Tensile strength and number of flax fibers layers for prosthetic specimens

6-3-1-2 Results and Discussions for Modulus of Elasticity:

Figures (6-4), (6-5), and (6-6) show the modulus of elasticity values of laminated composite materials for each of the specimen groups developed in this investigation.

The relationship between the volume fraction of natural fibers in PMMA resin and the specimens' modulus of elasticity is shown in Figures (6.4, 6.5, and 6.6). It's worth noting that the modulus of elasticity values grew as the volume fraction increased. This could be attributed to the strengthening process and the bonding strength's nature, which forms a complete interface between the reinforcing elements and the matrix resulting in improving the efficiency of force transmission from the matrix to the fiber. The results are consistent with those mentioned in the reference [202]. The tensile modulus of fiber layers increases when a woven glass fiber or carbon fiber was added with higher results found when reinforcing with carbon fibers than with glass fibers. The hybrid laminated composite specimens can withstand higher loads because glass and carbon fibers have a higher modulus of elasticity and resistance to crack propagation than the PMMA [203]

Figures (6-6) further show that as the volume fraction of flax hybrid laminations increases, the values of modulus of elasticity for flax hybrid laminations rise higher than for sisal and cotton hybrid laminations. This is because the flax fiber differs from sisal and cotton fibers in that the former has a greater young modulus than the latter, particularly the fibers that bear the majority of the external stress applied to the composite material specimen [201]. While reinforcing with cotton fibers resulted in the lowest tensile properties of any other lamination. Because carbon fibers have higher tensile characteristics and fracture dispersion resistance when associated with the PMMA, laminated composite specimens with three layers of reinforcing flax fibers and carbon reinforcement layers have a higher modulus of elasticity with (5.6 GPa). than specimens with one, two, or three layers. As a result, composites particularly the fibers that bear the majority of the load can withstand larger loads [203and 204]. While the least tensile modulus values were observed in lamination (1) with (1.67 GPa.).

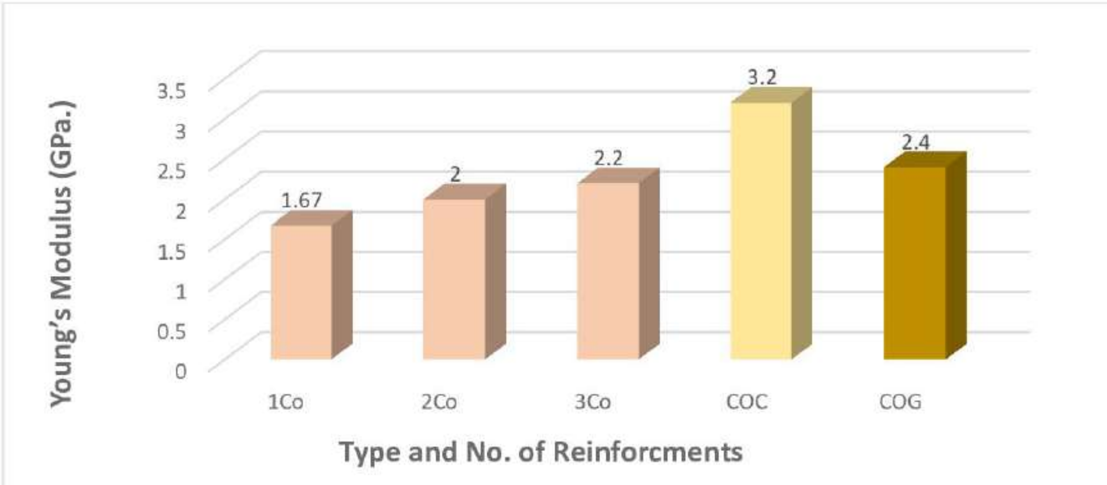


Figure (6.4): Modulus of elasticity and number of cotton fiber layers specimens.

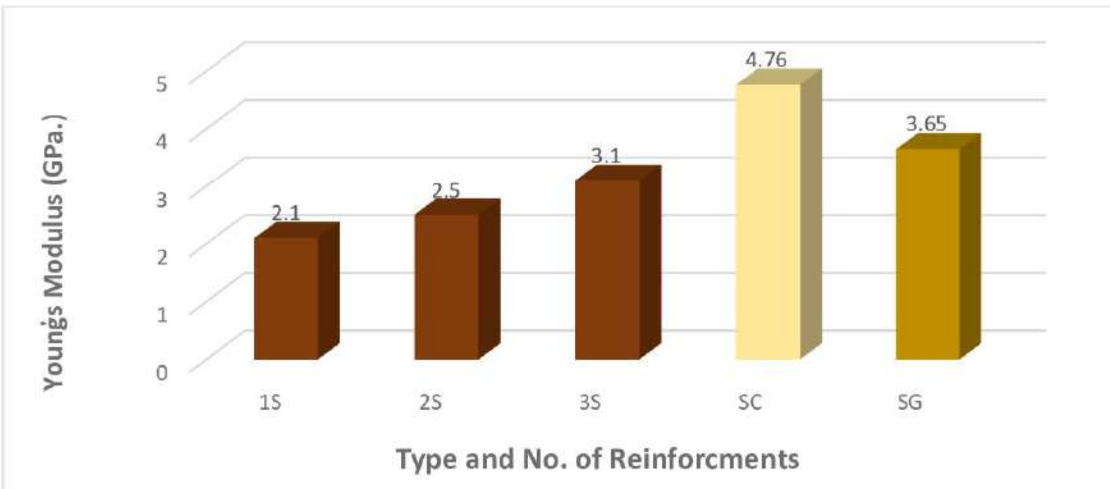


Figure (6.5): Modulus of elasticity and number of sisal fiber layers specimens.

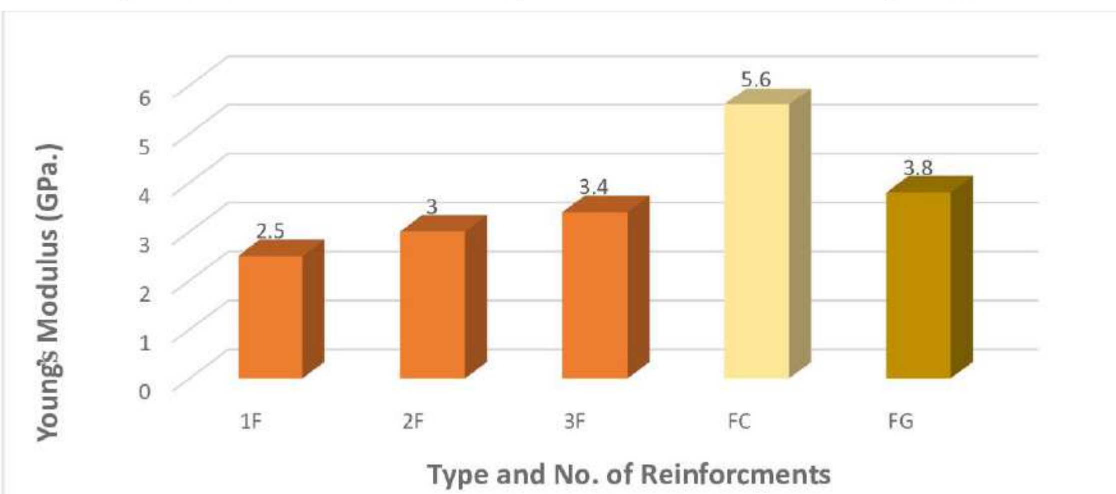


Figure (6.6): Modulus of elasticity and number of flax fibers layer specimens.

6-3-1-3 Results and Discussions of the Elongation Percentage:

Figures (6.7), (6.8), and (6.9) show the values of elongation percentage at the break of hybrid composites for all specimens set in this study.

The relationship between the volume fraction and the elongation percentage of the specimens for this lamination group is depicted in Figures (6.7,6.8 and 6.9).). It clearly shows that increasing the number of flax reinforcing layers resulted in a decrease in the elongation percentage values for specimens. This is due to the occurrence of fiber exerting the stiffening influence within PMMA and therefore putting a mechanical curb on composites. Furthermore, the reduction in percentage elongation is affected by the interference between fibers and matrix. This behavior can be accredited to the establishment of strong structures [205].

While the specimens with hybrid (cotton glass) and (cotton carbon) reinforcements had the highest percentage of elongation at break with higher results found when reinforcing with glass fibers than with carbon fibers. With (cotton glass) lamination group has the highest percentage among all the fifteen lamination groups. Since reinforcements have a greater stiffness than PMMA, they thus impose a mechanical constraint on the specimens [204].

In general, the elongation of natural fiber-reinforced composites is lower than that of hybrid (natural and synthetic) reinforced composite materials, indicating that adding these reinforcements to PMMA did not improve its elasticity.

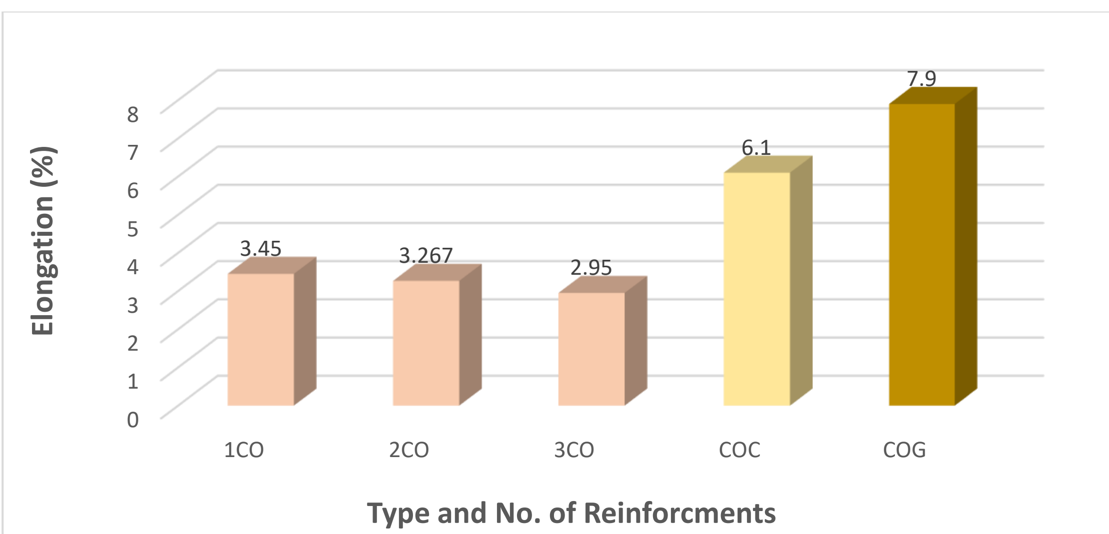


Figure (6.7): Elongation percentage and number of cotton layers for prosthetic socket laminated composite specimens.

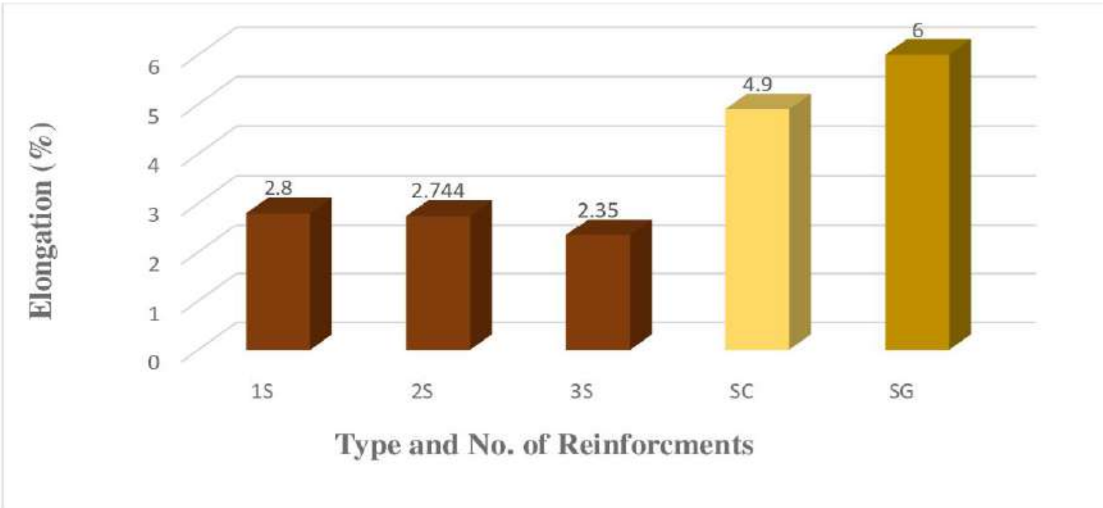


Figure (6.8): Elongation percentage and number of sisal layers for prosthetic specimens.

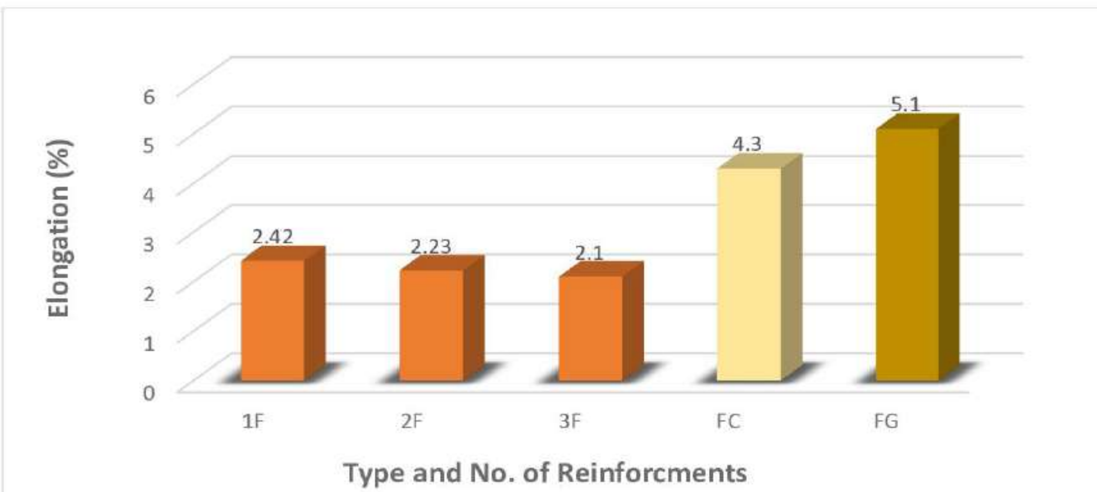


Figure (6.9): Elongation percentage and number of flax layers for prosthetic specimens.

6-3-2 Flexural Test Results:

6-3-2-1 Results and Discussions of Flexural Strength:

Figures (6.10), (6.11), and (6.12) demonstrate flexural strength values for composite beam specimens using hybrid fibers, respectively.

The volume fraction and flexural strength are shown in Figures (6.10, 6.11, and 6.12). It's worth noting that when the volume fraction of all the lamination groups rose, so did the flexural strength [206]. This is owing to the bonding process and nature indicated in the items (6-3-1).

It can also be noted that with the addition of carbon and glass fibers to the fiber layers, higher values of flexural strength than those from specimens with one, two, or three layers were obtained with higher results found when reinforcing with carbon fibers than with glass fibers. This is because the addition of these types of synthetic fibers, which have higher flexural properties, improves mechanical properties [203 and 207].

Figure (6.12) shows that the flexural characteristics of specimens improve as the number of sisal layers increases [204]. With each increase in the volume fraction, the strength of sisal laminations is higher than those of flax and cotton hybrid laminations. This is because the sisal fiber differs from flax and cotton fibers in terms of flexural strength, with the former having a higher flexural strength than the latter [201]. It's also clear that the cotton reinforcement had the lowest flexural properties of all the fifteen lamination groups, implying that they didn't enhance the matrix material's characteristics to any degree and that the matrix's bending properties prevailed in the composites' overall performance [199 and 208].

In addition, figures (6.12) show that laminated specimens with three layers of reinforcing sisal fibers and carbon reinforcement layers have the highest flexural characteristics in comparison to specimens with one, two, or three layers. This can be credited to the fact that carbon fibers have a higher flexural strength than the PMMA matrix. As a consequence, the flexural properties of hybrid specimens are enhanced [203]. While the least flexural strength values were observed in lamination (1) with (53.33 MPa.).

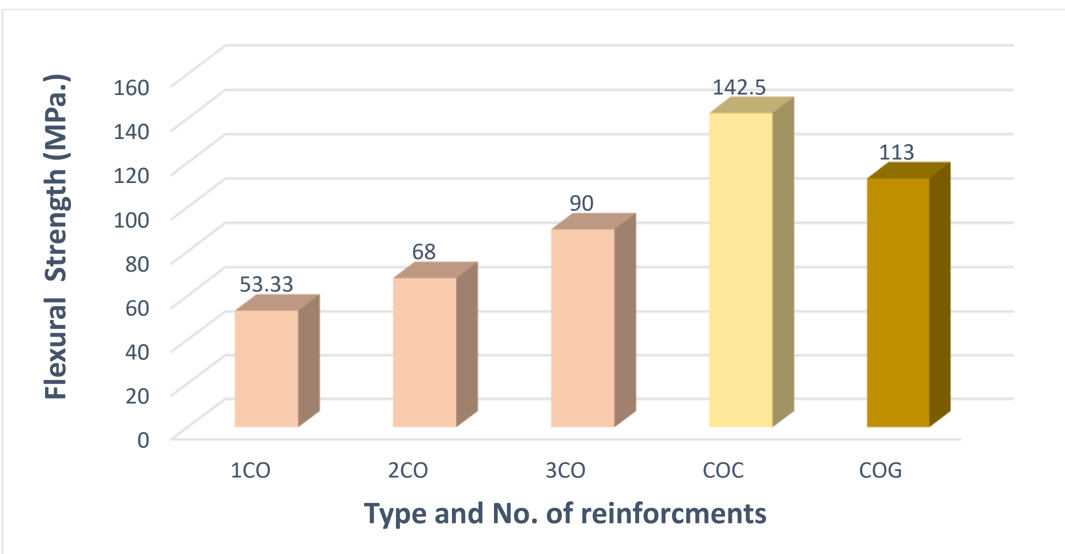


Figure (6.10): Flexural strength and number of cotton fiber layers for prosthetic specimens.

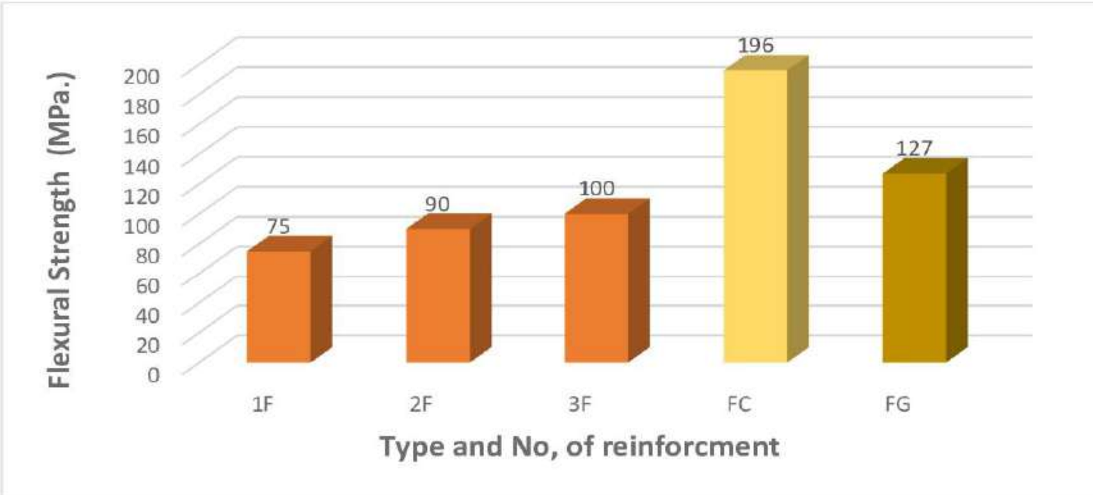


Figure (6.11): Flexural strength and number of flax fiber layers for prosthetic specimens.

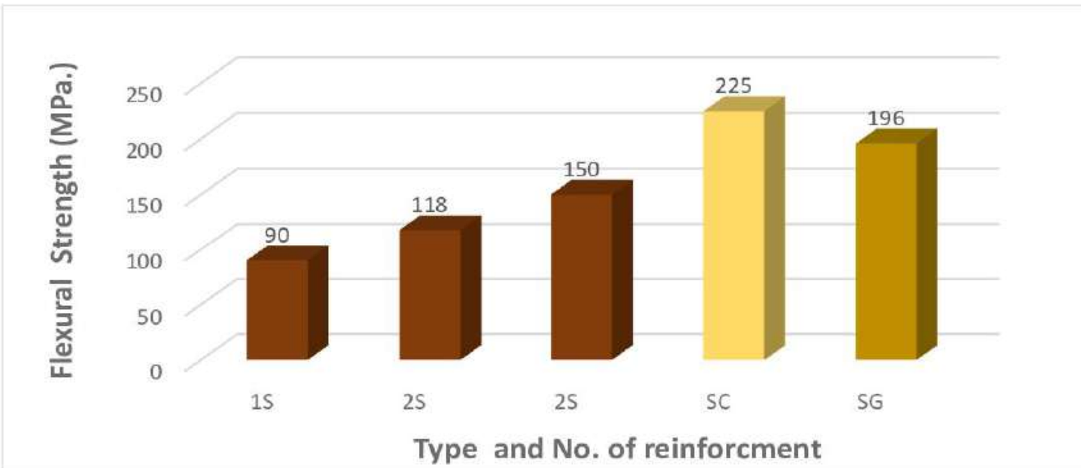


Figure (6.12): Flexural strength and number of sisal fiber layers for prosthetic specimens.

6-3-2-2 Results and Discussions of Flexural Modulus:

The flexural modulus of the specimens is shown in figures (6.13, 6.14 and 6.15) as a function of the volume fraction of fibers in PMMA resin. As the volume percentage grew, so did the values of flexural modulus [22]. This is due to the fibers' high modulus, which enables them to withstand a wide range of loads while also preventing crack propagation within the lamination composite due to the fibers' strengthening mechanism. As a result, the composite specimens' flexural moduli improve [207].

Carbon and glass fibers were utilized to increase the flexural modulus of natural fiber laminations with higher results found when reinforcing with carbon fibers than with glass fibers. The enhancement of the PMMA matrix's stiffness, as well as the contribution of carbon and glass fibers to natural fiber-reinforced composites with their high flexural modulus qualities, may explain this behavior [209].

Figures (6.15) demonstrate the relationship between the number of fiber layers (sisal, perlon, glass, and carbon) added to the PMMA matrix and the flexural modulus. According to these results, the modulus improved as the number of reinforcing sisal fiber layers increased [210]. Furthermore, when compared to their counterparts from the other natural fiber-reinforced groups of laminations, which were reinforced with flax and cotton fibers, the sisal-reinforced composite materials had the greatest values of bending modulus. This behavior could be explained by sisal fiber's improved compatibility and mechanical properties [201]. It's also clear that the cotton reinforcement had the lowest flexural properties of all the fifteen lamination groups, implying that they didn't enhance the matrix material's characteristics to any degree and that the matrix's bending properties prevailed in the composites' overall performance [199 and 208].

The flexural modulus of a sisal fiber-reinforced composite increases much more when a woven mat of glass fiber is added, as shown in figure (6.15) when compared to other lamination groups. This could be due to glass fibers having a greater flexural modulus than sisal and PMMA matrix. As a consequence, the modulus has improved. Nonetheless, when the fifteen lamination groups were compared, the three layers of sisal fiber with carbon fiber had the highest flexural modulus for laminations and reached (7.2 GPa.). This is owing to the presence of high-strength and stiff carbon fibers, which ensure load distribution from matrix to fiber and efficient sisal-matrix adhesion [211, 212, and 213]. While the least flexural modulus values were observed in lamination (1) with (2 GPa.).

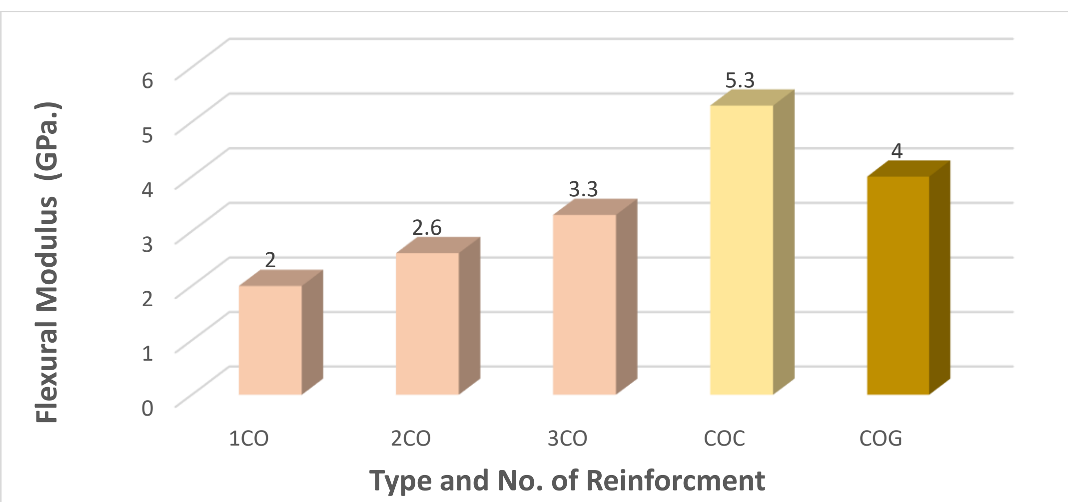


Figure (6.13): Flexural modulus and number of cotton layers for prosthetic specimens.

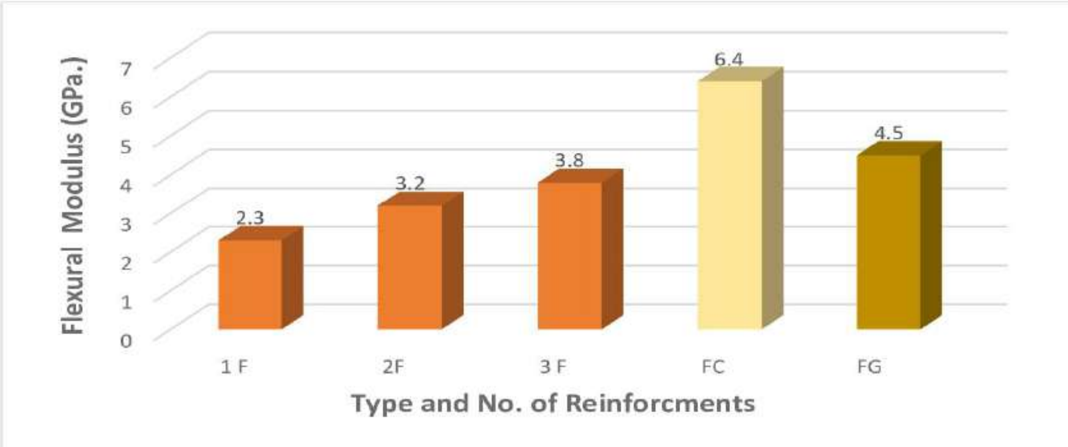


Figure (6.14): Flexural modulus and number of flax layers for prosthetic specimens.

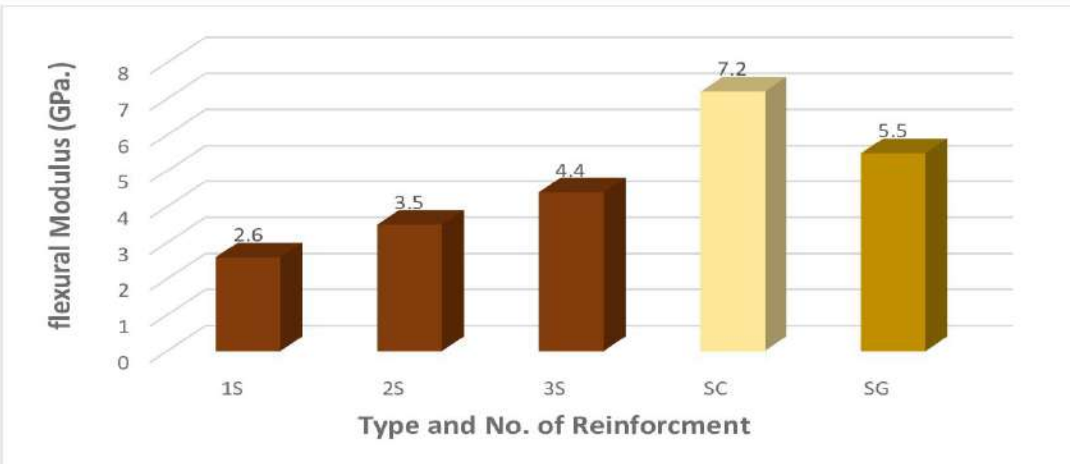


Figure (6.15): Flexural modulus and number of sisal layers for prosthetic specimens.

6-3-3 Results and Discussions of Maximum Shear Stress:

Figures (6.16), (6.17), and (6.18) illustrate the specimens' maximum shear stress for the first, second, and third lamination groups, respectively.

The association between the volume fraction of natural fibers reinforced PMMA and the maximum shear stress for these laminations is shown in the figure (6.16, 6.17and 6.18). It's worth noting that maximum shear stress grew as the volume fraction increased. due to fibers' capacity to avert crack spread inside the PMMA via the reinforcement mechanism, in addition to the matrix's and fibers' remarkable compatibility and bonding [211].

Additionally, the maximum shear stress for the laminations strengthened by glass fiber and carbon fiber is greater than the maximum shear stress for the natural fiber-reinforced laminated specimens with higher results found when reinforcing with carbon fibers than with glass fibers. The addition of carbon and glass fibers to natural fibers leads to the increased maximum shear stress that is associated with the other laminations because the carbon and glass fibers have greater mechanical features [212].

From this figure (6.18), it can be perceived that shear stress increase with raising the number of layers of sisal fibers. It is also clear that the presence of sisal with a PMMA matrix has the highest maximum shear stress obtained among flax and cotton fibers due to the ability of these reinforcements to hinder crack propagation, in addition to the strong bonding of PMMA with the matrix [211 and 213]. It's also obvious that the cotton type of reinforcements had the lowest maximum shear stress of all the fifteen lamination groups, which may be explained by the fact that cotton reinforcement has a low bonding strength, which contributes to its low maximum shear stress in the PMMA matrix [213].

In general, the addition of carbon and glass fiber to composite specimens has a substantial effect on their maximum shear stress and reached the highest value (13.8 MPa.) with hybrid (sisal carbon) reinforcements. This is because of the enhanced mechanical characteristics related to the incorporation of carbon fibers. Furthermore, the greater bond strength that may happen among the fibers and matrix, as well as having a much higher max shear stress than the PMMA matrix, may account for this increase [207]. While the least max. shear stress values were observed in lamination (1) with (2.5 MPa.).

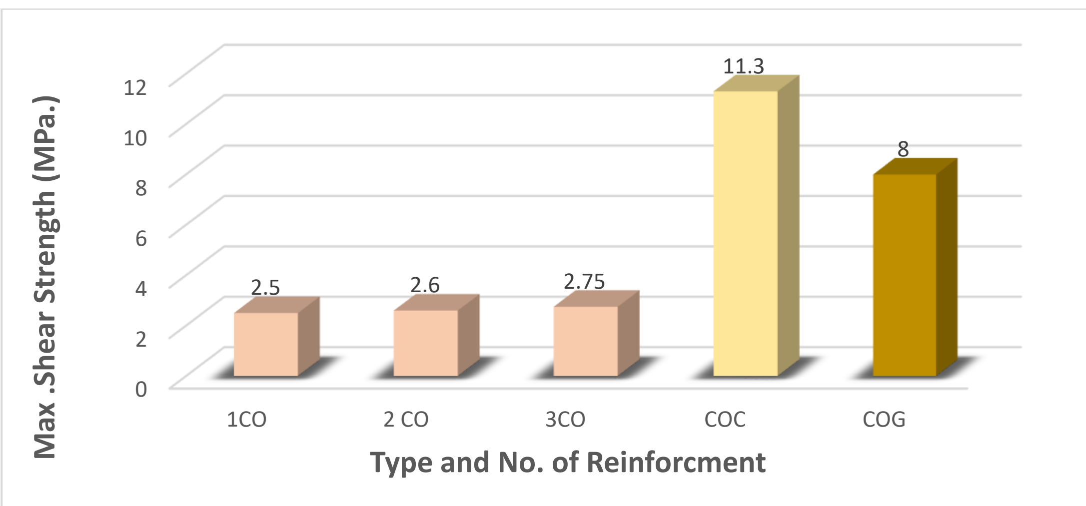


Figure (6.16): Max. shear stress with the number of cotton fiber layers specimens.

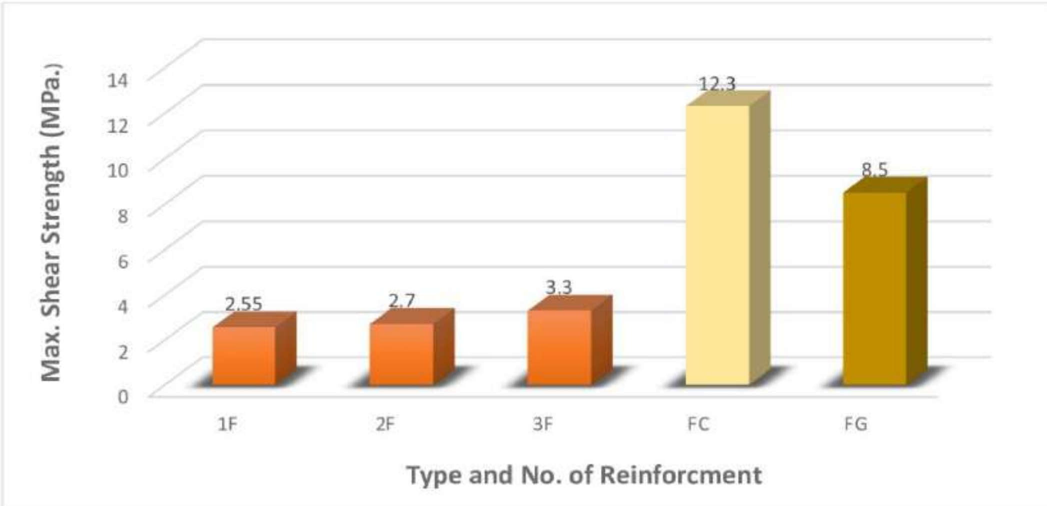


Figure 6.17: Max. shear stress with the number of flax fiber layers specimens.

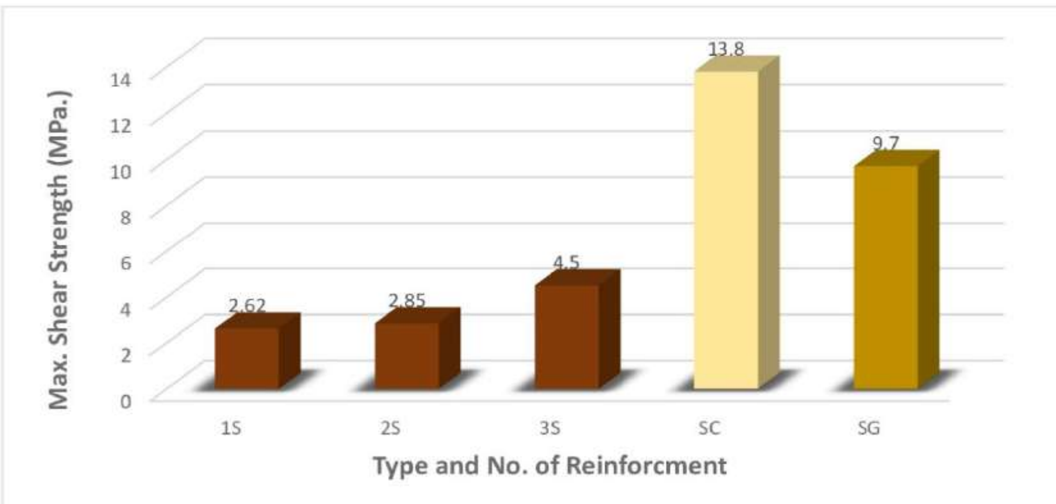


Figure 6.18: Max. shear stress with the number of sisal fiber layers specimens.

6-3-4 Results and Discussions of Impact Test:

6-3-4 -1 Results and Discussions of Impact Strength**:**

Figures (6.19), (6.20), and (6.21) illustrate the impact strength values for the various composite specimen groups.

The relationship between the volume fraction and impact strength of fiber-reinforced specimens is shown in Figures (6.19,6.20 and 6.21). It's worth noting that as the volume fraction increased, the impact strength numbers improved. This is because as reinforcement layers increase in thickness, the value of engaged energy rises, improving impact strength as the accumulation of strengthening layers averts crack growth. These findings are consistent with those reported in reference [214].

Furthermore, these figures also depict the impact strength effect of carbon and glass fibers. it shows that the impact strength values for laminations strengthened by glass and carbon fibers are greater than the impact strength for specimens strengthened only by natural fiber layers with higher results found when reinforcing with carbon fibers than with glass fibers. This could be attributed to the fact that glass and carbon fibers have a higher impact strength than the PMMA matrix, thus meeting the effective impact strength of specimens and enhancing resistance to impact loads [215].

Furthermore, when compared to their counterparts in the other groups of composite materials, which were reinforced with flax and sisal fibers, the composite materials reinforced with cotton fibers have the highest values of impact strength. This is because cotton fiber differs from flax and sisal fibers in terms of impact strength, with the former having a larger impact strength than the latter [201]. When the fifteen laminations are compared, three layers of cotton fiber with carbon fiber have the highest impact strength values (83.5 (KJ/m^2). While the least impact strength values were observed in lamination (11) with (17 KJ/m^2)

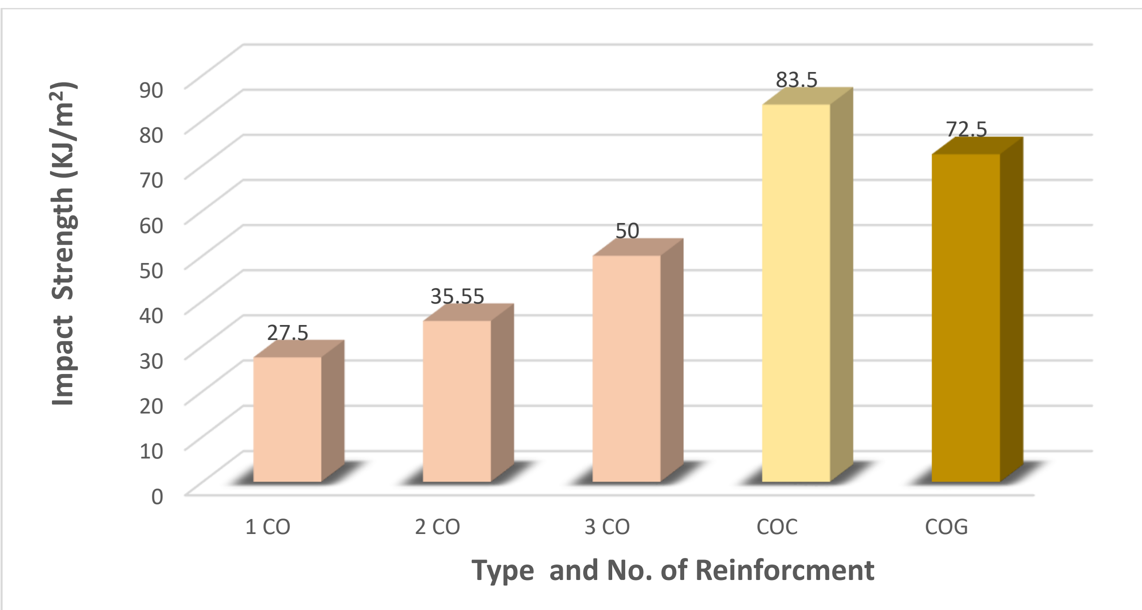


Figure (6.19): Impact strength with the number of cotton fiber layers for prosthetic specimens.

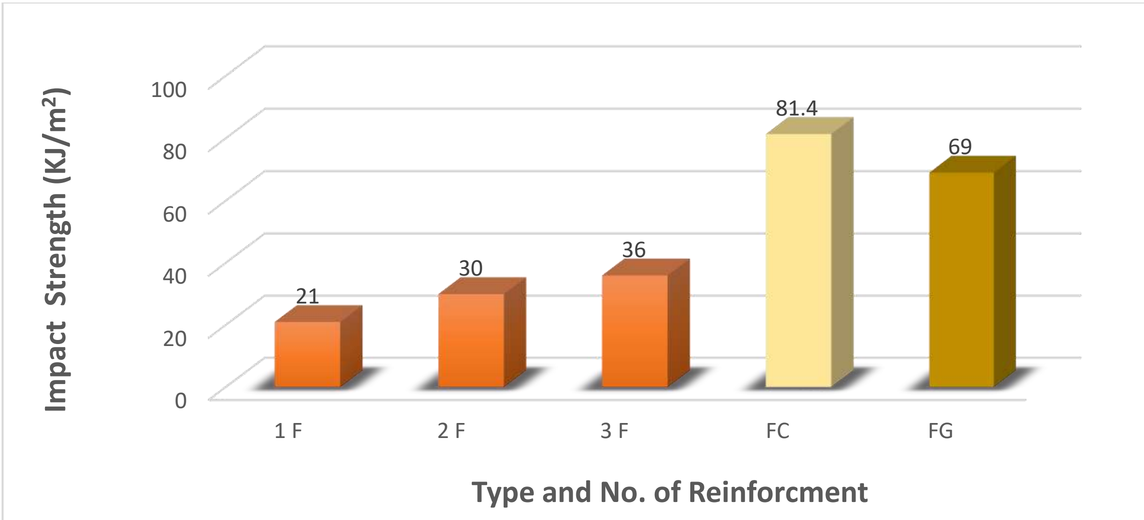


Figure (6.20): Impact strength with the number of flax fiber layers for prosthetic specimens.

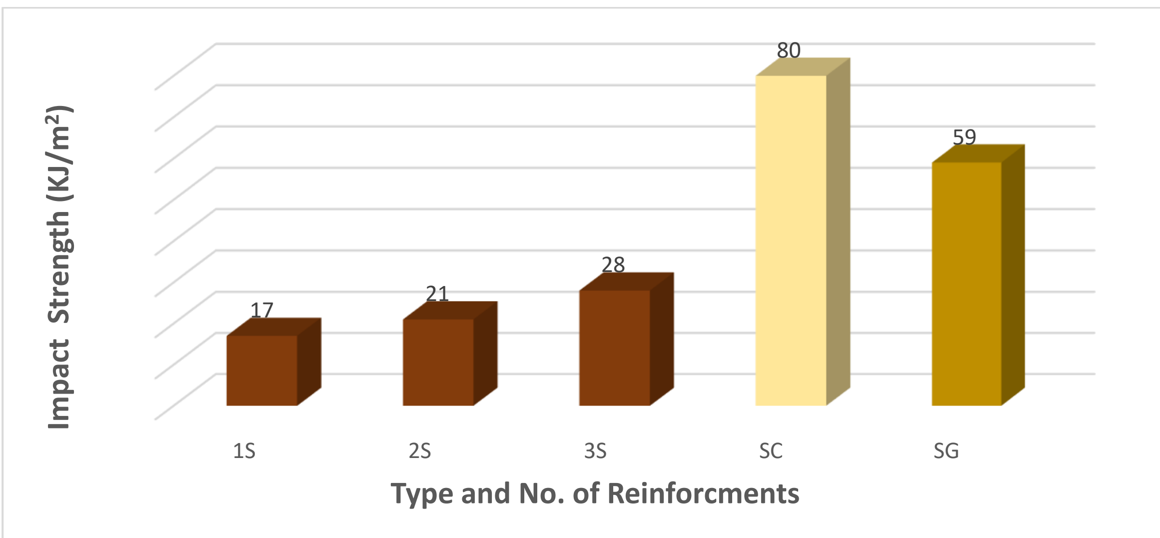


Figure (6.21): Impact strength with the number of sisal fiber layers for prosthetic specimens.

6-3-4-2 Results and Discussions of Fracture Toughness:

Figures (6.22), (6.23), and (6.24) show the fracture toughness values of hybrid composite materials for all samples prepared in this study.

The relationship between the volume fraction and the specimens' fracture toughness is shown in Figures (6.22,6.23 and 6.24). It's worth noting that the fracture toughness of the hybrid composite materials rose as the volume fraction increased. This is because fracture toughness is affected by the impact strength and flexural modulus values. The higher impact strength and flexural modulus for fibers with increasing strengthening layers so did the fracture toughness of materials [216].

It can also be seen that by incorporating glass or carbon fibers into a PMMA, the fracture toughness rises with higher results found when reinforcing with carbon fibers than with glass fibers. This may be because glass and carbon fibers have higher flexural modulus and fracture toughness than PMMA, and better resistance to crack prorogation higher than specimens made of natural fibers alone resulting in improved hybrid laminated composite specimen fracture toughness [87].

The fracture toughness of composite specimens increases with the number of sisal layers until it reaches its maximum value, as shown in figures (6-24). With each increase in the volume fraction, the fracture toughness values for the sisal hybrid laminations are higher than those for the flax and cotton hybrid laminations. This is because the addition of sisal fibers improves the mechanical characteristics, which is attributable to the nature of sisal fibers, which have a higher fracture toughness than the PMMA matrix [203].

Figure (6.24) also shows that laminated composite specimens with three layers of reinforcing sisal fibers and carbon reinforcement layers have the highest fracture toughness when compared to specimens with one, two, or three layers and it reached (24 $MPa.m^{1/2}$) for hybrid (sisal carbon) reinforcements. This could be owing to the use of carbon fiber, which increased the amount of energy required to fracture the specimen. The reinforcements act as a barrier, preventing crack growth. This impediment is determined by the bonding strength of the contact between the PMMA matrix and the reinforcing elements [215 and 216]. While the least fracture toughness values were observed in lamination (11) with ((6.64 $MPa.m^{1/2}$)

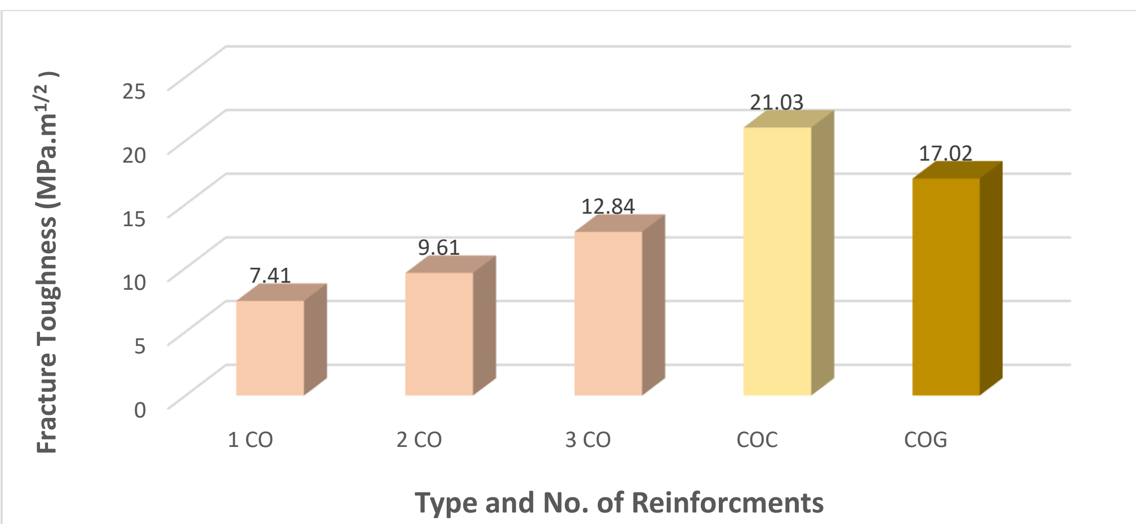


Figure (6.22): Fracture toughness with the number of cotton fiber layers for prosthetic specimens.

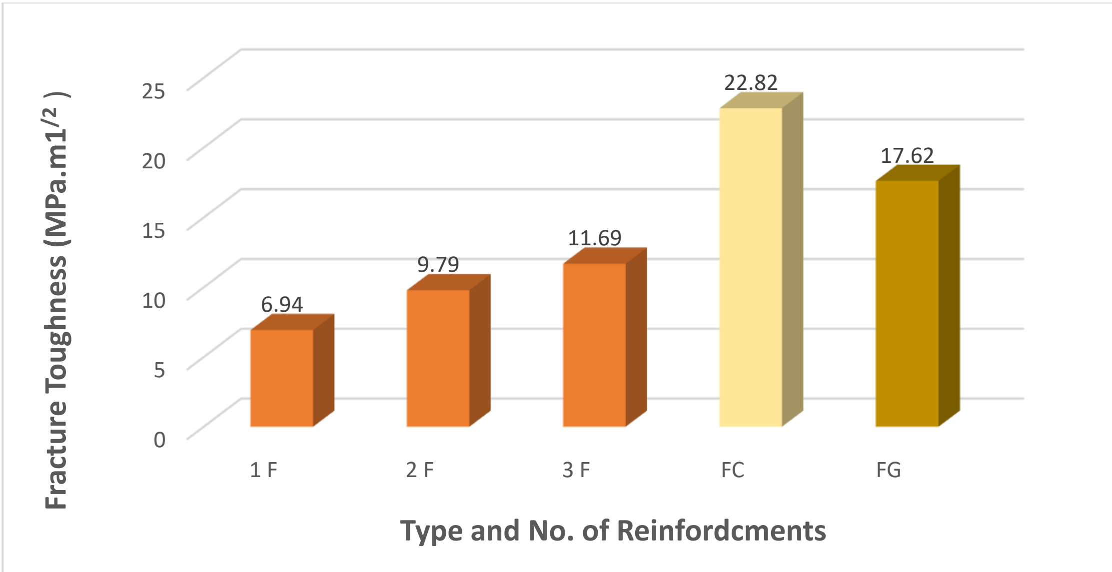


Figure (6.23): Fracture toughness with the number of flax fiber layers for prosthetic specimens.

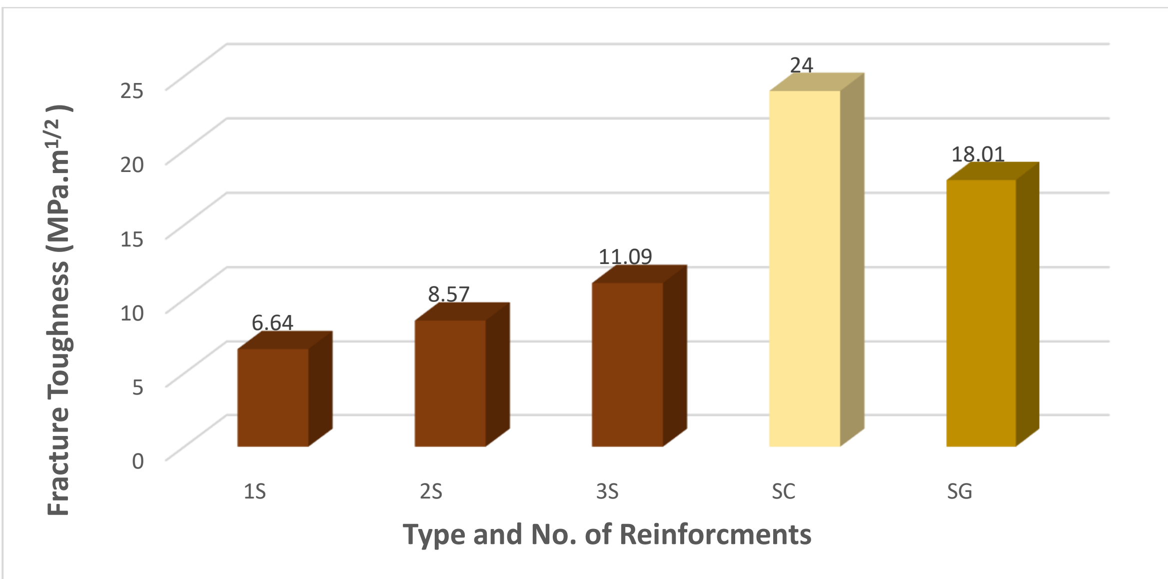


Figure (6.24): Fracture toughness with the number of sisal fiber layers for prosthetic specimens.

6-3-5 Results and Discussions of Compression Test:

6-3-5-1 Results and Discussions of Compressive Strength:

The relationship between the volume fraction and the compression strength of the specimens is shown in figures (6.25, 6.26, and 6.27). It's worth noting that when the volume fraction rose, the compression strength numbers increased as well. This is owing to the bonding strength and nature of these reinforcements, which have high compression strength. Furthermore, it could be attributed to these fibers' ability to strengthen the resin and prevent crack propagation [217]

It's also worth noting that the inclusion of glass and carbon fibers improved compression strength with higher results found when reinforcing with carbon fibers than with glass fibers. This is because glass and carbon fibers have higher compressive strengths than PMMA polymer, subsequent in the effective hybrid laminations' compressive strength [218]

Furthermore, the observed compression strength values for flax samples were greater than the values and rate of strength for the sisal and cotton lamination groups. This is because the addition of these fibers improves the mechanical properties, which is due to t he nature of these fibers, which have a higher compression strength than PMMA polymers [201]. As a result, the three layers of flax fiber with carbon fiber have the greatest compressive strength when comparing the fifteen lamination groups and it reached (119 MPa.) for hybrid (flax carbon) reinforcements. This could be because carbon fibers have a higher compressive strength than the PMMA matrix, which allows them to absorb, transfer, and distribute load uniformly throughout the cross-section of the specimen composite. As a consequence, the compressive strength of the specimens is enhanced [218]. While the least compressive strength values were observed in lamination (1) with (21 MPa)

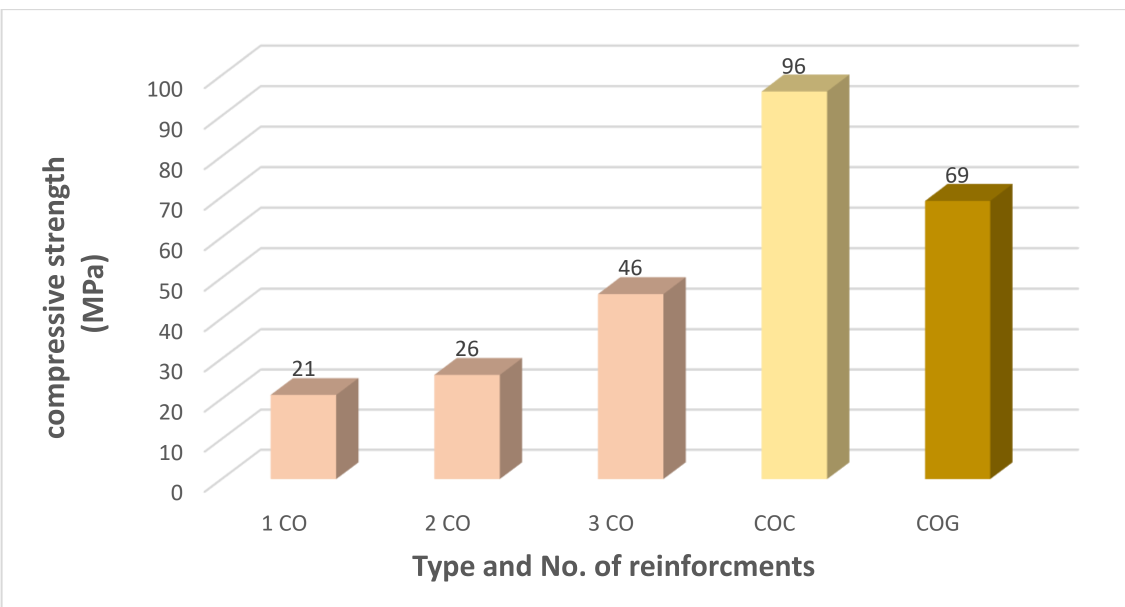


Figure (6.25): Compressive strength with the number of cotton fiber layers for prosthetic specimens.

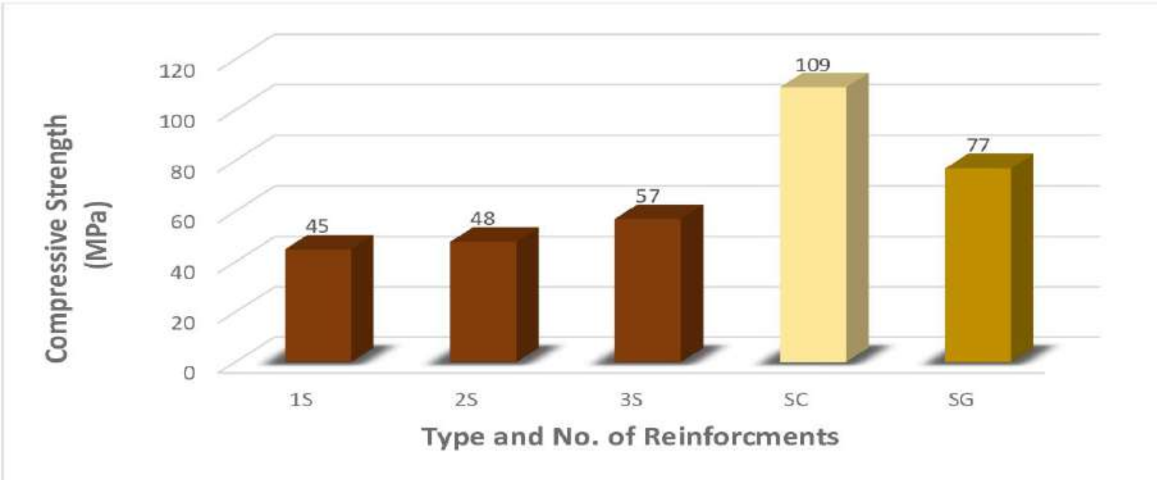


Figure (6.26): Compressive strength with the number of sisal fiber layers for prosthetic specimens.

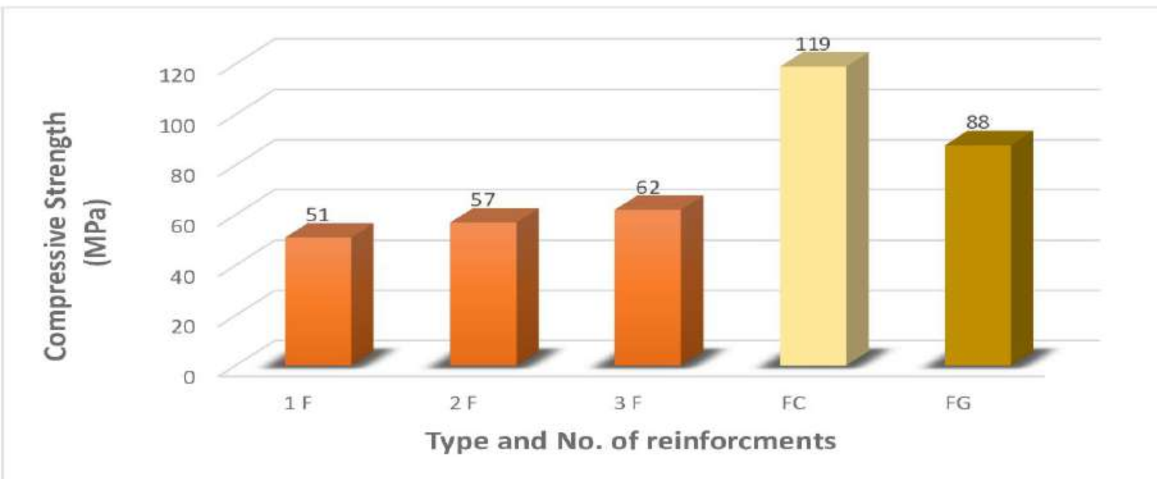


Figure 6.27: Compressive strength with the number of flax fiber layers for prosthetic specimens.

6-3-6 Results and Discussions of Hardness Test:

Figures (6.28), (6.29), and (6.30) illustrate the relationship between the number and type of reinforcement fiber layers in PMMA and the mean surface hardness of specimens.

Figure (6.28. 6.29 and 6.30) represents the relationship between the volume fraction and the specimens' (Shore-D) hardness. As the number of fiber layers increases, the values of the hardness property appear to rise. Furthermore, the formation of strong physical crosslinks at the interfacial zone amid the PMMA and the reinforcement materials may lead to the transfer of pressure over this interface, as well as the PMMA's resistance to plastic deformation due to the controlled movement of the PMMA molecules along the stress direction by the fibers [219]

It can also be noticed that the additions of carbon and glass fibers have an obvious influence on the hardness of hybrid laminations more than the natural fibers alone with higher results found when reinforcing with carbon fibers than with glass fibers. This is owing to the enhancement of the mechanical characteristics that are related to the incorporation of these reinforcements [220].

It is also worth noting that the hardness values for flax hybrid laminations rise significantly more than those for sisal and cotton hybrid laminations as the volume fraction increases. This is because the addition of flax fibers, which have high hardness properties when compared to the PMMA matrix, improves the mechanical properties [221]. In general, specimens with three layers of flax and carbon fibers have the highest hardness value of any of the fifteen lamination groups and reached (86 Shore D). This could be credited to fibers that prevented load from penetrating the composite's surface and, as a result, raised the hardness, as well as fibers that enhanced the composite's modules, which provided to increase the hardness. This is because hardness is a function of relative fiber volume and modules [220]. While the least compressive strength values were observed in lamination (1) with (76 Shore D).

Figure (6.28): Hardness (Shore-D) of Laminated Composite Materials and Woven Cotton Fibers layers for prosthetic sockets.

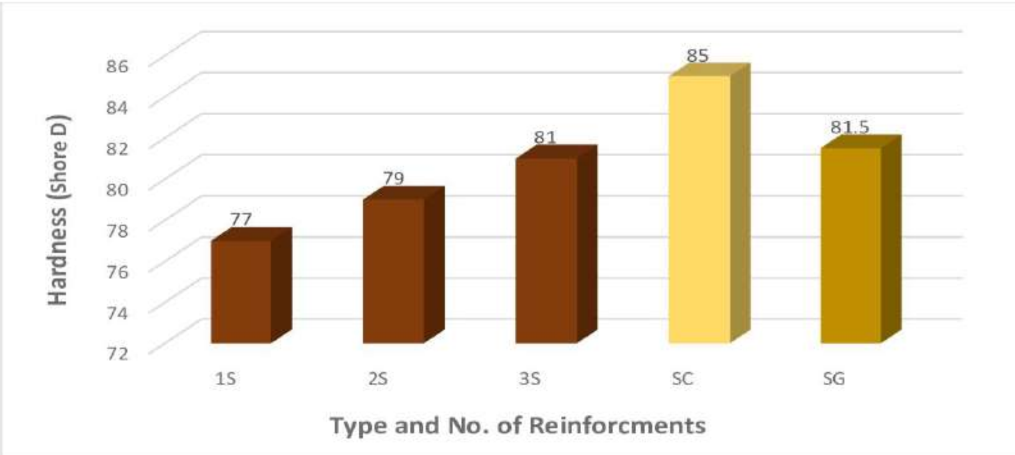


Figure (6.29): Hardness (Shore-D) of Laminated Composite Materials and Woven sisal Fiber layers for prosthetic sockets.

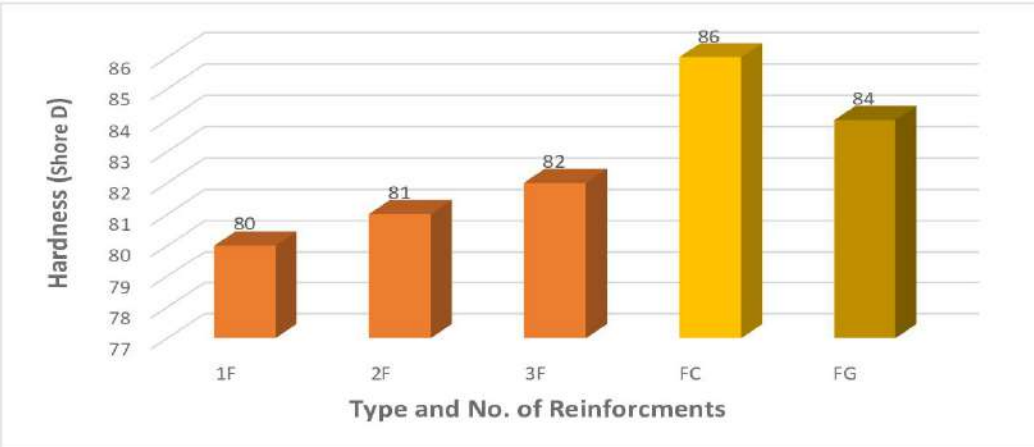


Figure (6.30): Hardness (Shore-D) of Laminated Composite Materials and Woven flax Fiber layers for prosthetic sockets.

6-3-7 Results and Discussions of Weathering Tests:

6-3-7-1 Results and Discussions of Tensile strength:

Throughout their service life, these materials are subjected to a variety of environments, including UV radiation, moisture, varying low and high temperatures, water spraying, and possibly more complex conditions under changing humid conditions. Environmental degradation and damage are well-developed issues in FRP composites [229].

Figures (6.31, 6.32, and 6.33) depict the tensile strength versus type and number of laminations for samples without weathering (dry samples) and samples with accelerated weathering conditions, respectively.

The strength of dry specimens progresses as the fiber content increases. As can be perceived, the strength of the dry specimens is greater than the strength of the samples underneath the combined influence. Water penetration within polymers can be accountable for the weakening of the bond between the fiber and the polymer material [222]. In addition to the photo-oxidation degradation induced by UV radiation absorption of lignin, a constituent of natural fibers, which is one of the contributing factors causing the rupture of the bonds due to the effect of their wavelength [223].

The tensile strength of a PMMA composite was also improved when a woven mat of glass and carbon fibers was added particularly for flax fiber-reinforced lamination groups with higher results found when reinforcing with carbon fibers than with glass fibers. This may be due to the fibers' properties. This is owing to the increased mechanical characteristics associated with the incorporation of these types of reinforcements, which are stronger than natural fibers alone [221].

Figure (6.32) indicate that the flax fiber-reinforced composite had the highest ultimate tensile strength in comparison to counterparts in the other composite material groups, which were reinforced with cotton and sisal fibers. This is because the flax fiber differs from sisal and cotton fibers in terms of tensile strength, with the former having a higher tensile strength than the latter. The least ultimate tensile strength values for samples under the combined effect were observed in lamination (1) with (37 MPa.)[201]. This can be explained by the fact that natural fibers have high cellulose and are hydrophilic. It causes the fiber to swell, which can impair the mechanical and dimensional features of composites due to the formation of microcracks in the fiber-matrix region, allowing water molecules to infiltrate the matrix [164, 166].

As a result, when the thirty lamination groups under the influence of combined weathering were compared, the three layers of flax fiber with carbon fiber consume the highest UTS values (291 MPa.). This is due to the inclusion of carbon fibers, which, when compared to the matrix, have a higher tensile strength and resistance to crack propagation. As a result, the polymer composite specimens can withstand higher loads, particularly the fibers, which carry the majority of the external stress stratified to the sample, and the bearing extent for fibers increases proportionately with their volume fraction [203 and 224].

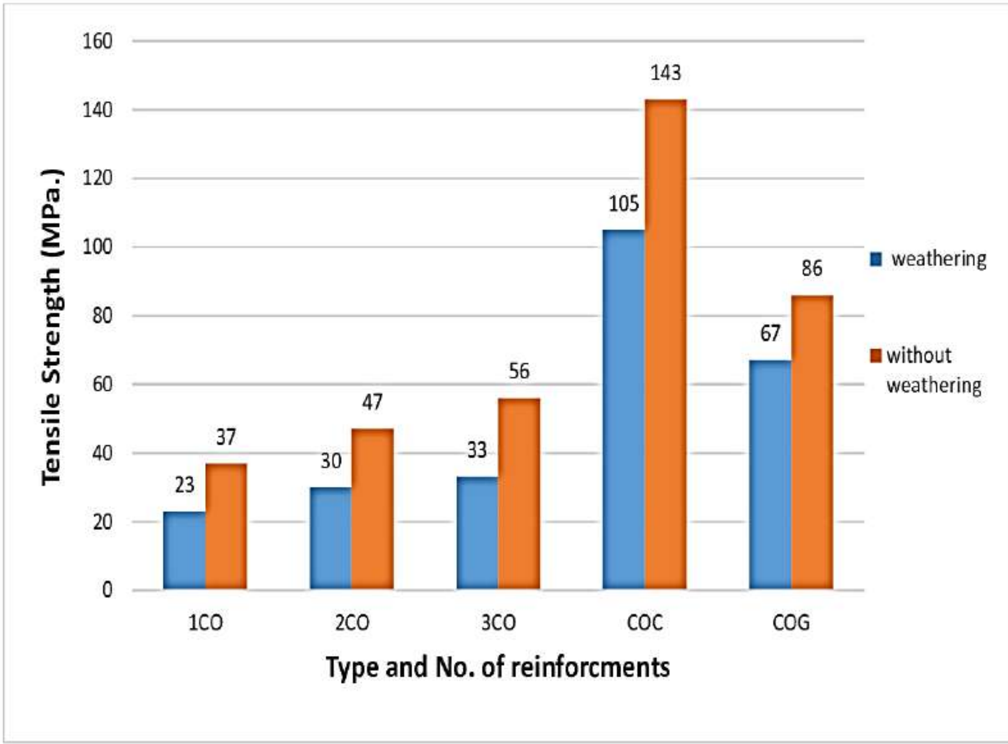


Figure (6.31): Tensile strength and number of cotton fiber layers for prosthetic specimens.

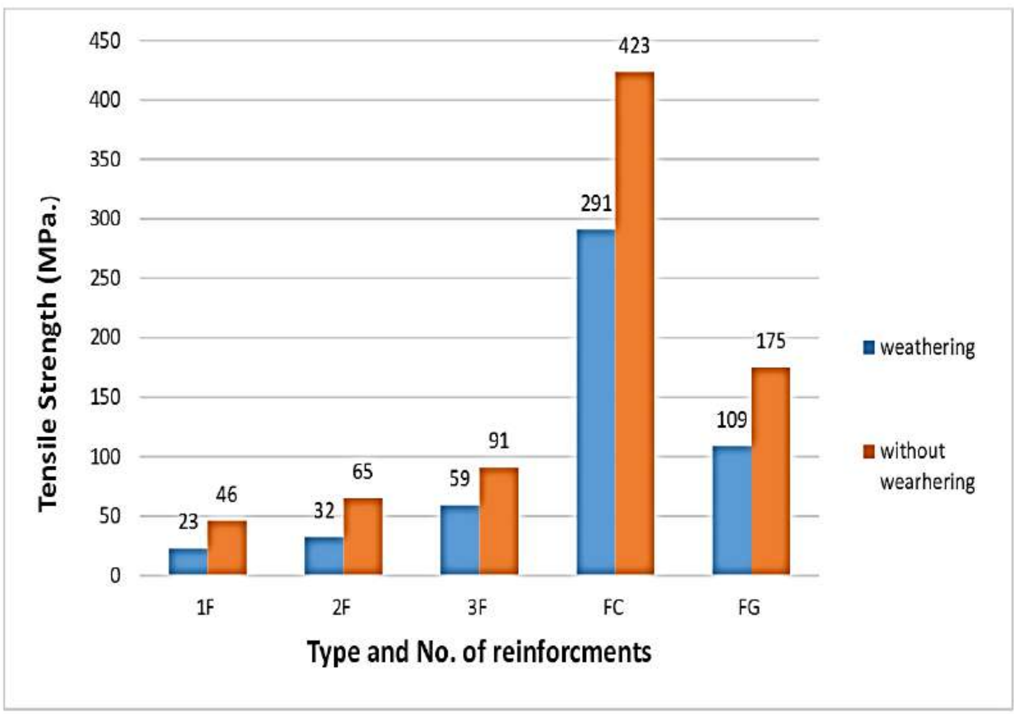


Figure (6.32): Tensile strength and number of flax fiber layers for prosthetic specimens.

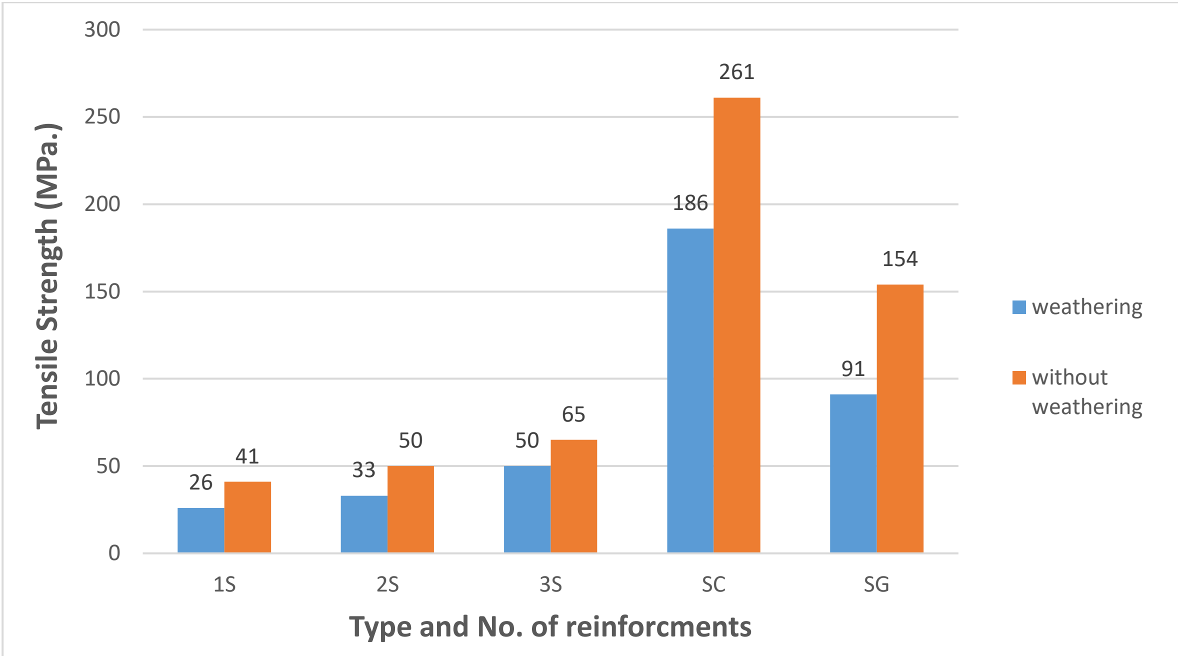


Figure (6.33): Tensile strength and number of sisal fiber layers for prosthetic specimens.

6-3-7-2 Results and Discussions of Modulus of Elasticity:

Figures (6.34), (6.35), and (6.36) illustrate the relationships between the tensile modulus values of samples with and without combined effects, as well as the kind and number of reinforcements. The values of tensile modulus altered after the combined weathering impact, with tensile modulus decreasing for all samples associated with the dry laminations. The degradation of the fibers and the fiber/matrix interfacial bonding may be linked to the decrease in tensile modulus. UV radiation and water spraying cycles in the accelerated weathering chamber affected the contents of the natural fiber's cellulose, hemicellulose, and lignin. Along with the effect of UV energy on natural fiber and polymer via the chain session procedure [225].

The addition of glass and carbon fibers also has a noticeable effect on the modulus of elasticity with higher results found when reinforcing with carbon fibers than with glass fibers [196].

Flax hybrid laminations have a greater modulus of elasticity than sisal and cotton hybrid laminations as the volume fraction increases. This is because flax differs from sisal and cotton fibers in that the former has a greater young modulus than the latter particularly the fibers that bear the majority of the external stress applied to the composite material specimen. The least tensile modulus values for samples under the combined effect were observed in lamination (1) with (0.51 GPa.) [201]. This can be explained by the fact that natural fibers have high cellulose and are hydrophilic. It causes the fiber to swell, impairing the mechanical and dimensional features of composites due to the formation of microcracks in the interface region [164, 166]. Under the influence of combined weathering, the three layers of flax fiber with carbon fiber consumed the largest values of modulus of elasticity for composites as compared to the thirty groups with (3.38 GPa.). This is owing to the presence of carbon fibers, which ensure the extent of loads from matrix to fiber and contribute to carbon fibers' high strength and stiffness [207].

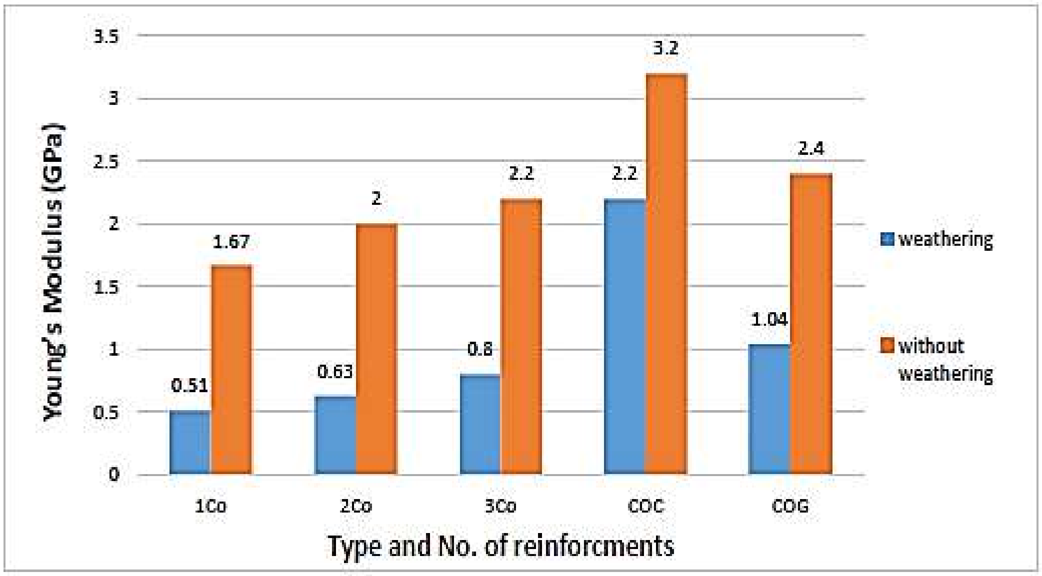


Figure 6.34: Modulus of elasticity and number of cotton fiber layers for prosthetics specimens.

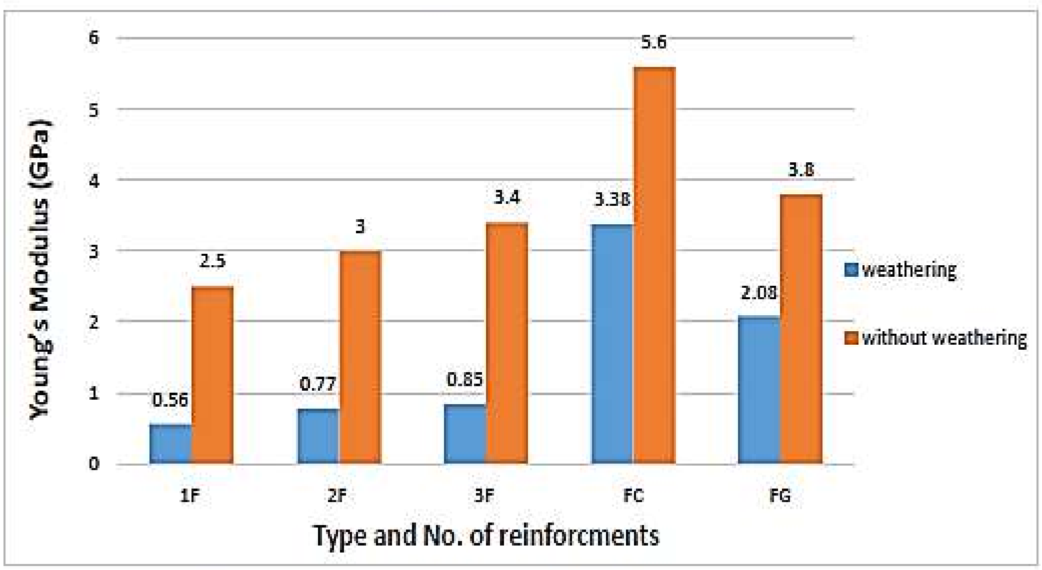


Figure 6.35: Modulus of elasticity and number of flax fiber layers for prosthetic specimens.

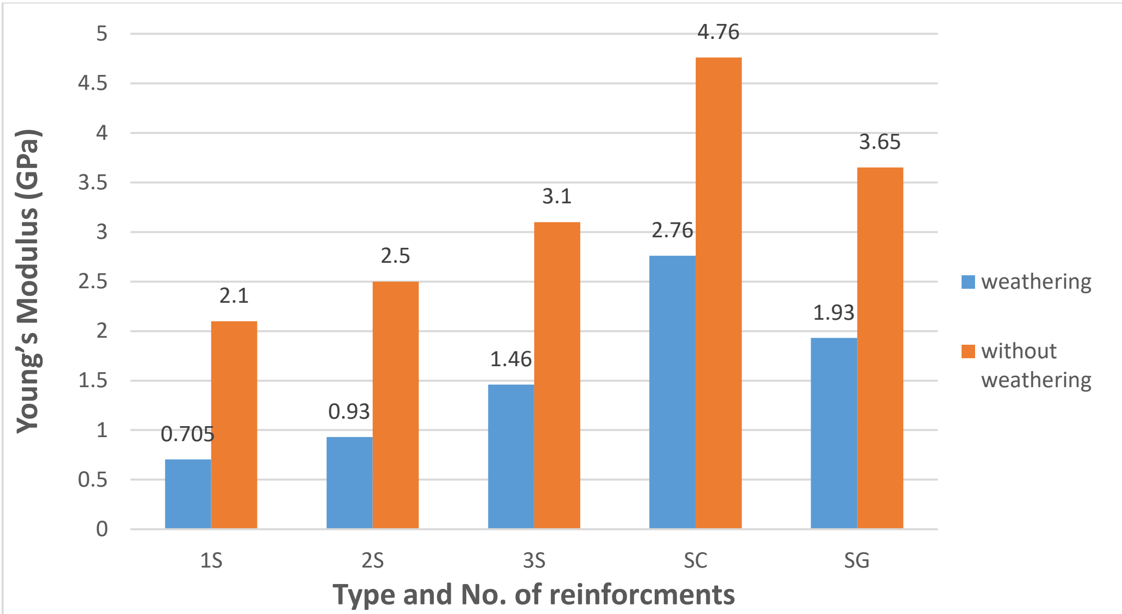


Figure 6.36: Modulus of elasticity and number of sisal fiber layers for prosthetic specimens.

6-3-7-3 Results and Discussions of Flexural Strength:

Figures (6.37, 6.38, and 6.39) demonstrate the flexural strength versus the type and number of fiber layers for dry samples and samples subjected to accelerated weathering cycles.

Flexural strength improved with increasing fiber content. Dry samples exhibit stronger flexural strength than those underwater spraying cycles. This could be due to increased moisture absorption and UV penetration, besides the production of more microcracks due to fiber swelling, which reduces the interface region when bending loads are imposed [226, 166].

Furthermore, the flexural strength values for the laminations strengthened by glass fiber and carbon fiber are greater than values for purely natural fiber-reinforced composites with higher results found when reinforcing with carbon fibers than with glass fibers. This could be because glass fiber and carbon fiber have better flexural strength than PMMA matrix, resulting in increased hybrid laminated composite specimen strength [203].

In general, flexural strength values for sisal hybrid laminations are higher than those for flax and cotton laminations as the volume rises. This is because the sisal fiber differs from flax and cotton fibers in terms of flexural strength, with the former having a higher flexural strength [201]. The least flexural strength values for samples under the combined effect were observed in lamination (1) with (41 MPa.). This can be explained by the fact that high cellulose and hydrophilic natural fibers cause the fiber to swell, impairing the mechanical and dimensional characteristics due to the formation of microcracks in the fiber-matrix region [164, 166].

As a result, when the thirty lamination groups are compared, the three layers of sisal fiber with carbon fiber had the highest bending strength values (189 MPa.). This is due to the fibers' high flexural modulus, which allows them to carry a large number of loads, and their capacity to prevent crack development inside polymer composites due to their strengthening mechanism. Consequently, the flexural modulus of the specimens improves [43].

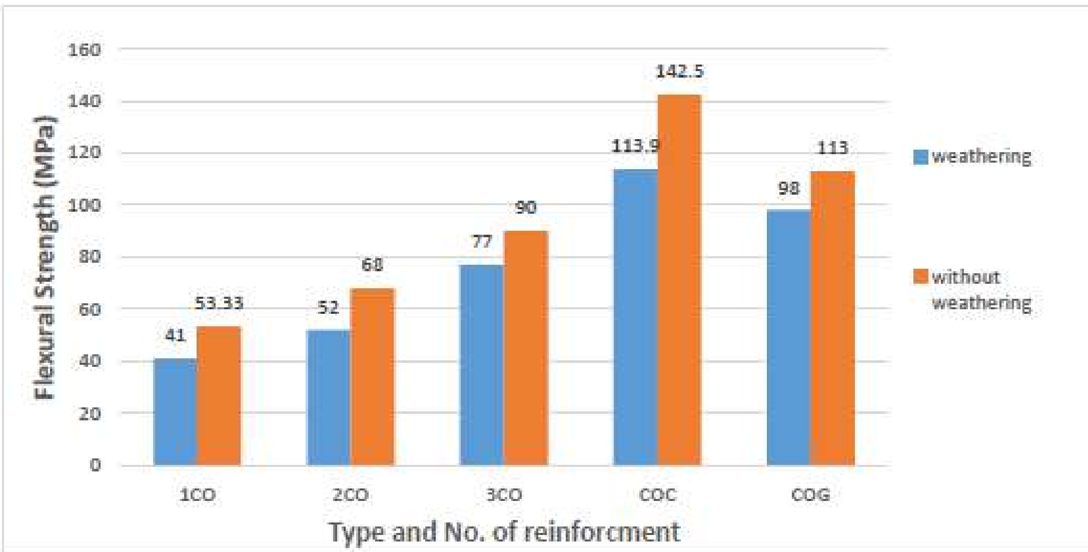


Figure (6.37): Flexural strength and number of cotton fiber layers for prosthetic composite.

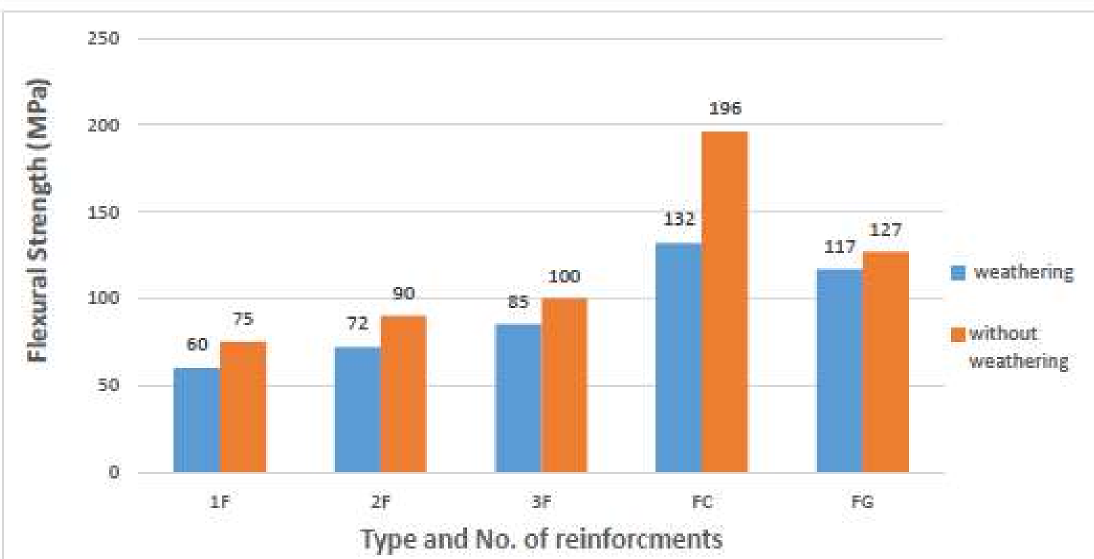


Figure (6.38): Flexural strength and number of flax fiber layers for prosthetic composite.

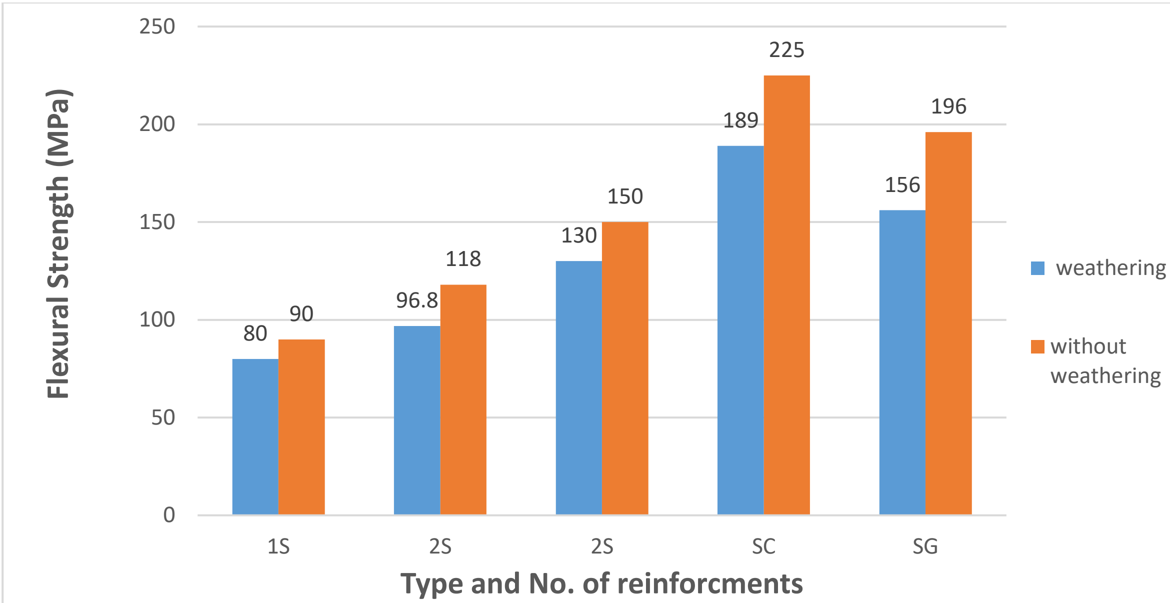


Figure (6.39): Flexural strength and number of sisal fiber layers for prosthetic composite.

6-3-7-4 Results and Discussions of Flexural Modulus:

The results of the flexural modulus versus type and number of fiber layers are included in figures (6.40), (6.41), and (6.42) for samples without (dry) and samples under the combined action of UV and water spraying cycles. These figures present a substantial difference in flexural modulus before and after UV and water spraying cycles. The loss of flexural features following UV and water spraying cycles can be attributed to poor bonding of the lamination materials' bonds and a weak fiber-matrix interface as a result of water absorption and UV exposure [226 and 227]. It can also be seen that incorporating a woven mat of glass or carbon fiber into layers of sisal, flax, and cotton enhances the flexural modulus with higher results found when reinforcing with carbon fibers than with glass fibers [209].

In general, composite materials reinforced with sisal fibers have a higher flexural modulus than those reinforced with flax or cotton fibers. This is due to the characteristics that differentiate sisal fiber from flax and cotton fibers, with the former having higher flexural strength than the latter [201]. The least flexural modulus values for samples under the combined effect were observed in lamination (1) with (1.2 GPa.). This can be explained by the fact that natural fibers have high cellulose and are hydrophilic. It causes the fiber to swell, which can impair the mechanical and dimensional features of composites due to the formation of microcracks in the fiber-matrix region, allowing water molecules to infiltrate the matrix [164, 166]. When the thirty lamination groups were compared, the three layers of sisal fiber with carbon fiber offered the highest flexural modulus for composites with (6 GPa.). This is owing to the availability of high-strength and stiff carbon fibers, which ensure load distribution from matrix to fiber and good adhesion amid sisal and matrix [206 and 207].

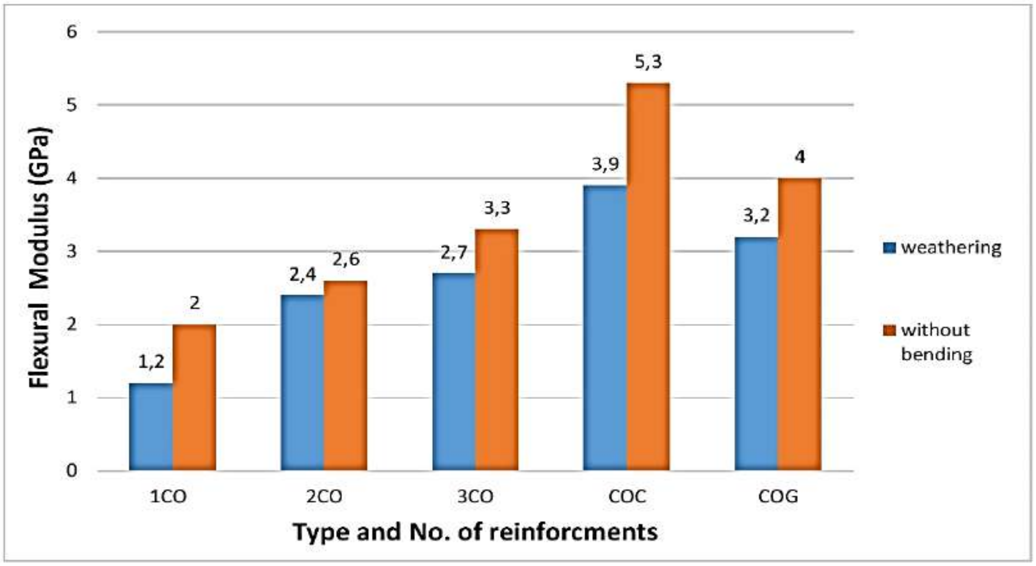


Figure (6.40): Flexural modulus and number of cotton fiber layers for prosthetic composite.

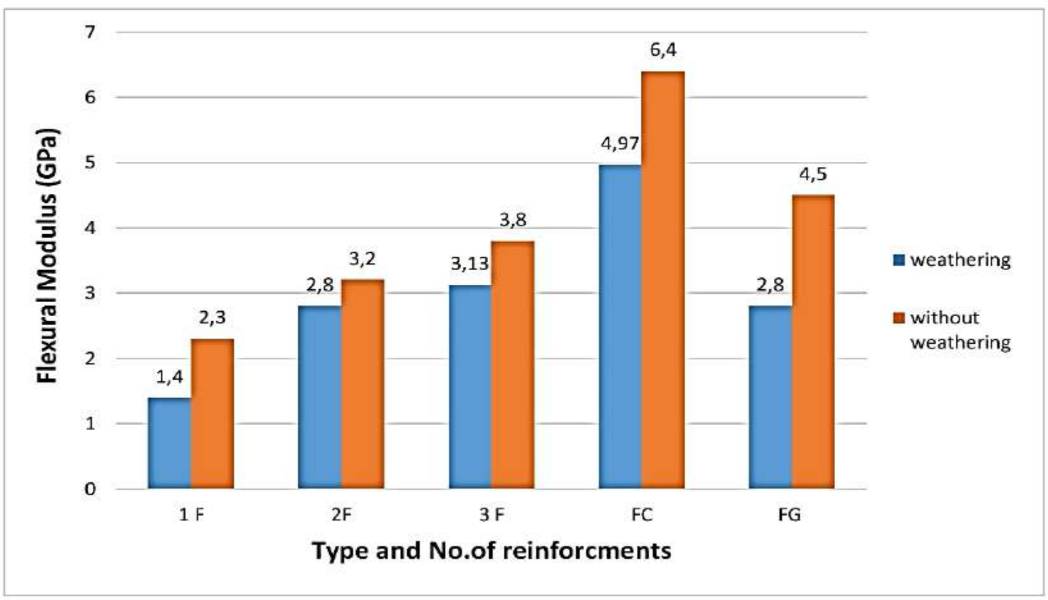


Figure (6.41): Flexural modulus and number of flax fiber layers for prosthetic composite.

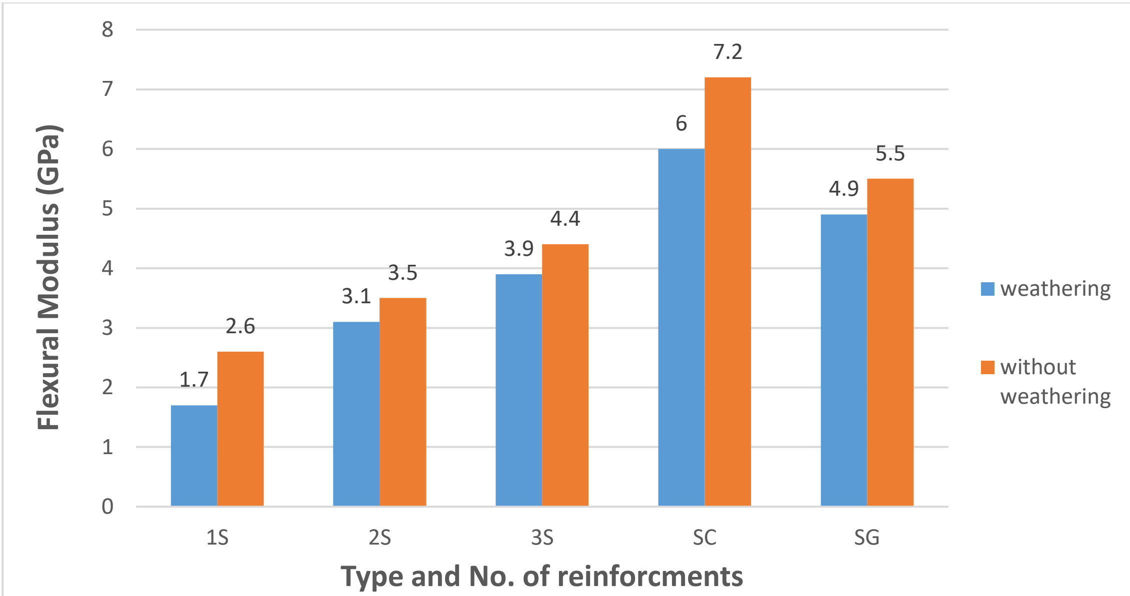


Figure (6.42): Flexural modulus and number of sisal fiber layers for prosthetic composite.

6-3-7-5 Results and Discussions of Compression Test:

Figures (6.43), (6.44), and (6.45) show compression strength versus reinforcing layer type and number for samples without weathering (dry) and with accelerated weathering effects. After the accelerated weathering effect, there was a change in compression strength values, with strength decreasing for all samples. This could be due to the formation of microcracks, which result in low interfacial shear strength amid PMMA and the fiber reinforcements, resulting in weak physical bonding [163]. It should also be noted that the inclusion of carbon and glass fibers enhances the strength values with higher results found when reinforcing with carbon fibers than with glass fibers. The explanation for this behavior could be that glass and carbon fibers have a higher compressive strength than PMMA polymer, ensuing in the hybrid laminations' effective compressive strength [217].

Figure (6.44) indicate that the flax fiber-reinforced composite had the highest compression strength when compared to its equivalents in the other composite materials groups, which were reinforced with cotton and sisal fibers. This is due to a feature that differentiates flax fibers from sisal and cotton fibers, the former has higher compression strength than the latter with three layers of flax fiber and carbon fiber having the highest compressive strength values. This could be because flax and carbon fibers have a higher compressive strength than the PMMA matrix of (108 MPa.) [218]. The least compression strength values for samples under the combined effect were observed in lamination (1) with (11.5 MPa.). This can be explained by the fact that natural fibers have high cellulose and are hydrophilic. It causes the fiber to swell, which can impair the mechanical and dimensional features of composites due to the formation of microcracks in the fiber-matrix region, allowing water molecules to infiltrate the matrix [164, 166].

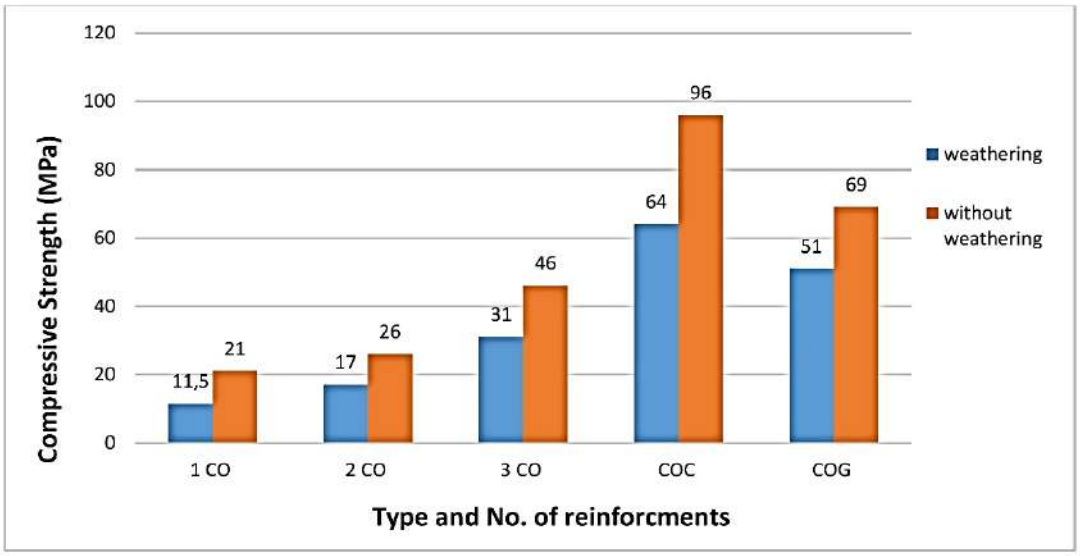


Figure (6.43): Compressive strength and number of cotton fiber layers for prosthetic composite.

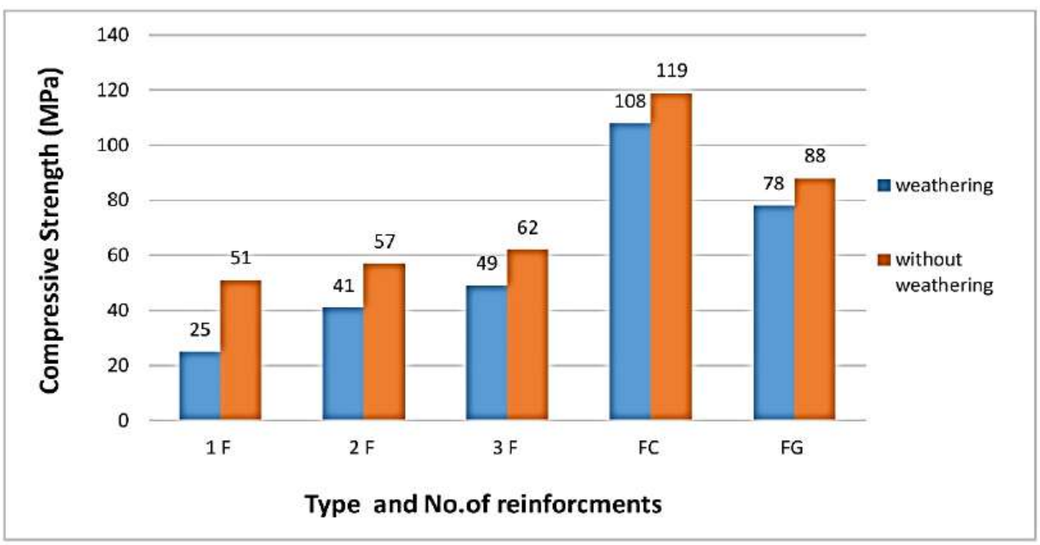


Figure (6.44): Compressive strength and number of flax fiber layers for prosthetic socket laminated composite.

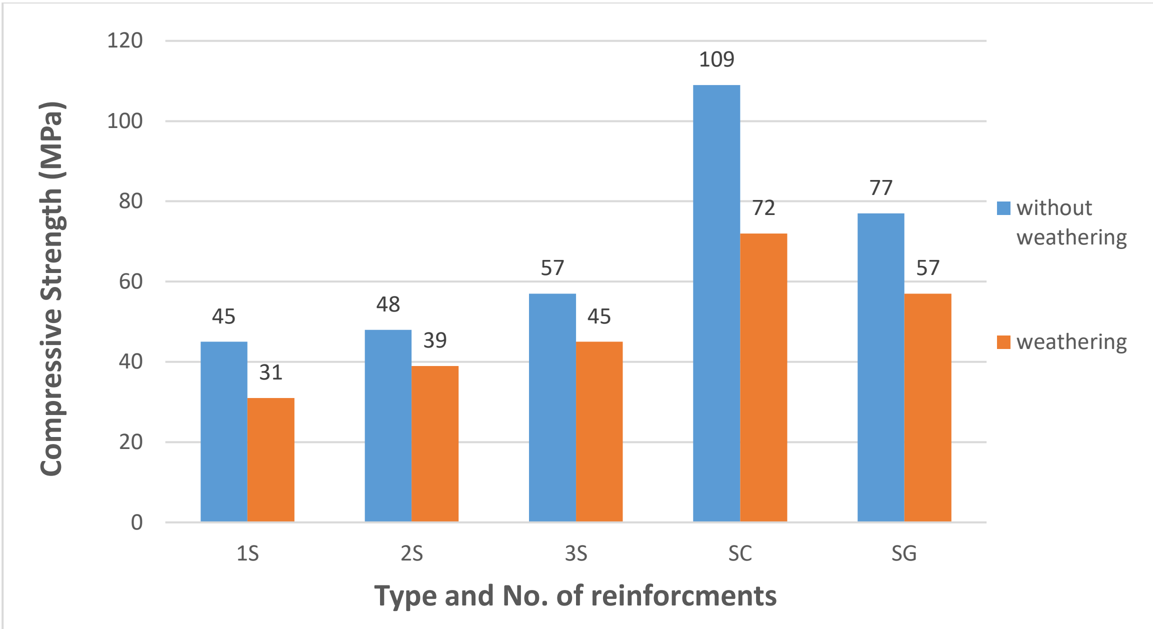


Figure (6.45): Compressive strength and number of sisal fiber layers for prosthetic composite.

6-4 Physical Test Results:

6-4-1 Results and Discussions of Density Test:

The relationship between the volume fraction and density is depicted in figures (6.46, 6.47, and 6.48). It's worth noting that the density increased as the volume fraction rose. This is due to the lamination's absorption ability being slightly enhanced in the presence of these reinforcements, and strong bonding between PMMA and cotton fibers, which leads to increased density [217].

The density of the PMMA composite increased when a woven mat of glass or carbon fiber was added. This may be because glass fiber and carbon fiber have a higher density than the PMMA matrix, causing the density of hybrid laminated composite specimens to increase [144].

It is also obvious that the composite materials reinforced with flax fibers have higher density values than the composite materials reinforced with cotton and sisal fibers. This is owing to the differences in density between flax, sisal, and cotton fibers, with the former having a higher density than the latter [201]. In general, specimens with three layers of flax and glass fibers appear to have the highest density value of all the fifteen lamination groups and reached (1.276). This could be because they have a higher density than the PMMA matrix, allowing for better packing of polymer chains, which is characteristic of glass fibers. As a result of this, the density of the specimen increases. Furthermore, it appears that the matrix material bonded better to certain materials than to others, resulting in a higher density [227]. While the least impact strength values were observed in lamination (11) with (1.101 gm/cm^3)

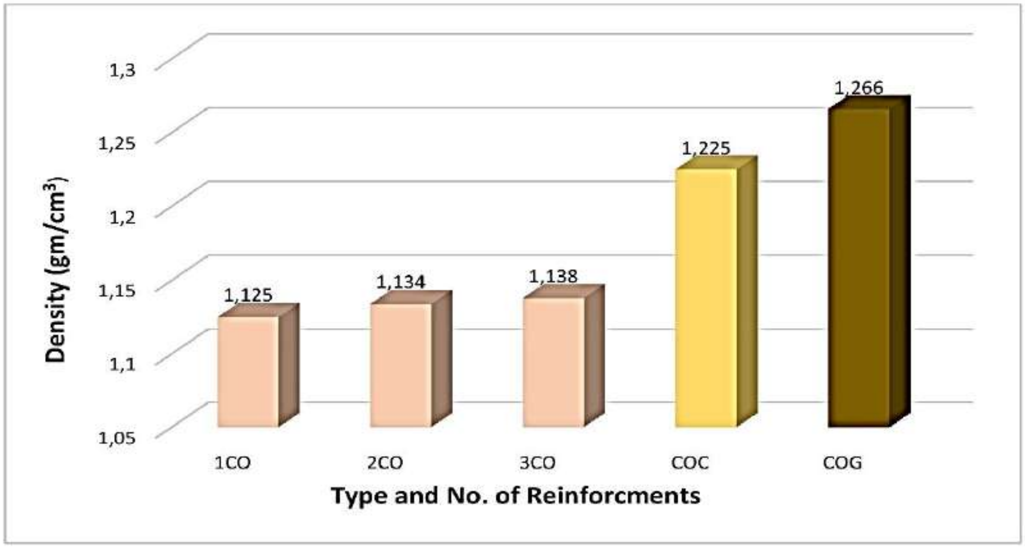


Figure (6.46): Density of laminated composite materials and woven cotton fibers for prosthetic specimens.

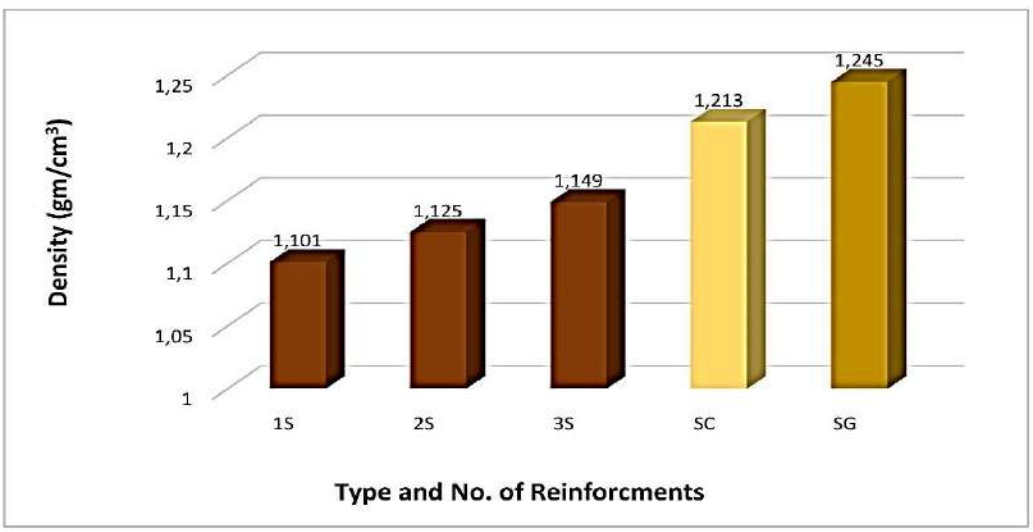


Figure (6.47): Density of laminated composite materials and woven sisal fibers for prosthetic specimens.

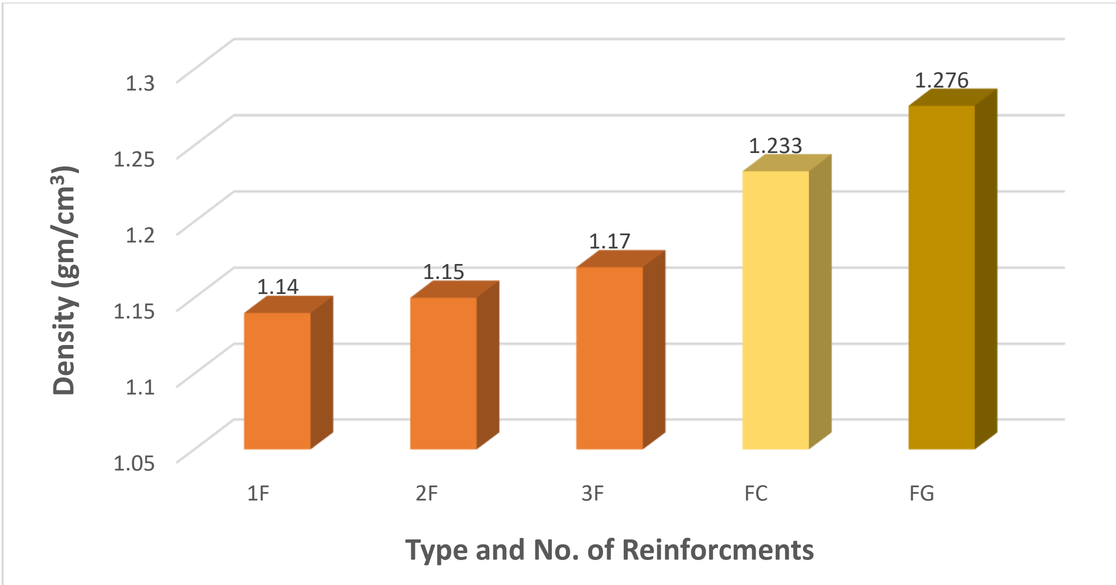


Figure (6.48): Density of composite materials and flax fibers for prosthetic specimens.

6-4-2 Results and Discussions of Water Absorption Test:

Figures (6.49, 6.50, and 6.51) characterize the relationship between the volume fraction and water absorption percentage of the specimens. The values of the water absorption percentage decreased as the volume fraction increased. This is because, with the addition of reinforcements, most of the spaces and voids that existed within the PMMA matrix will be reduced or filled by these materials [228]. Furthermore, when comparing the values of water absorption percentage for the laminations strengthened by natural fiber to those strengthened by carbon and glass fibers, it can be seen that the absorption percentage for laminations strengthened by natural fiber is greater. This is due to the differences between glass and carbon fibers and natural fibers, such as the former having a higher density than the latter, and the natural fibers, which are dry and have many spaces or voids between the reinforcements [227]. When compared to their counterparts in the other groups of laminations, which were reinforced with cotton and sisal fibers, the groups reinforced with flax fiber had the lowest values of water absorption percentage particularly when hybridized with glass fiber and reached (0.6187%). This could be due to the addition of these fibers replacing the hydrophilic PMMA resin, as well as the reinforcements filling the open pores and voids. Furthermore, the strong bonding at the interfacial zone amid PMMA and these reinforcements results in a reduction in micro-voids and open spaces in PMMA composite materials. As a result of these factors, the water absorption of PMMA composite materials decreases [229]. While sisal fiber-reinforced groups showed the highest reaching (4.72%) in lamination (11).

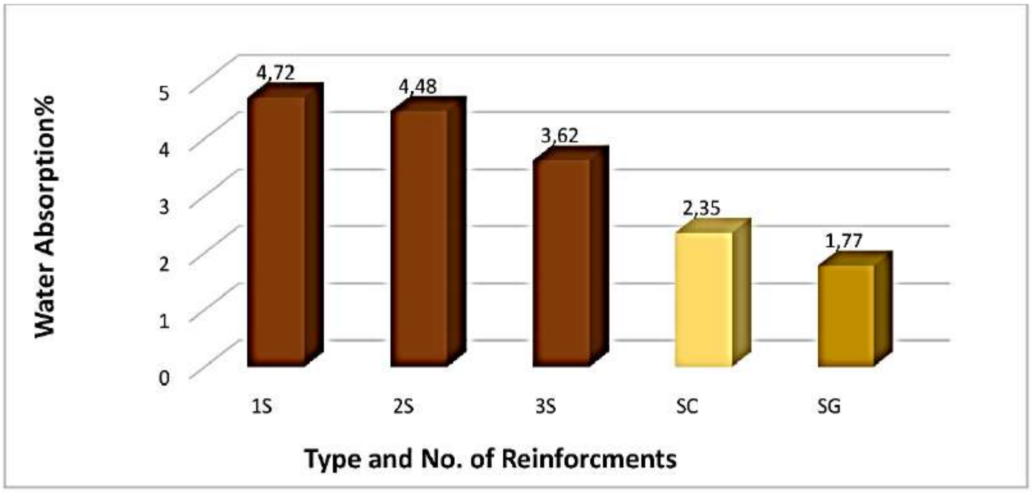


Figure (6.49): Water absorption percentage of laminated materials and woven sisal fibers.

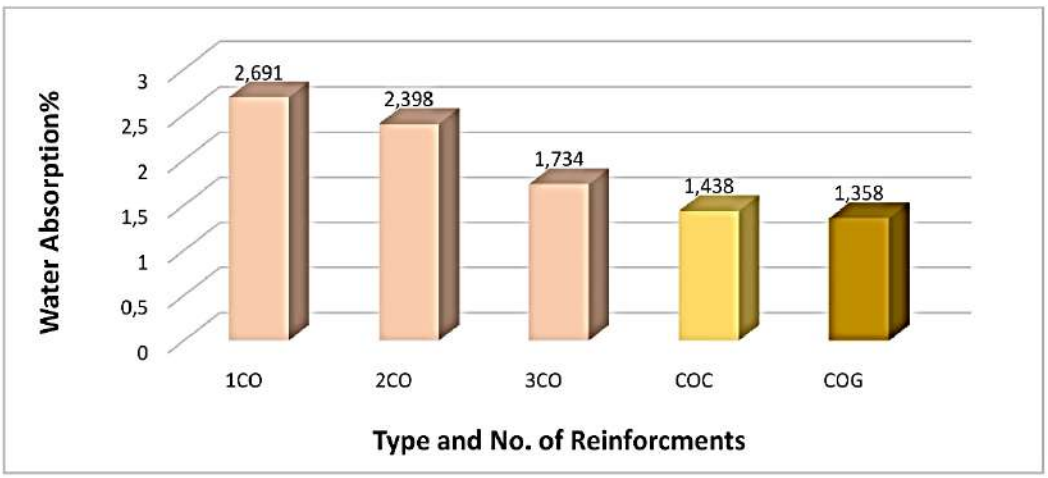


Figure (6.50): Water absorption percentage of laminated materials and woven cotton fibers.

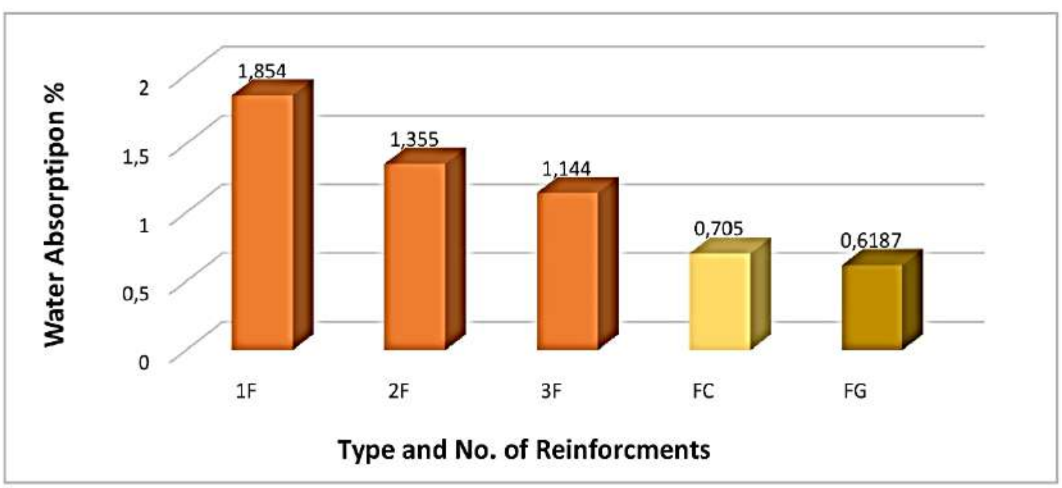


Figure (6.51): Water absorption percentage of laminated materials and woven flax fibers.

6-5 Morphological Test Results:

6-5-1 Results and Discussions of Surface Roughness Test:

Figures (6.52), (6.53), and (6.54) demonstrate the relationship between the type and number of layers of natural fibers reinforced PMMA and surface roughness for all lamination groups. The figures below describe the relationship between surface roughness and volume fraction. Surface roughness values were found to increase with increasing layers of flax, sisal, and cotton fibers for groups [230]. The increase in surface roughness values is because the test is focused on the exterior surface of specimens rather than the interior surface [231].

Surface roughness values and rates for sisal fiber-reinforced composite specimens are generally higher than those for flax and cotton composite specimens. This is due to the nature and features that differentiate sisal fiber from flax and cotton fibers, the former having a higher surface roughness than the latter having the least with (1.098 μm) [201].

The surface roughness of all groups increased when a woven mat of glass and carbon fibers was added to the PMMA composite. This may be because these fibers do not have a smooth surface, which causes the surface roughness of the hybrid laminated composite specimens to rise. As a result of evaluating the fifteen laminations, it was found that the three layers of cotton fiber with carbon fiber had the highest surface roughness for composites with (3.0995 μm)[151]

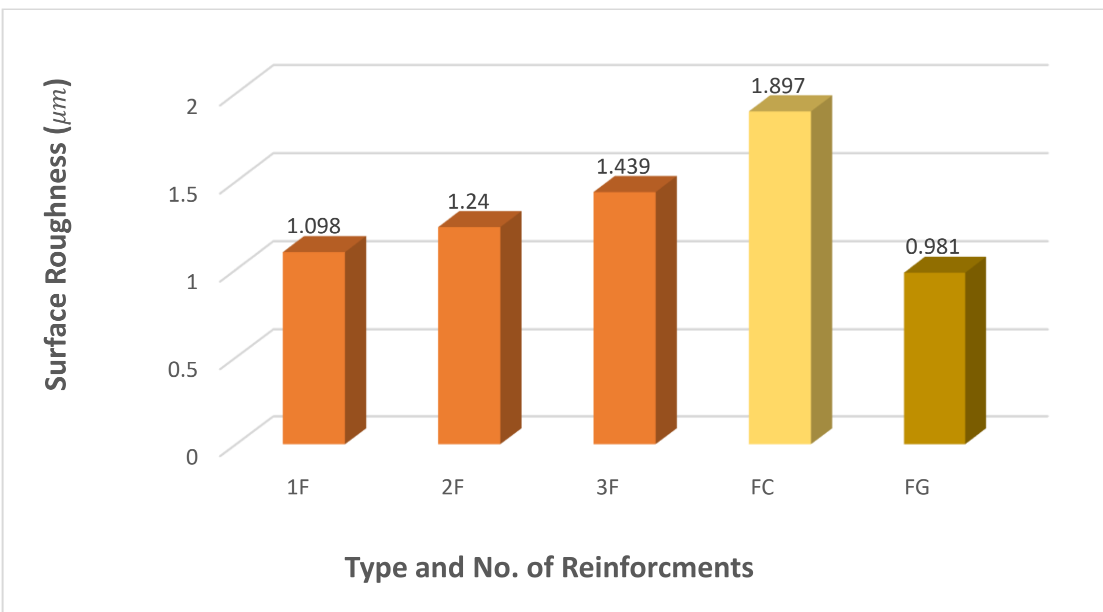


Figure (6.52): Surface roughness of laminated composite materials and woven flax fibers layers for prosthetic socket

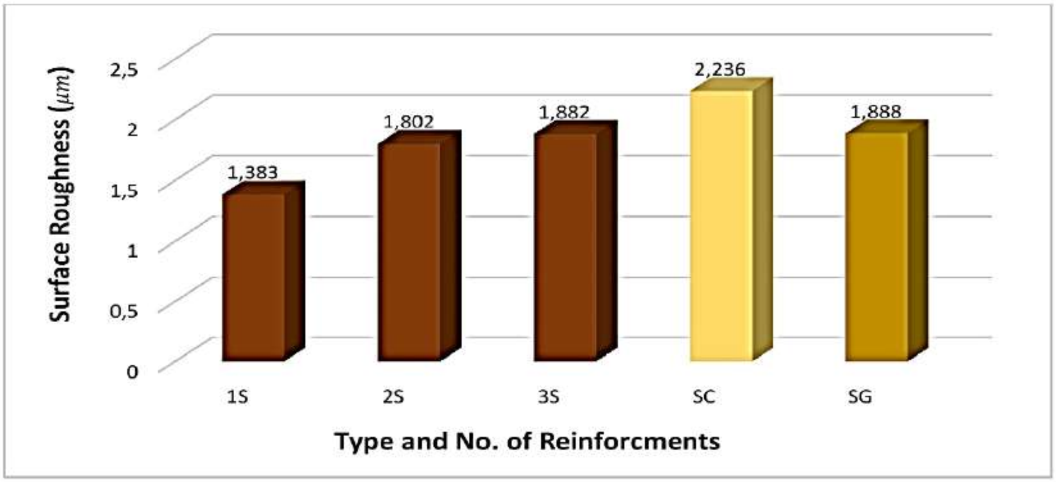


Figure (6.53): Surface roughness of laminated composite materials and woven sisal fibers layers for prosthetic socket.

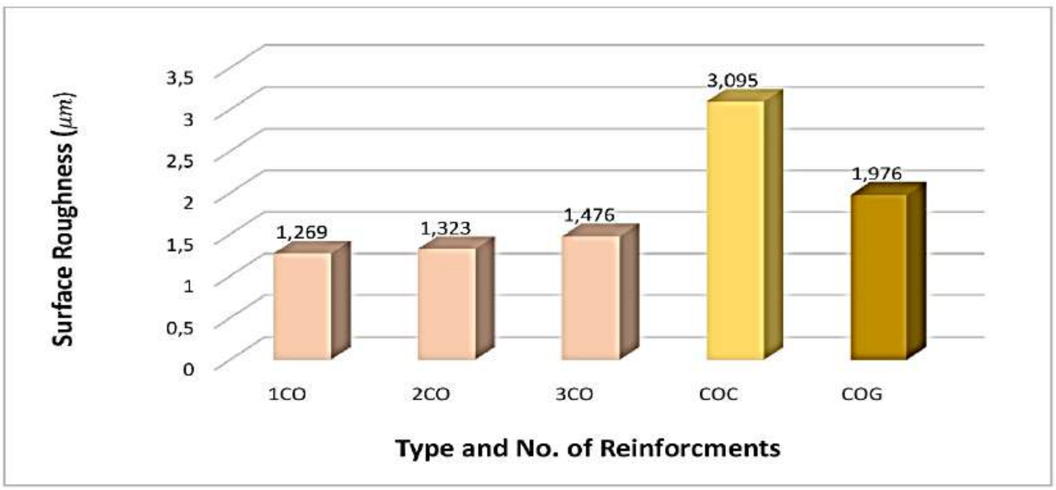


Figure (6.54): Surface roughness of laminated composite materials and woven cotton fibers layers for prosthetic socket.

6-6 Miscibility Test:

6-6-1 Results and Discussions of FTIR Analysis:

Figure (6.55) demonstrates the infrared spectrum of PMMA, which has the structure [–CH2–C (CH3) (COOCH3)–] –n. The backbone chain's (C–C) and (C–H) sets, the ester group's (C–C), (C=O), and (C–O) units, and the methyl substituent's C–H units all contribute to PMMA's infrared spectrum [232, 233].

PMMA's primary distinctive vibration bands (n) are found at 1723.40 cm-1 n (C = O) and 1461.35 and 1436.2 cm-1 n (C–O), respectively. 2953.52 cm-1 bands are related to (C–H) symmetric and asymmetric stretching modes, respectively, and 1376.03 and 1461.35 cm-1 bands are related to (C–H) symmetric and asymmetric stretching modes. As shown in figure 6.55, the 1237.03 cm-1 bands correspond to the torsion of the methylene group CH2, and the peak at 1190.71 cm-1 relates to the vibration of the ester group (C–O), while the (C–C) stretching bands are at 960.67 and 841.13 cm-1.

Figures (6.56, 6.57, and 6.58) characterize the infrared range of composites strengthened with diverse layers of natural fiber (flax, sisal, and cotton) and carbon and glass fibers. In these figures, all of the vibration bands of PMMA composites are reserved in the infrared spectrum (FTIR) of the group's composite specimens. No other original peaks were detected for the composites with the addition of flax, cotton, and sisal fibers, as evidenced by the infrared spectrum of these laminations. This is owing to the discovery of a physical bond in these specimens and the lack of cross-linking [197].

The FTIR spectrum for PMMA composite specimens reinforced by cotton fabric with various lamination patterns is shown in Figure (6.56). The intensity of bands varies significantly from (1723.10, 1434.78) cm-1 for (C=O) and (C-O) bands to (1722.67, 1434.92) cm-1 for (C=O) and (C-O) bands, respectively. Because of an increase in molecular interactions between these groups in PMMA and groups in cotton fibers, the intensity of the peak shifts is directly proportional to the kind and number of reinforcing layers.

The FTIR spectrum for PMMA composite specimens reinforced by flax fabric with various lamination patterns can be seen in Figure (6.57). The intensity of bands varies significantly from (1723.10, 1434.78) cm-1 for (C=O) and (C-O) bands to (1722.94, 1434.69) cm-1 for (C=O) and (C-O) bands, respectively. Because of an increase in molecular interactions between these groups in PMMA and groups in flax fibers, the intensity of the peak shifts directly proportional to the kind and number of reinforcing layers.

The FTIR spectrum of PMMA composite specimens reinforced by sisal fabric with various lamination patterns is portrayed in figure (6.58). The intensity of bands varies significantly between (1723.10 and1434.78) cm-1 for (C=O) and (C-O) bands and (1720.23 and 1435.53) cm-1 for (C=O) and (C-O) bands. Because of increased molecular interactions between these groups in PMMA and groups in cotton fibers, the intensity of the peak shifts in direct proportion to variations in the kind and number of reinforcing layers.

All these figures show that even when synthetic fibers like carbon and glass are added to natural fabric reinforcements, no new peaks emerge. Furthermore, there was no change in any of these peaks. This behavior is characterized by the discovery of physical bonds between composite constituents and indicates that the miscibility state of the composite constituents has improved, as well as the absence of any residual monomer or by-product that could cause toxicity, allergic, or inflammation in the human body.

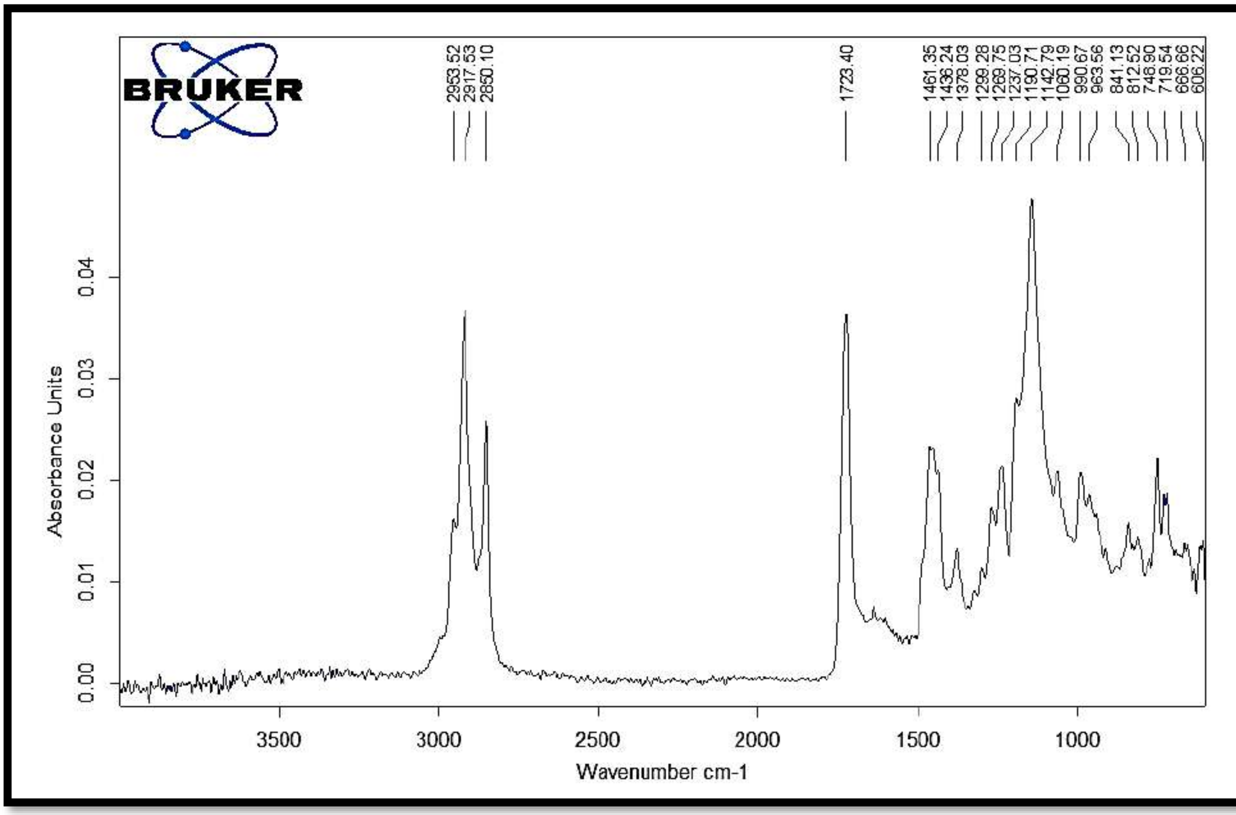


Figure (6.55): The Infrared Spectrum obtained for the PMMA Specimens.

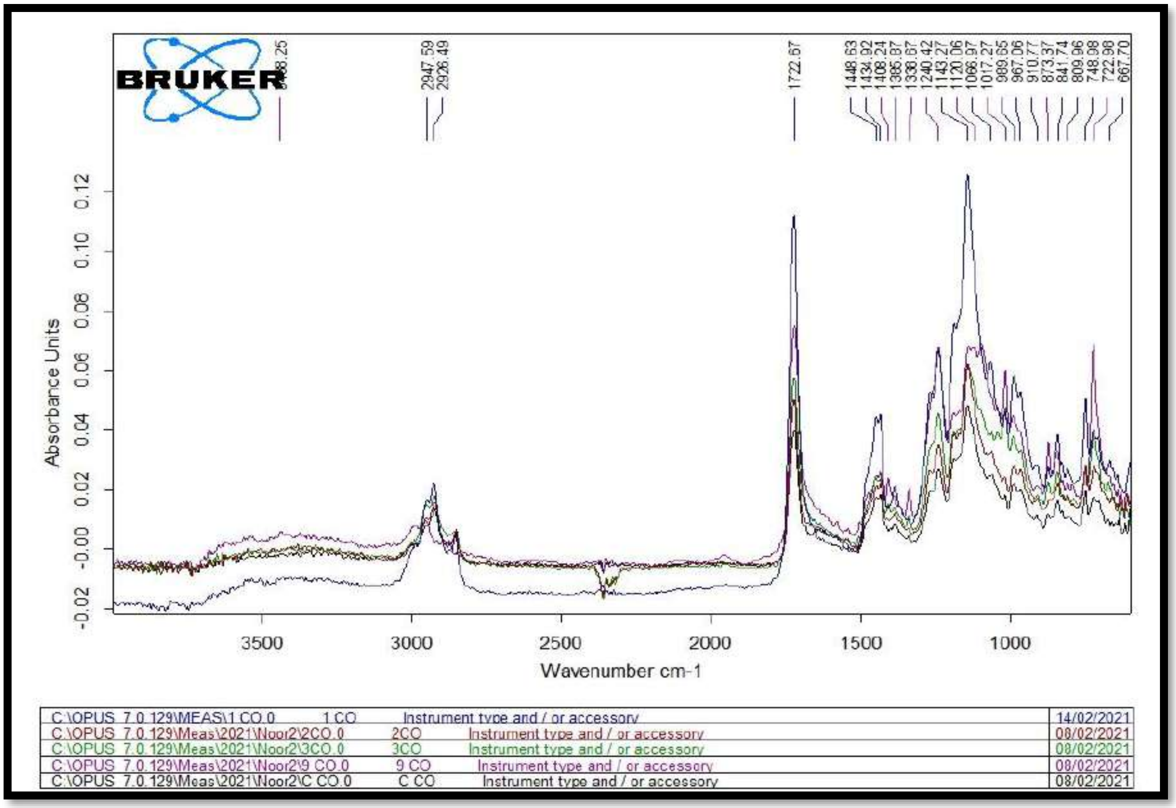


Figure (6.56): FTIR bands for prosthetic socket composites as a function of cotton fiber

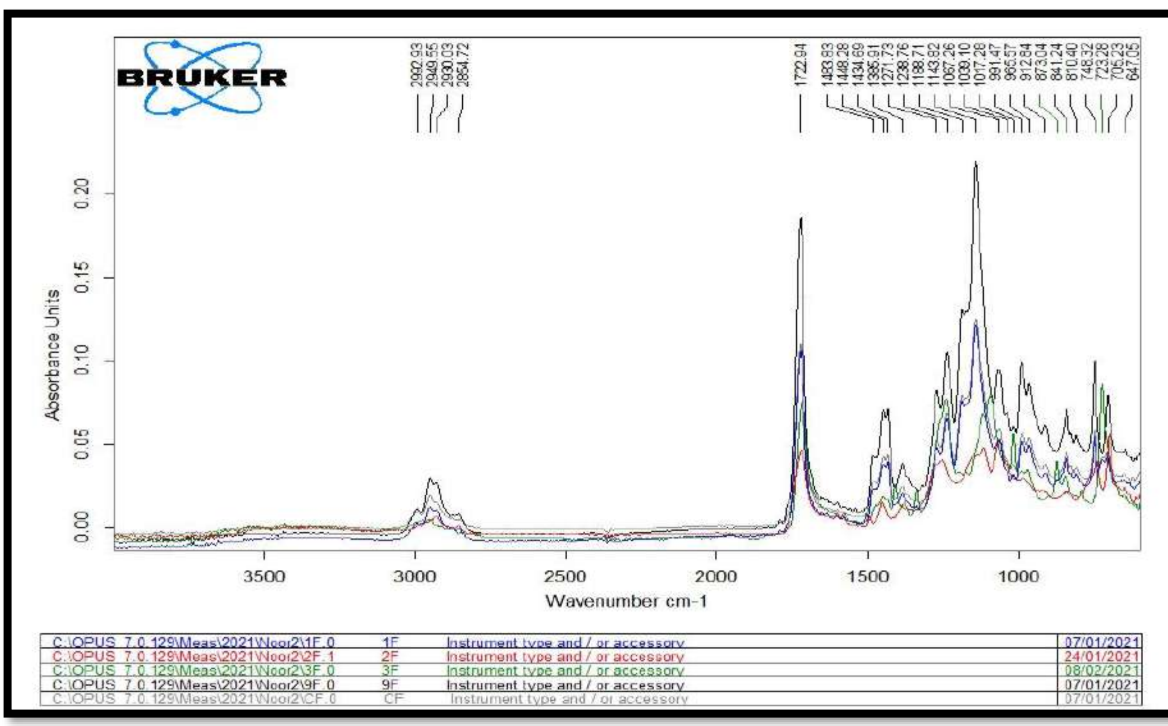


Figure (6.57): FTIR bands for prosthetic socket composites as a function of flax fiber

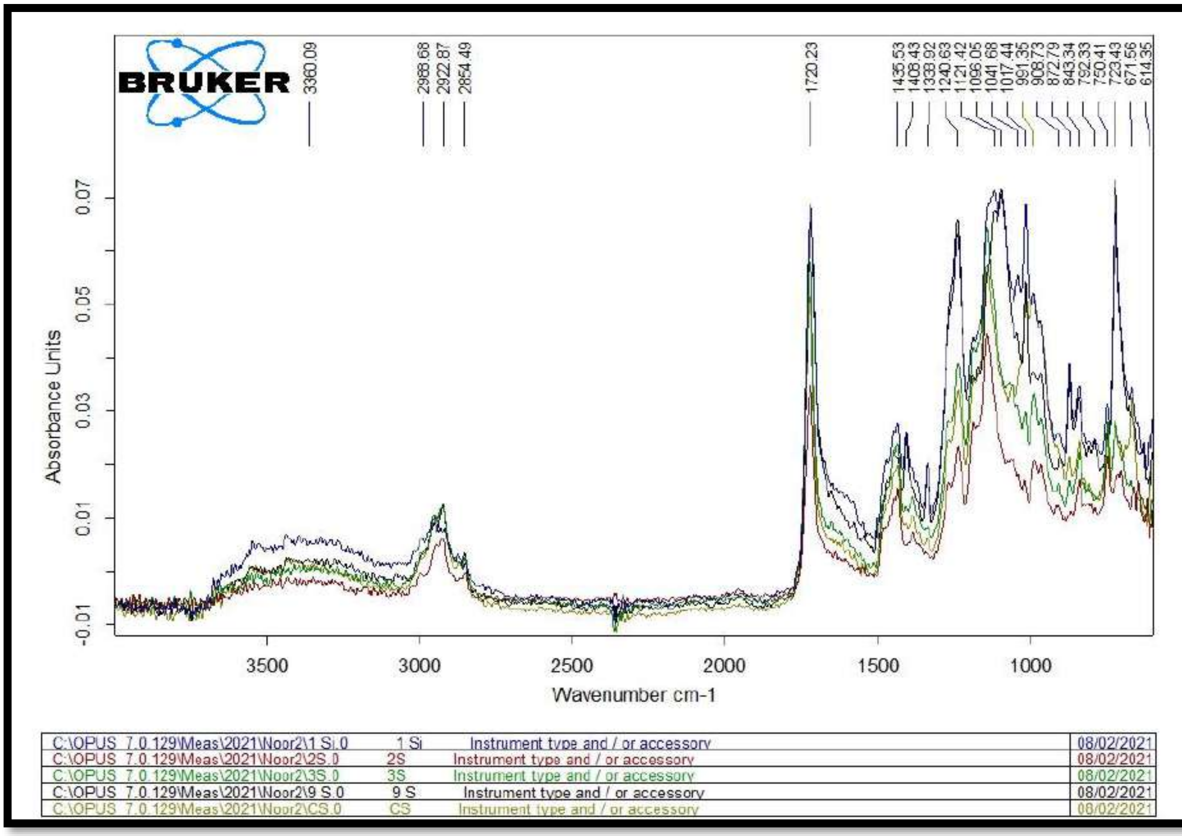


Figure (6.58): FTIR bands for prosthetic socket composites as a function of sisal fiber

6-4 Numerical Results:

6-4-1 Equivalent Stress (Von Mises Stress):

A numerical analysis is performed to determine the values of stresses produced in the socket parts that are prepared in this study as a result of the generation of interface pressure between the socket and the muscles and body weight while walking. The equivalent (Von-Mises) Stresses analysis provided us with information about the amount of stress and spread in the socket, as well as the deformation caused by the interface pressure in the socket.

The results showed that the highest stress generated in the socket was introduced with Lami nation 6 (2Perlon +1 Sisal+2Perlon) layers (equivalent to 26.83 MPa) and located at the center of the anterior side of the tibia bone, while the sides (posterior, medial, and lateral) partake pressur e that is less than the anterior side.

Figure (6.59) depicted the information found by comparing the values of equivalent (Von-Mises) stresses obtained for all composite samples, whereas Figure (6.60) depicted all the composite specimens' outline designs, which depicted the general spreading of the Von Mises stresses through the material as well as governing the estimated value and position of the extreme Von Mises stress.

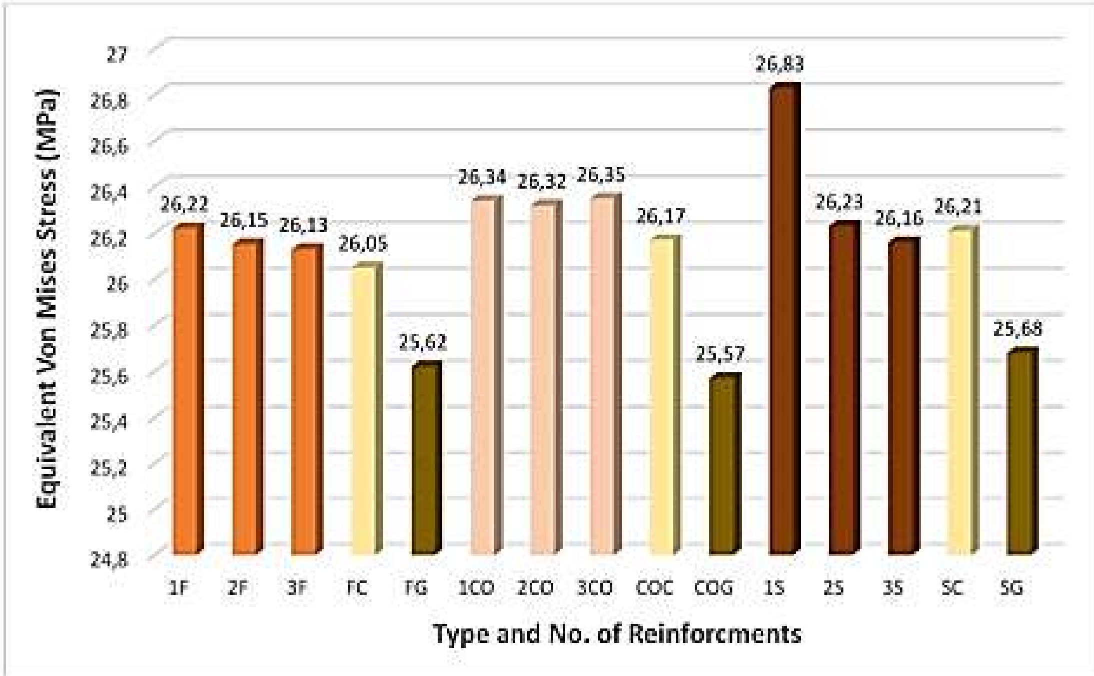
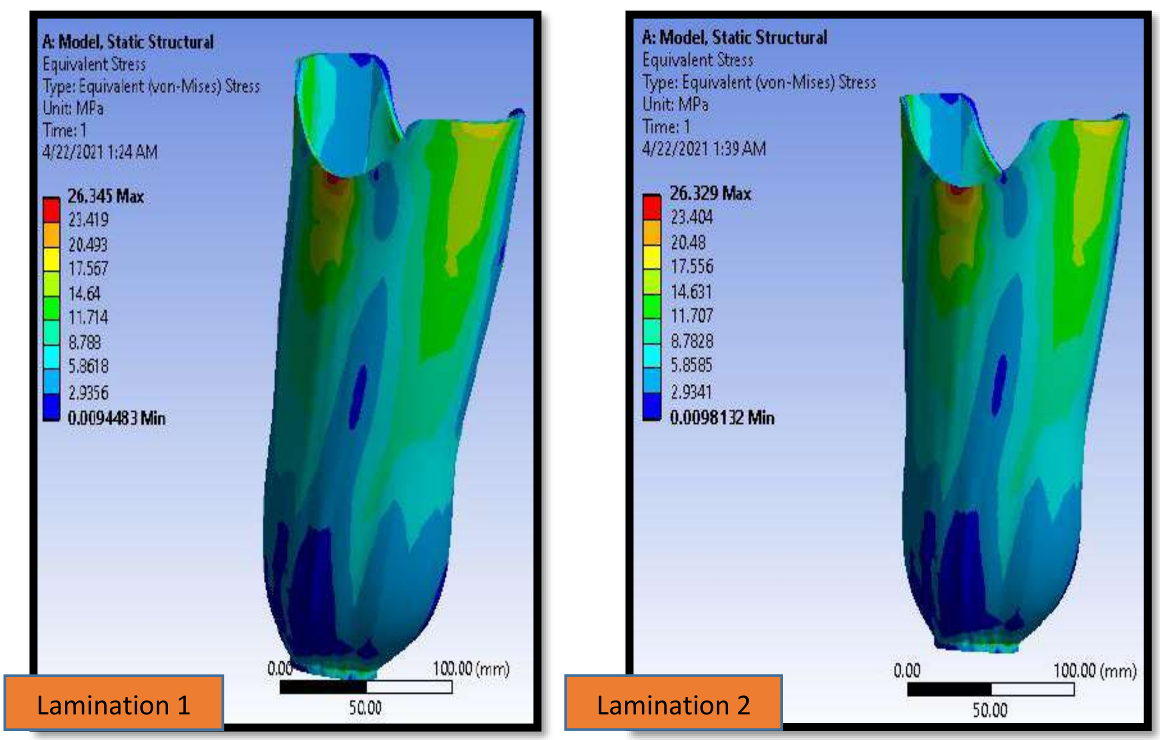
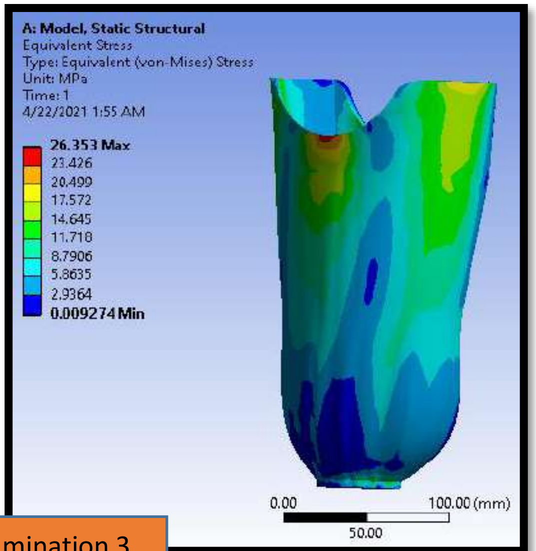
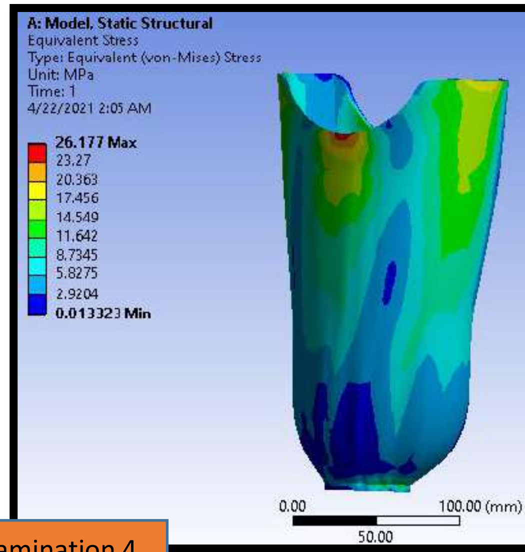


Figure (6.59): Equivalent (Von mises) stress distribution of Prosthetic Socket Laminate Composite Specimens.

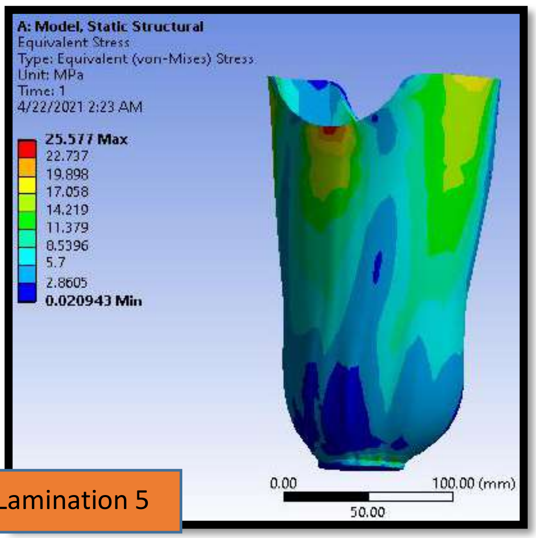




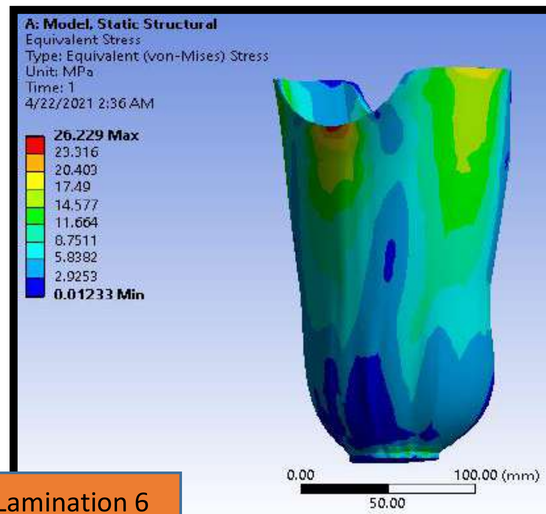
Lamination 3



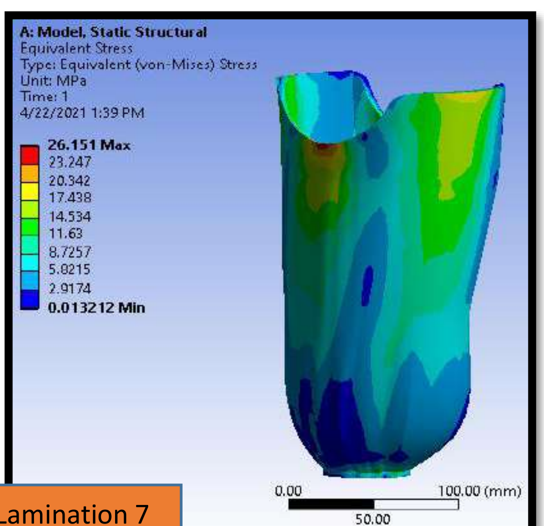
Lamination 4



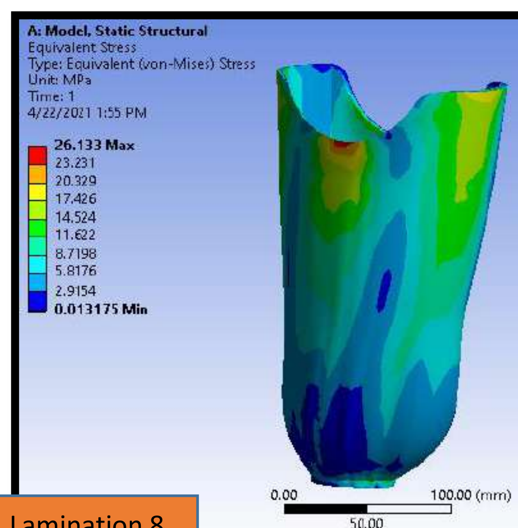
Lamination 5



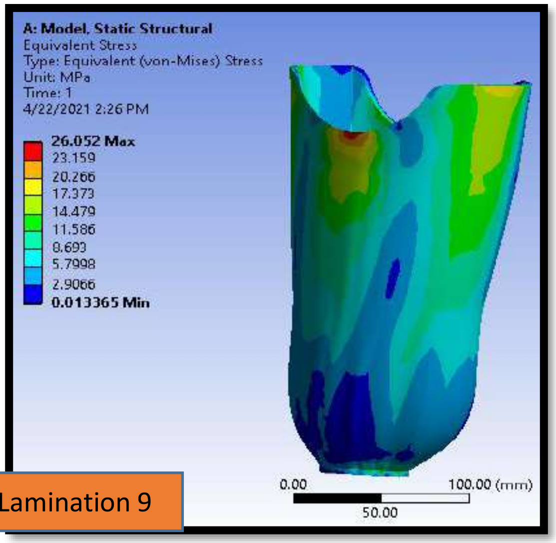
Lamination 6



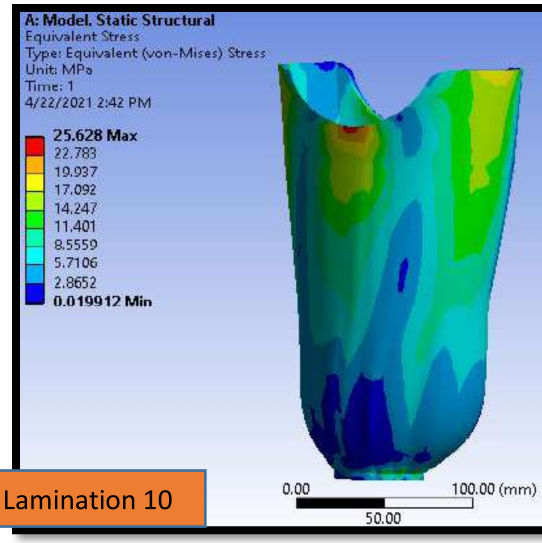
Lamination 7



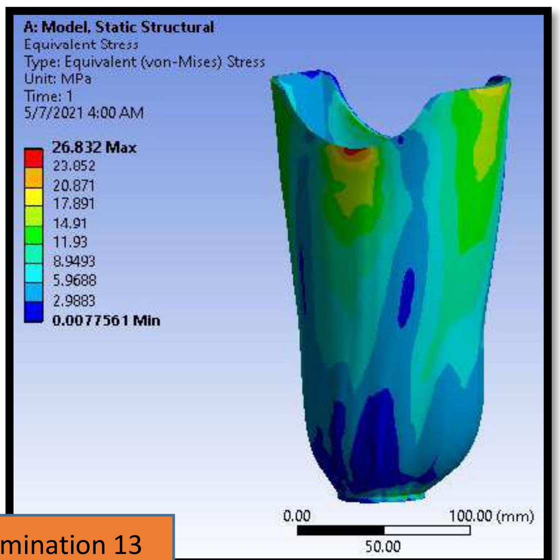
Lamination 8



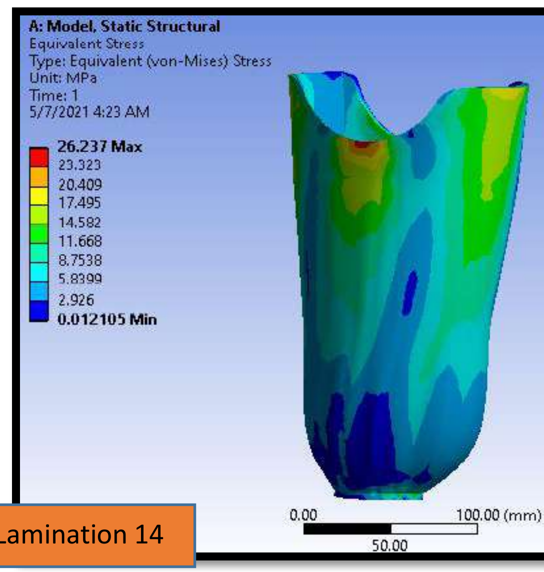
Lamination 9



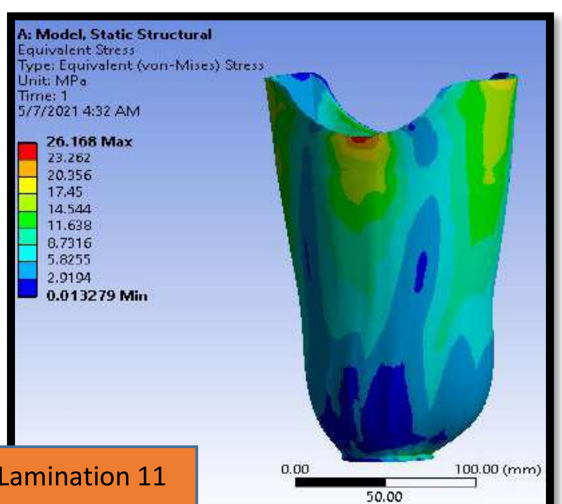
Lamination 10



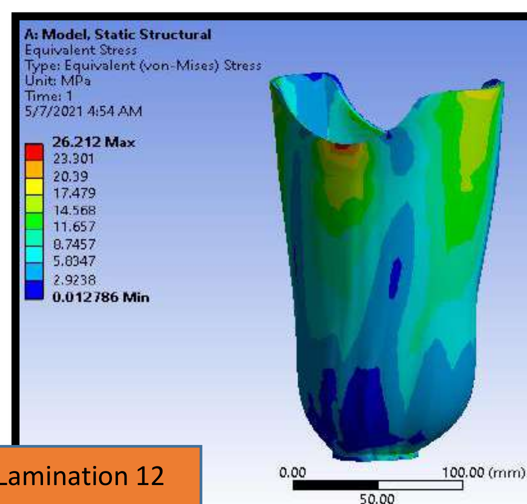
Lamination 13



Lamination 14



Lamination 11



Lamination 12

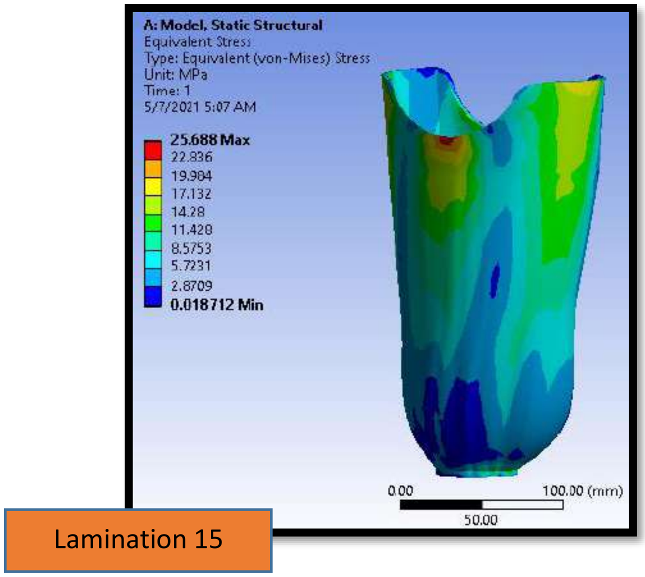


Figure (6.60): Contours of von mises stress of the Prosthetic Socket Laminated Specimens

6-4-2 Von Mises Elastic Strain:

According to figure (6.61), the highest equivalent elastic value of strain produced in the socket is equivalent to (0.016) located at the center of the anterior side of the tibia bone, but the sides (posterior, medial, and lateral) partake pressure that is less than the anterior side with Lamination 1 (2. Perlon +1 Cotton+2Perlon) layers, while the least equivalent strain is (0.0047) in hybrid (flax carbon) reinforcements lamination. The outline design of the equivalent elastic strain of all the lamination composites utilized in this study is shown in figure (6.62).

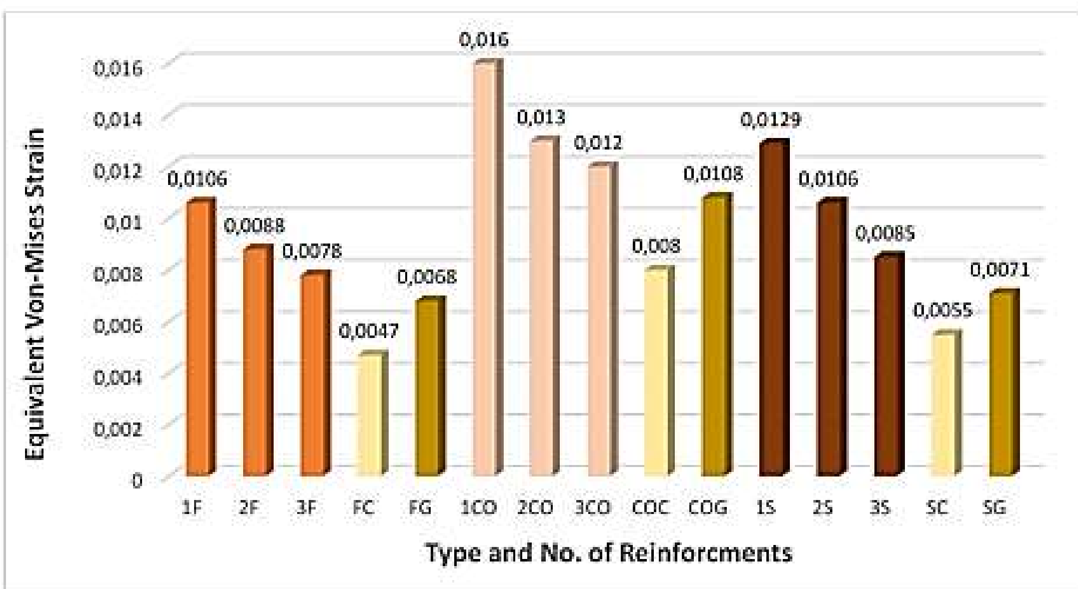
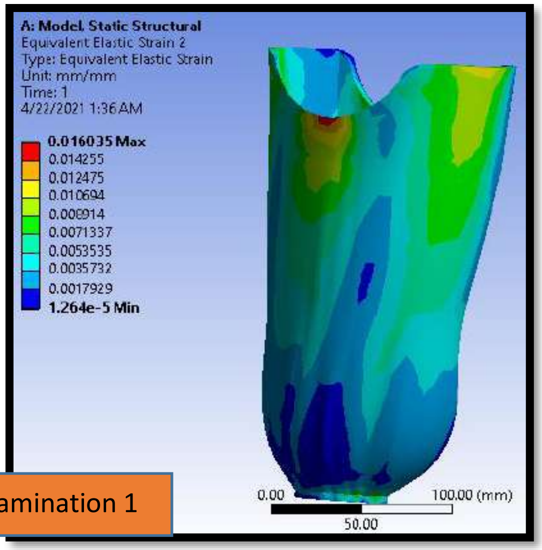
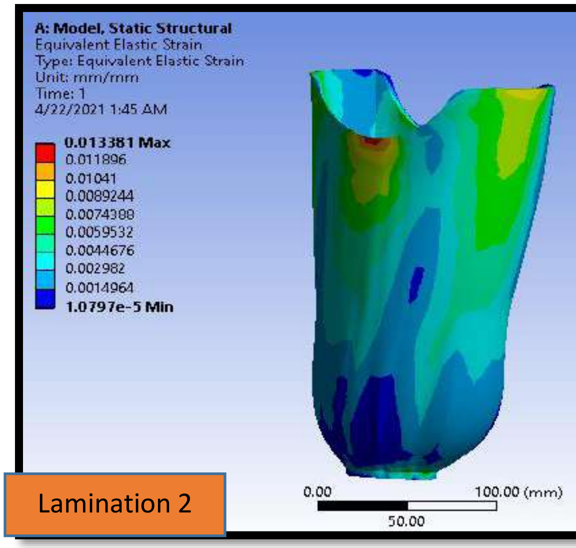


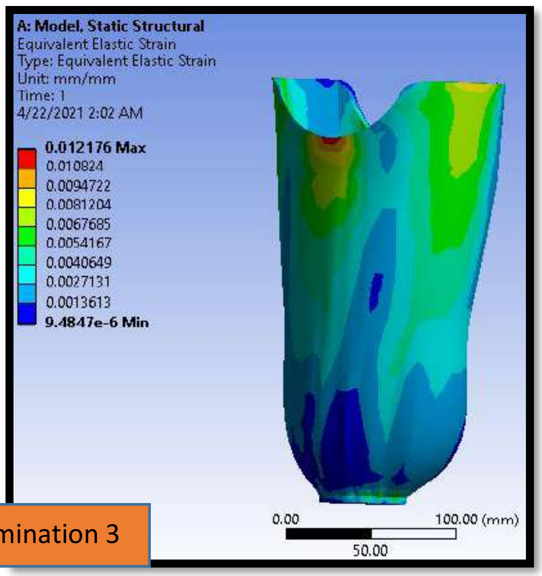
Figure (6.61): Equivalent (Von mises) strain distribution of the Prosthetic Specimens



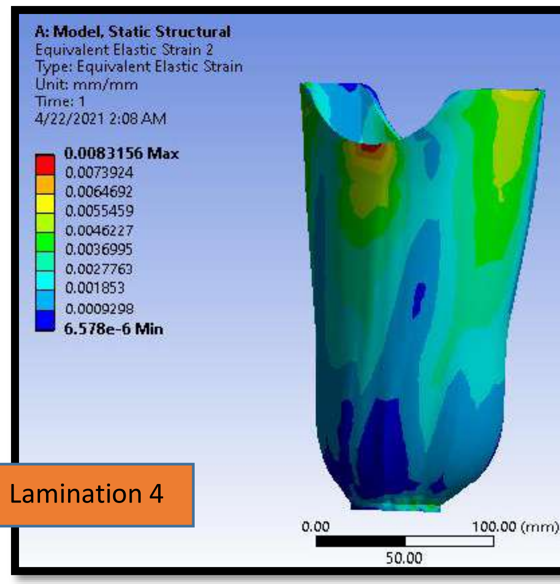
Lamination 1



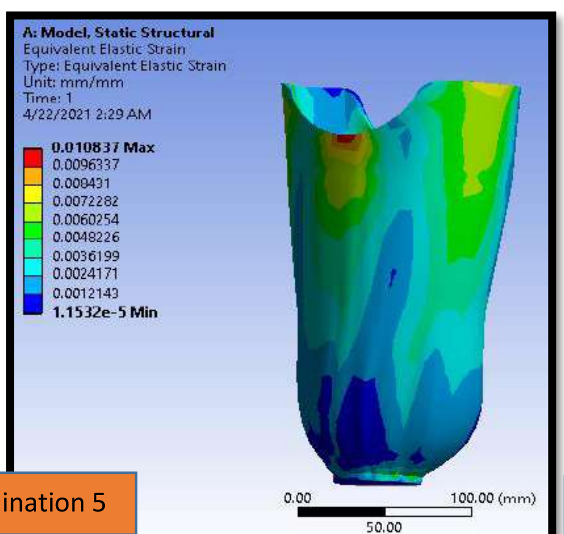
Lamination 2



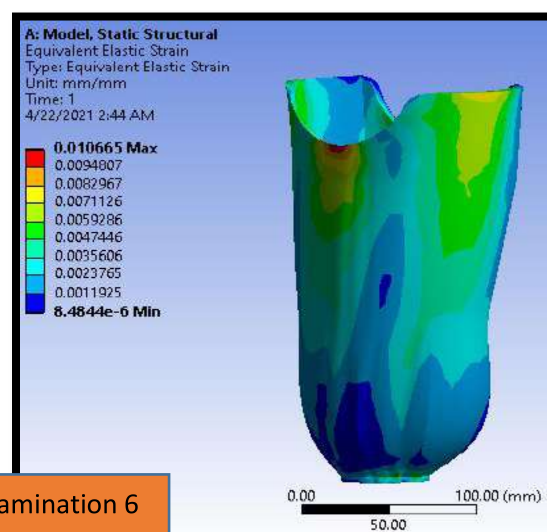
Lamination 3



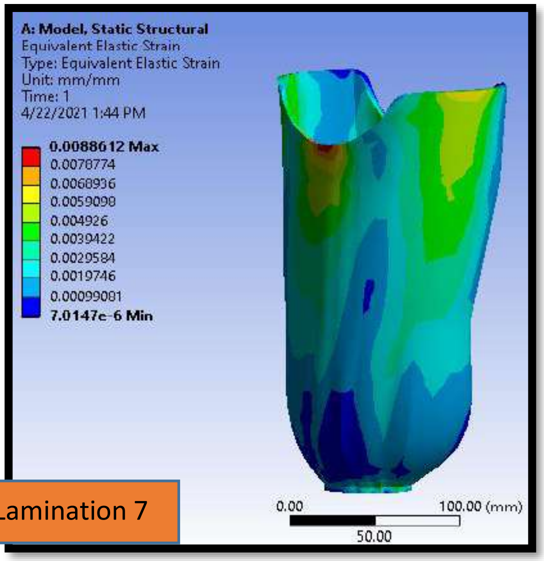
Lamination 4



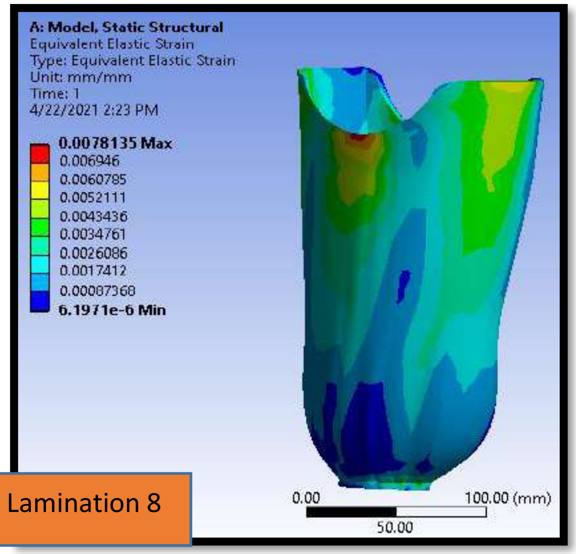
Lamination 5



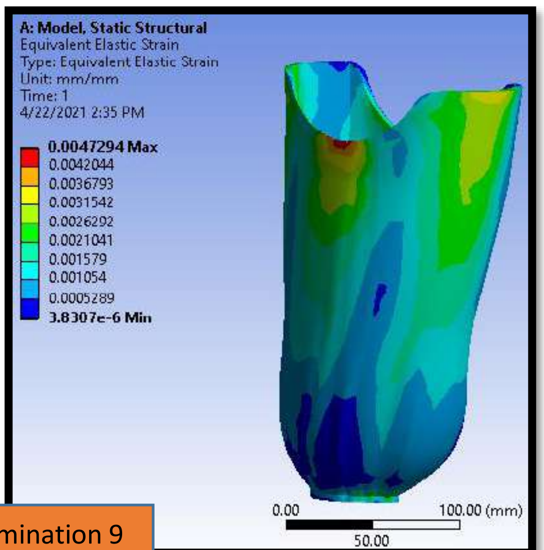
Lamination 6



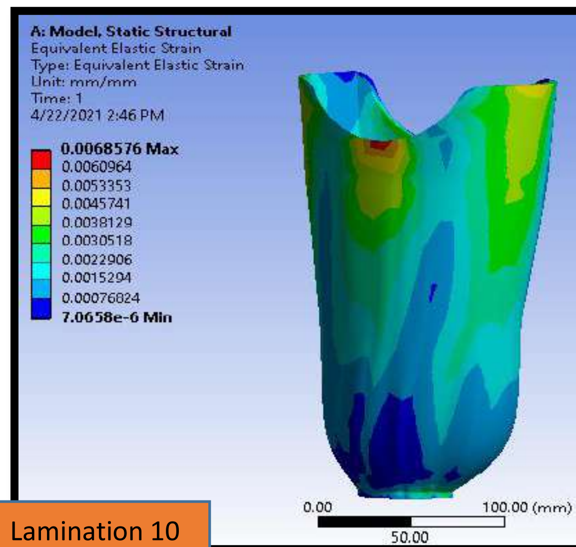
Lamination 7



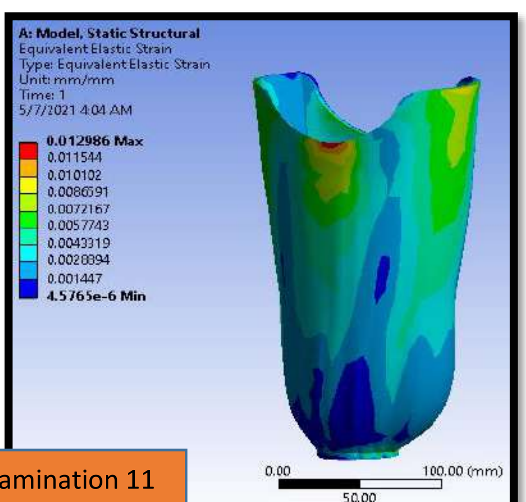
Lamination 8



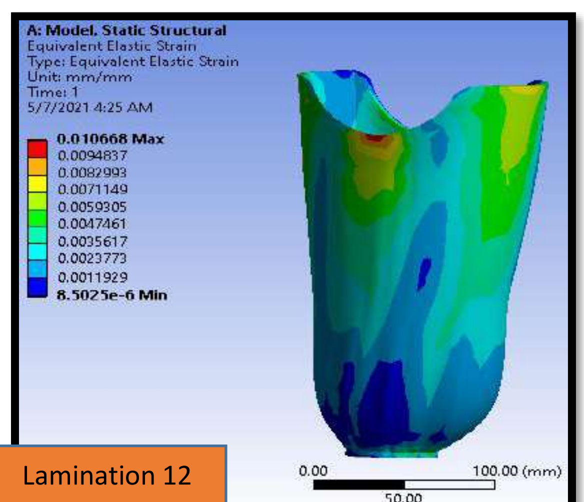
Lamination 9



Lamination 10



Lamination 11



Lamination 12

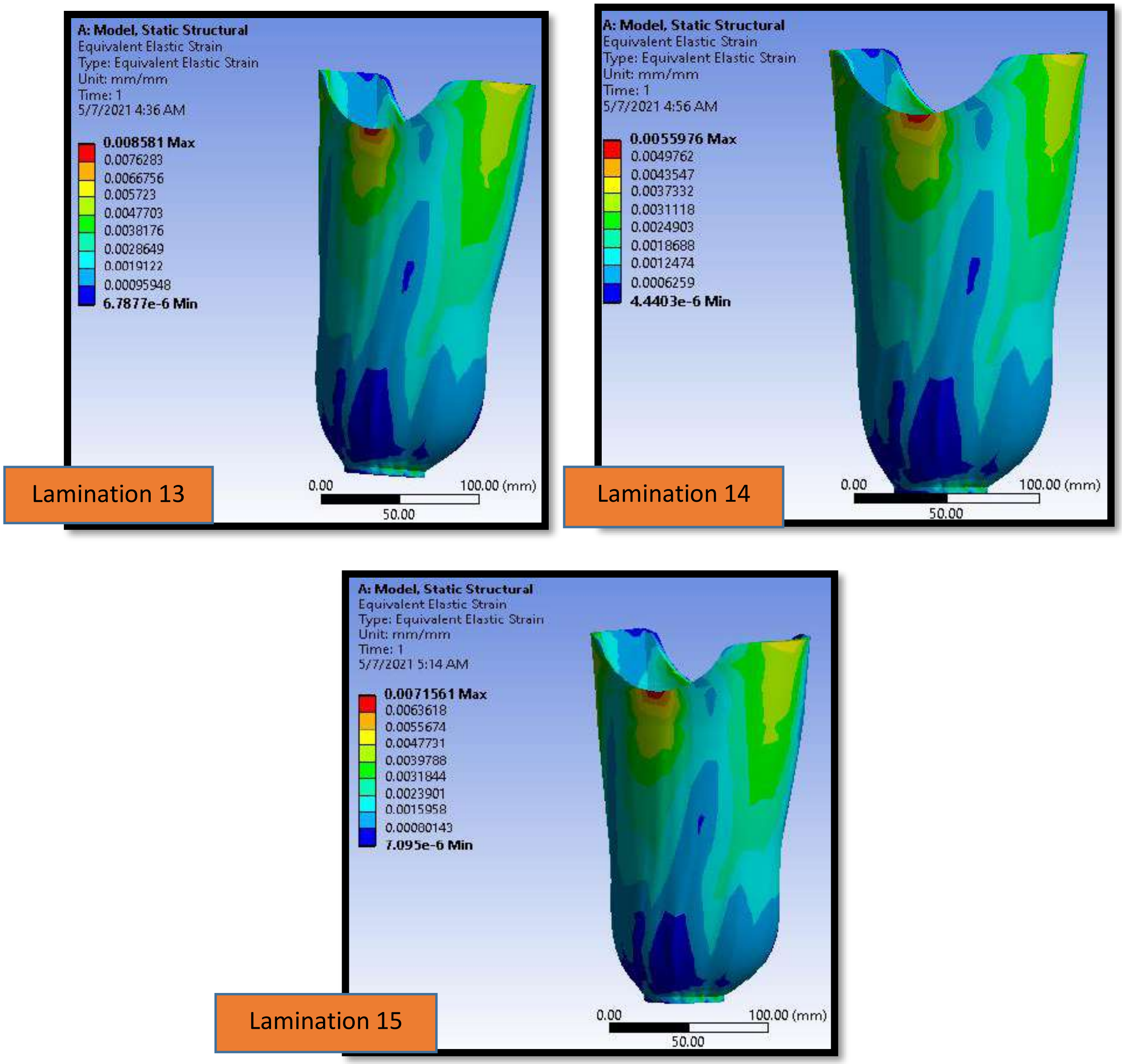


Figure (6.62): Contours of Von Mises strain of the Prosthetic Socket Specimens

6-4-3 Safety Factor on Socket Materials:

These are counterplots for mechanical failure at a given design life. The highest value of safety factor observed in Ansys is (15), but when the stress in a precise location develops greater than the strength of the material, the safety factor ratio evolves less than one, and with this, there is a risk, which mainly is that in an exact part of the model, the stress is greater than the strength the material can withstand and failure is projected earlier than the design life [173].

Figure (6.63) depicted the minimum numerical safety factors for all composite samples, with the combination of flax fibers and carbon fiber producing the best results, which can be attributed to the impressive properties of carbon fiber, while lamination (1) has the lowest safety factor, compared to the other fourteen lamination groups, which have 1.21, which can be attributed to the properties of cotton and perlon reinforcement fibers. Figure (6.64) depicts the distribution of the composite's safe and unsafe areas.

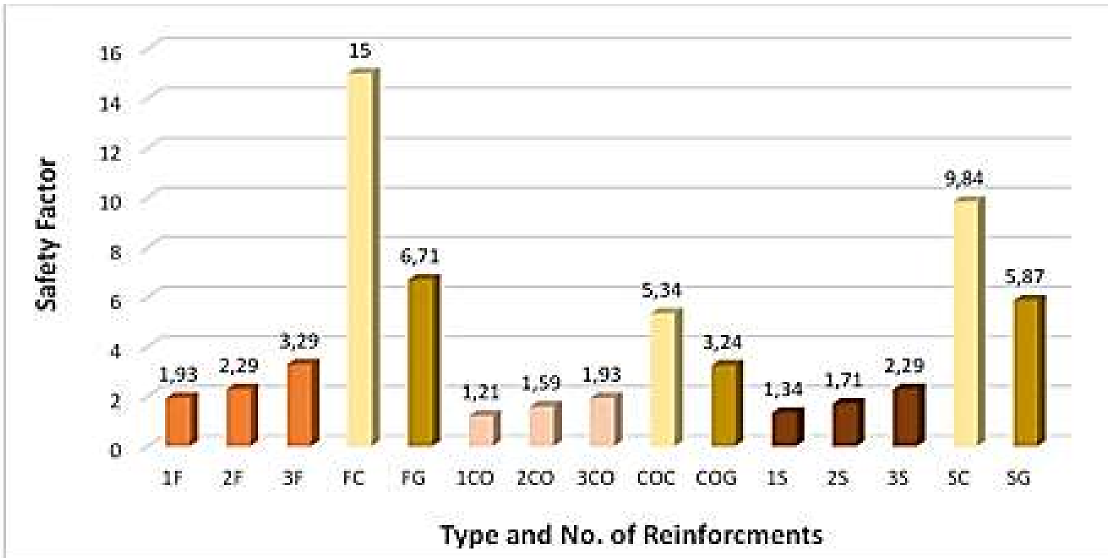
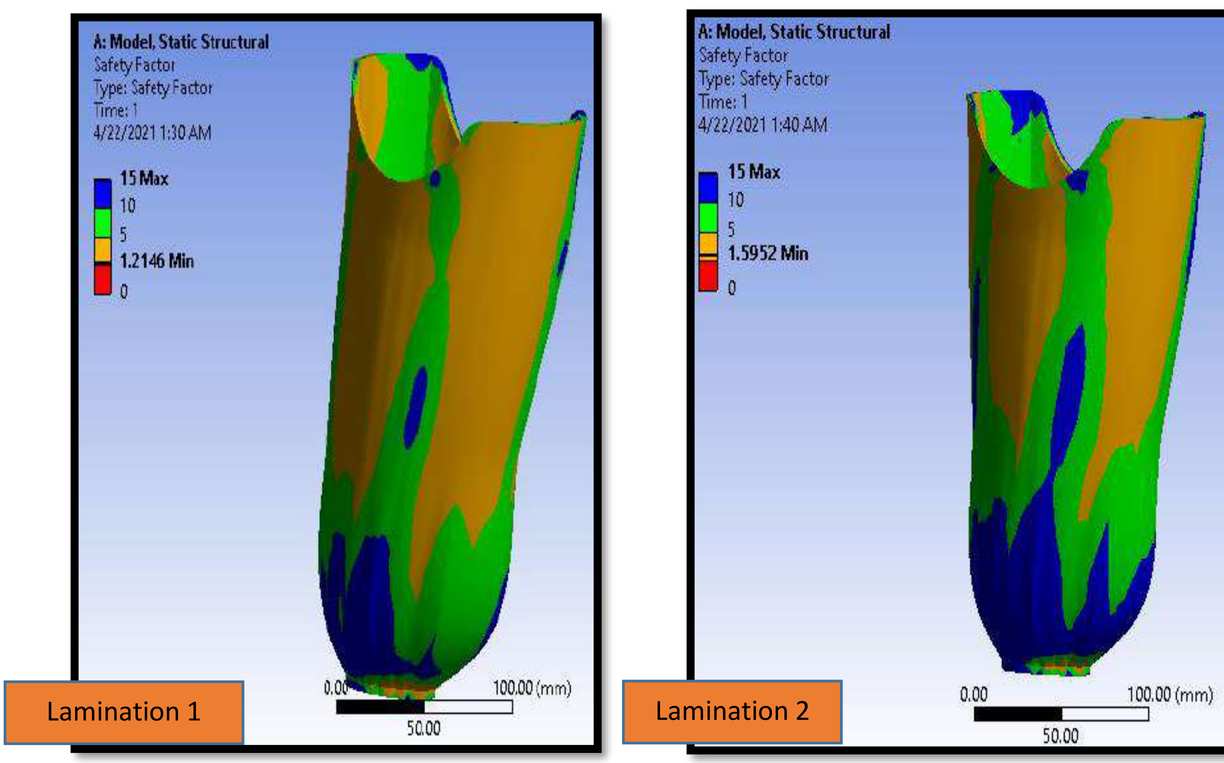
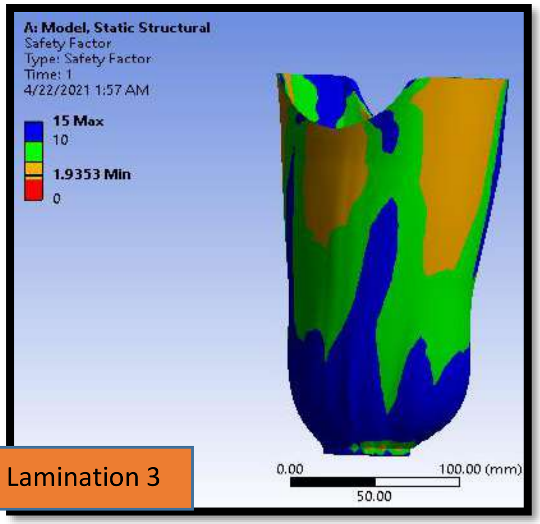
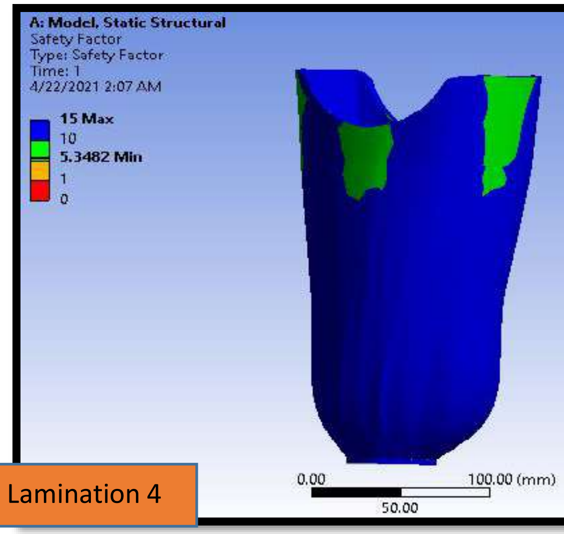


Figure (6.63): Numerical safety factor of the Prosthetic Socket Specimens

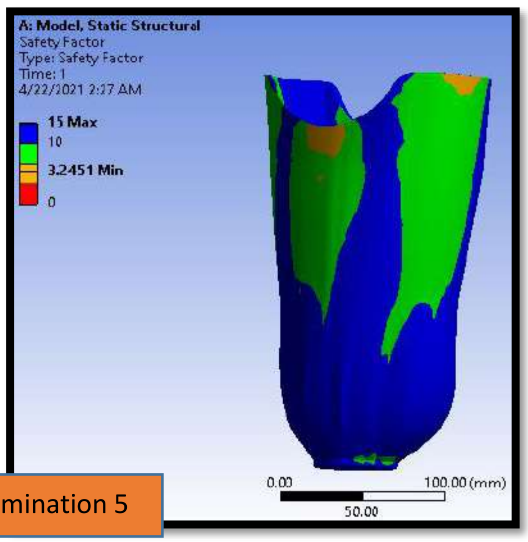




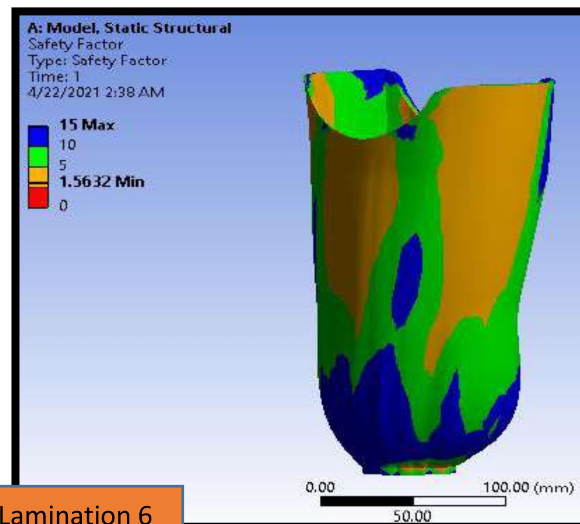
Lamination 3



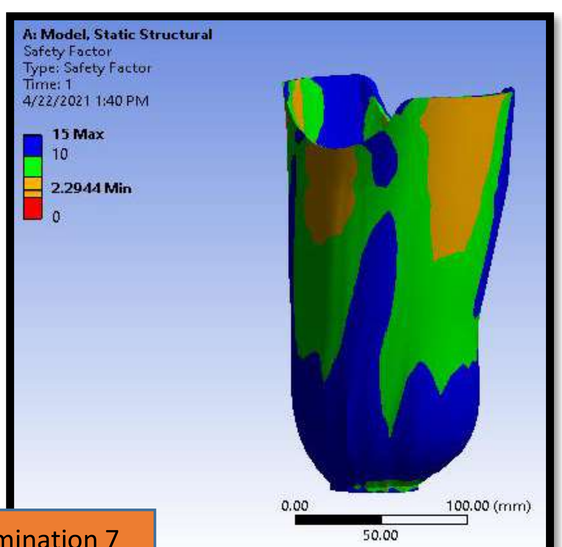
Lamination 4



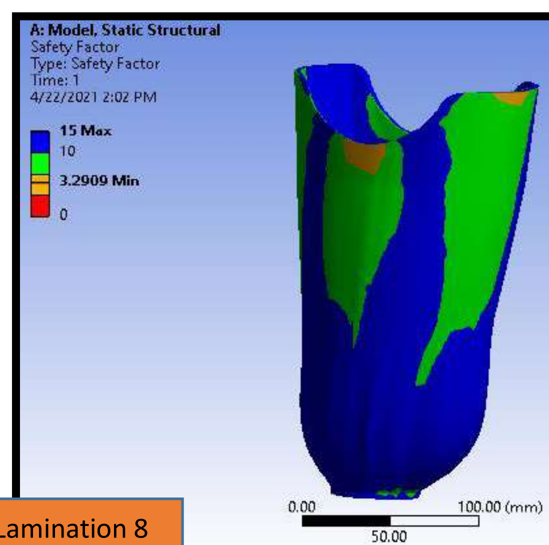
Lamination 5



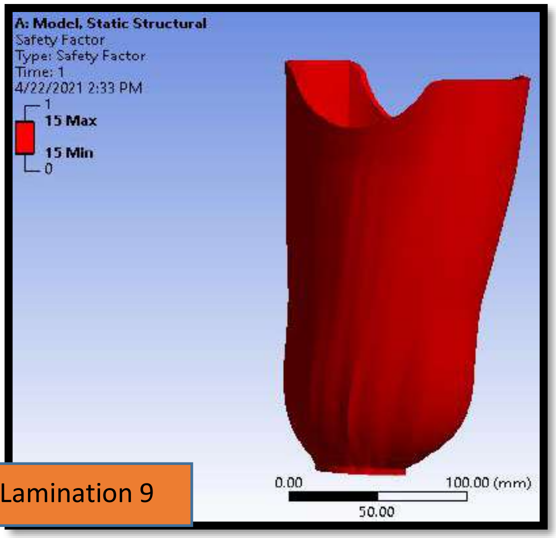
Lamination 6



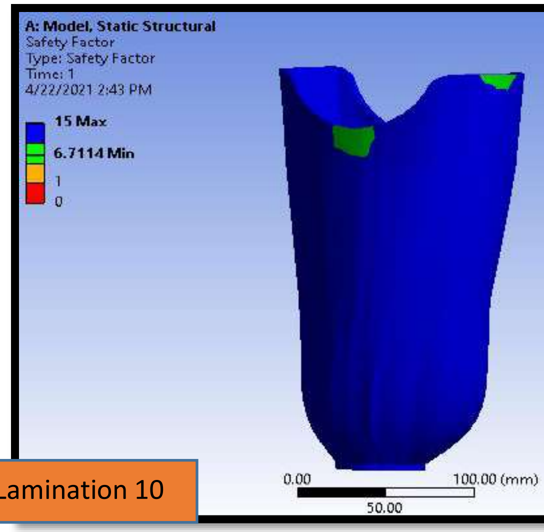
Lamination 7



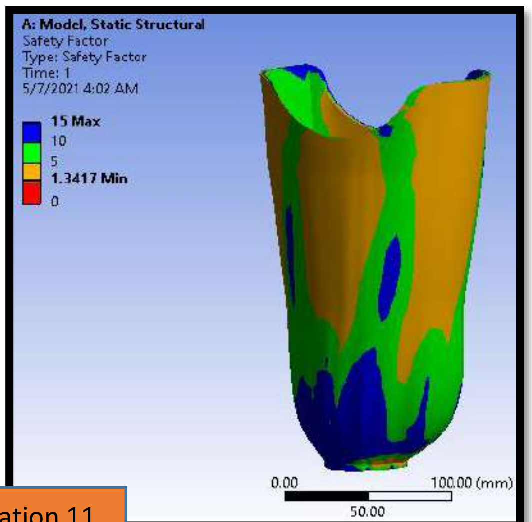
Lamination 8



Lamination 9



Lamination 10



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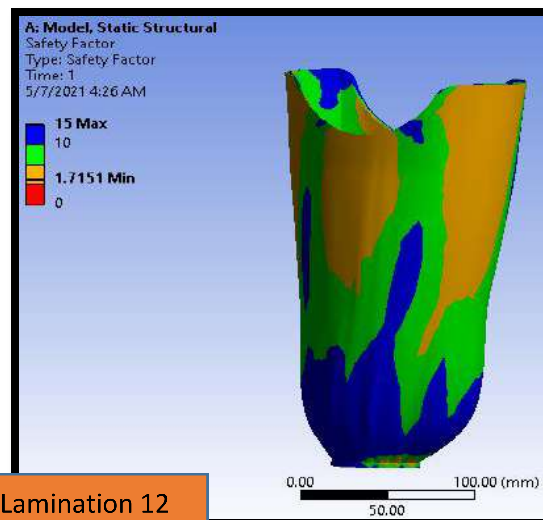
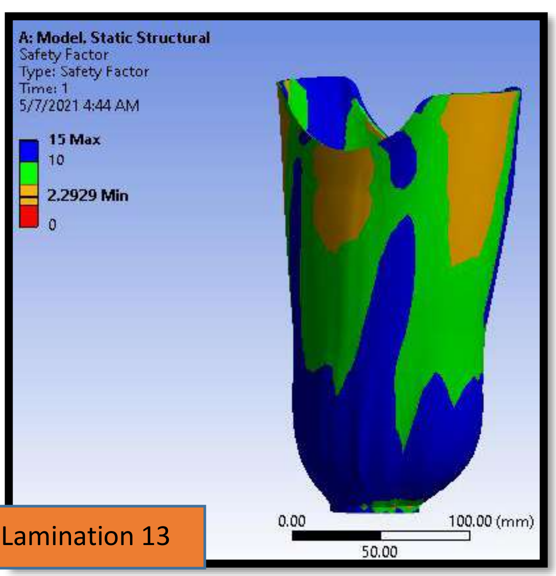
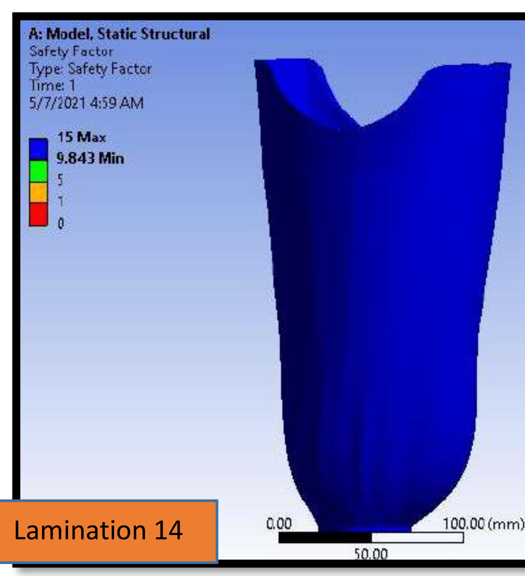


Lamination 12



Lamination 13



Lamination 14

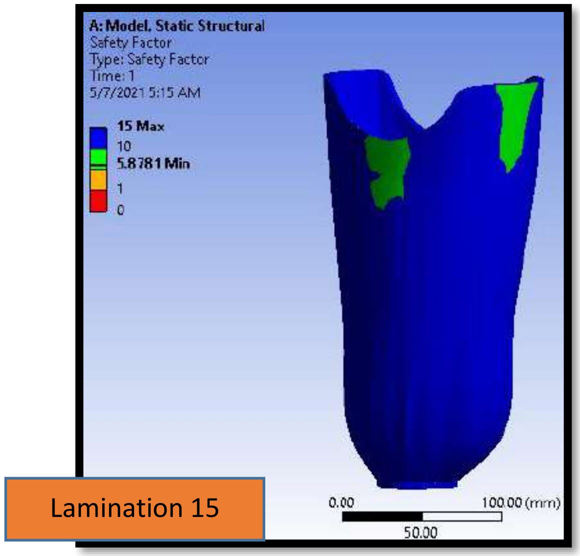


Figure (6.64): Contours of safety factor distribution of Prosthetic Composite.

6-4-4 The Numerical Analysis of Deformation:

The deformation study provided us with information on the values and locations of the socket's general behavior. For the model manufactured, the maximum deformation value of the socket can be seen in lamination 1 (2Perlon+1Cotton+2Perlon) of (9.05) mm, while the lowest extent of total deformation can be seen in lamination 2 (1perlon+1flax+1carbon+1flax+1carbon+1flax+1perlon) of (2.72) mm.

The results of comparing the total deformation values obtained for all composite samples and the association between the volume fraction of these new materials and the deformation of the specimens for all laminations are shown in figure (6.65). It was observed the total deformation decreased as the volume fraction increased [234]. While employing these composite materials, the deformation values for the socket are acceptable since the socket must deform within the range of the above values when applying the interface pressure to provide comfort to the patient's skin [48]. Figure (6.66) shows that the highest total deformation values were found in the lateral plane's center, while the lowest values were found in the socket's basal plane [235].

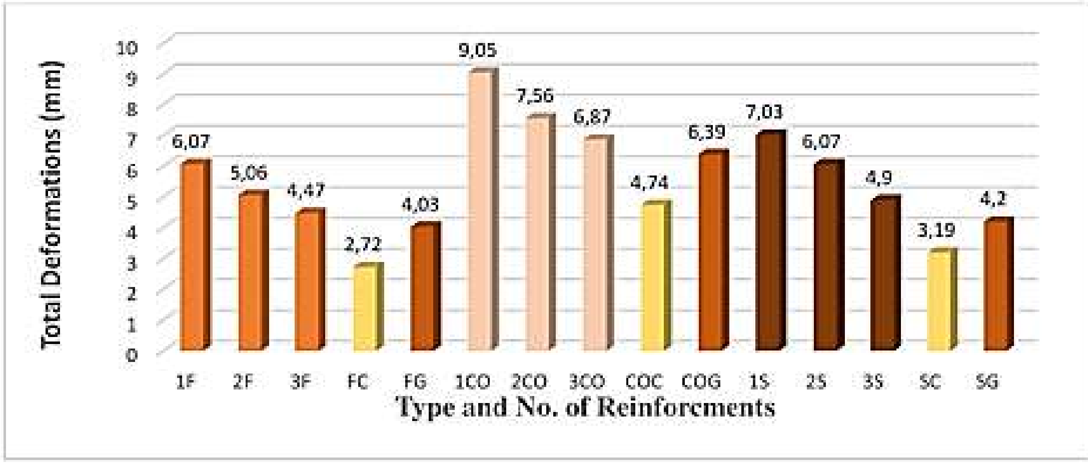
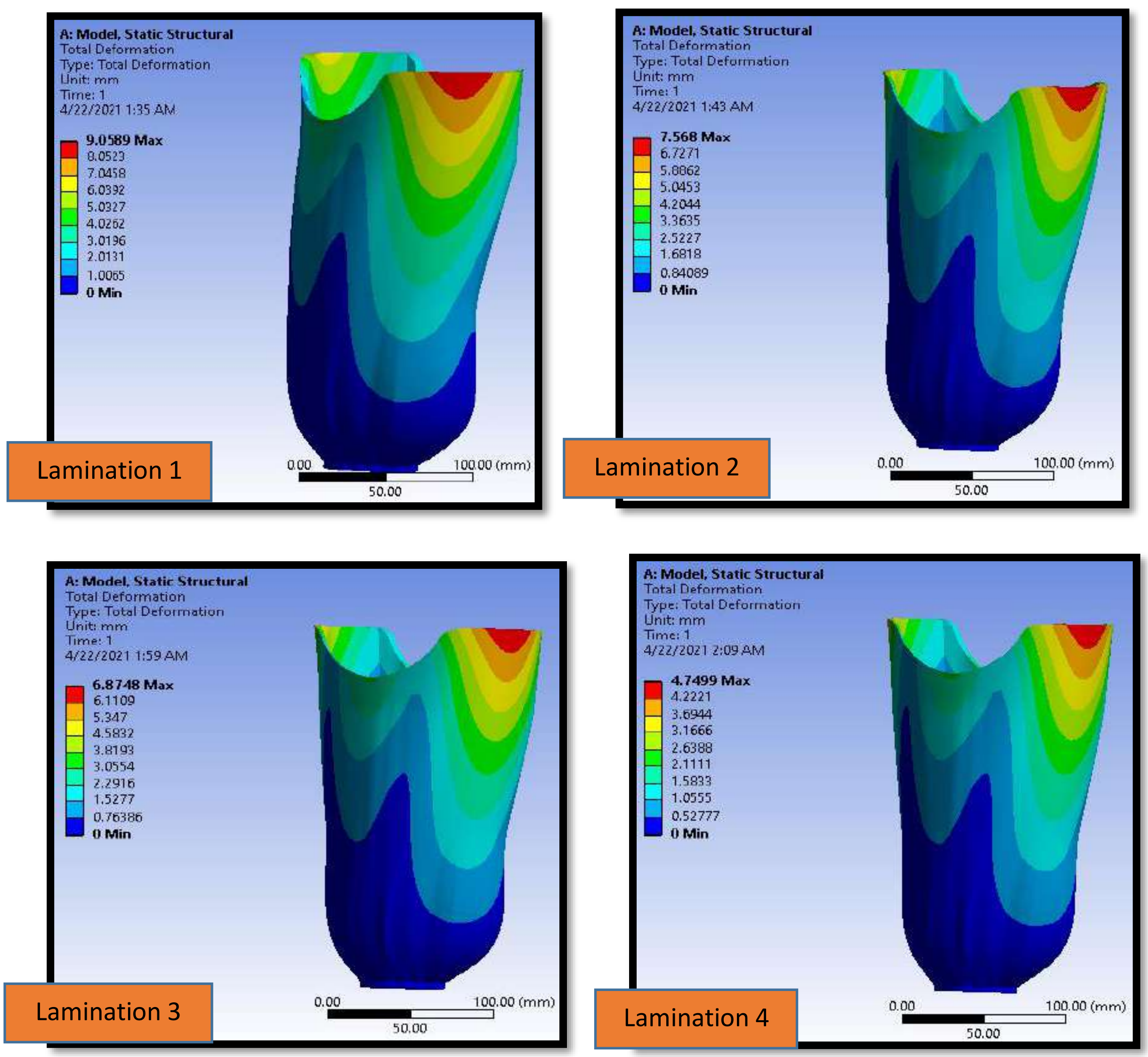
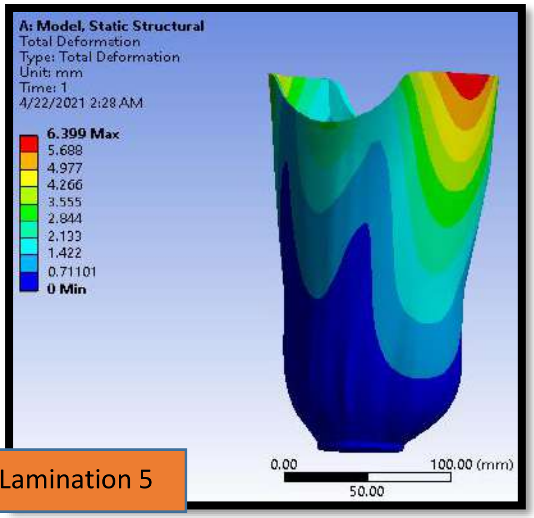
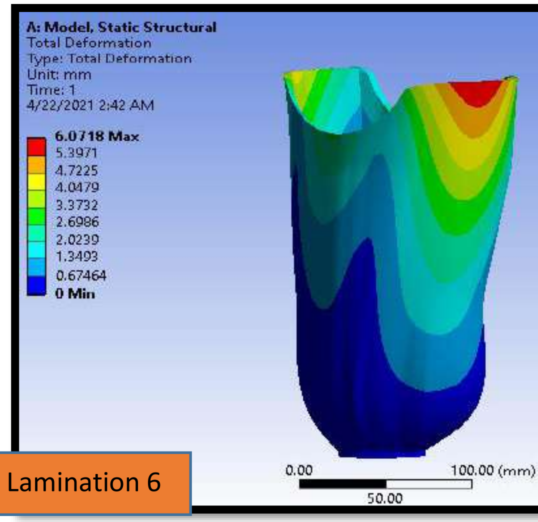


Figure (6.65): Total deformation distribution of prosthetic socket specimens.

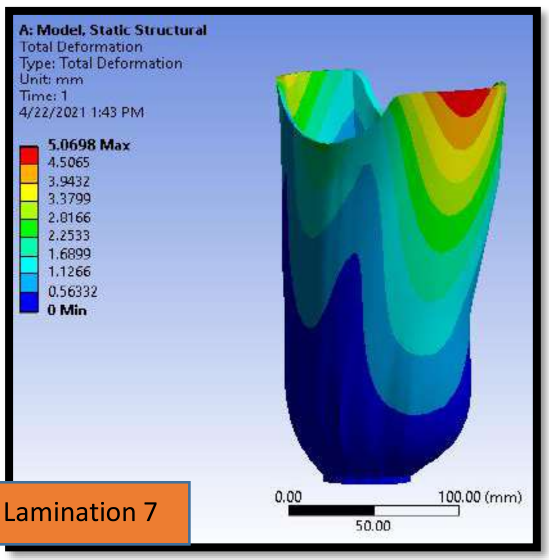




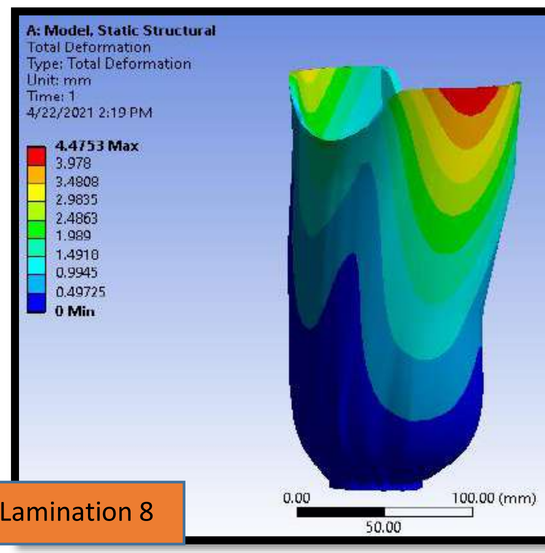
Lamination 5



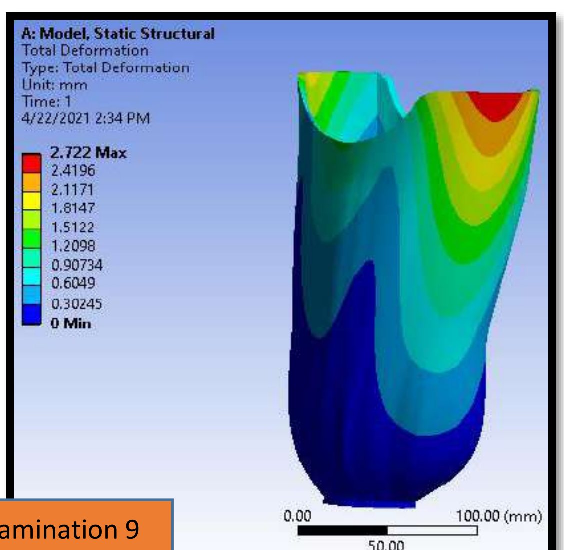
Lamination 6



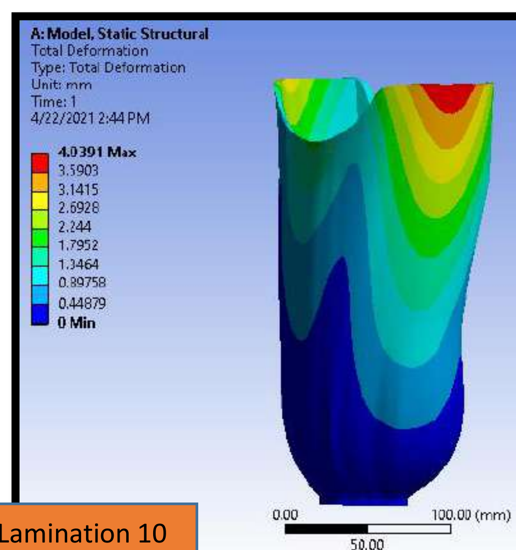
Lamination 7



Lamination 8



Lamination 9



Lamination 10

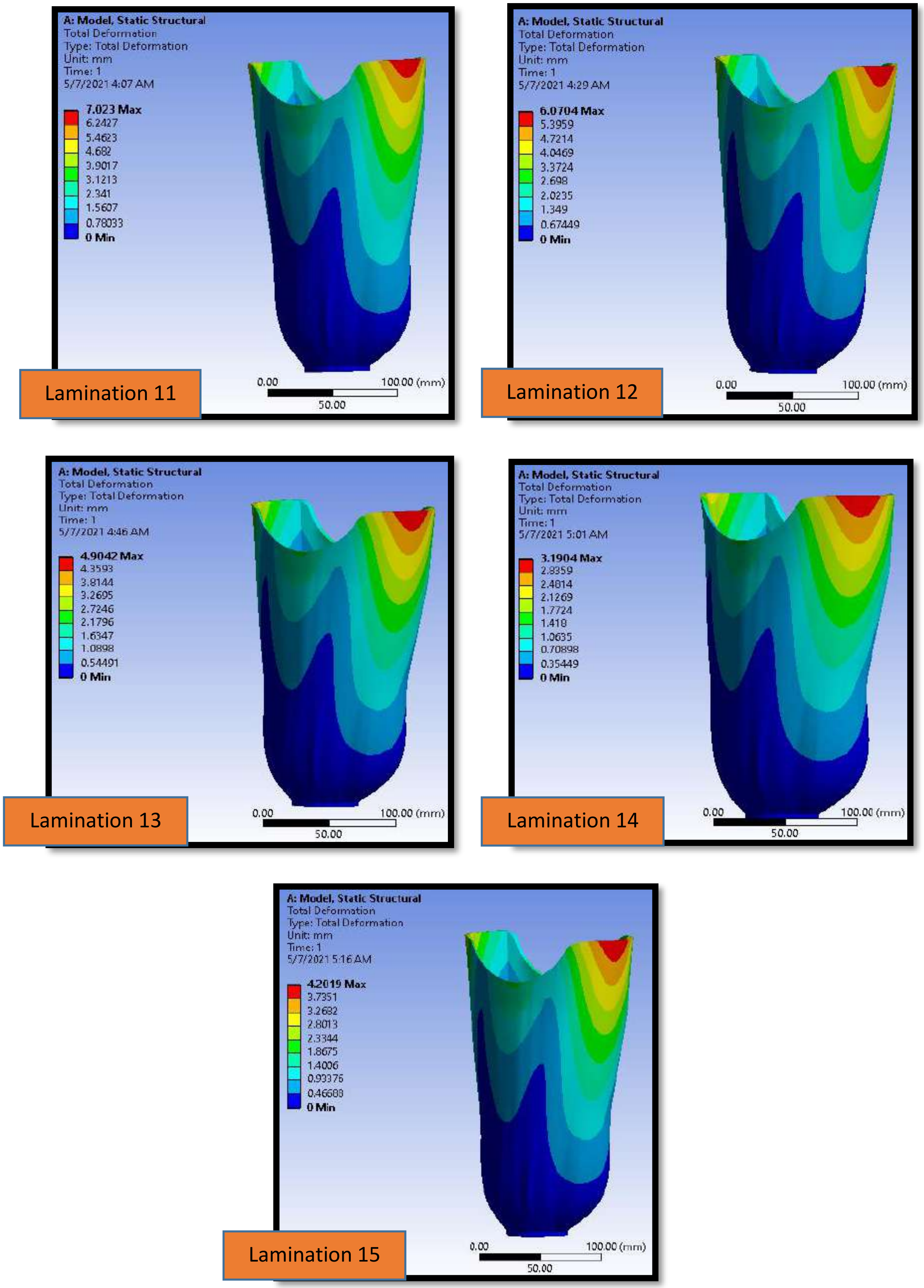


Figure (6.66): Contours of total deformation distribution of prosthetic composite.

6-5 Theoretical Results:

6-5-1Failure Index (K):

Figure (6.67) demonstrates the association between the failure index and the kind and number of reinforcements utilized in this study. It can be perceived that the cotton reinforcement in lamination (1CO) has a maximum failure index of (0.71). Furthermore, when associating the failure index for the laminations strengthened by natural fibers with the values for the laminations strengthened by carbon and glass fibers, it can be seen that the former are greater. This is due to the variation in characteristics between glass, carbon fibers, and, natural fibers. In general, (sisal carbon reinforcements) composites provide the lowest values among all other composites, with (0.1).

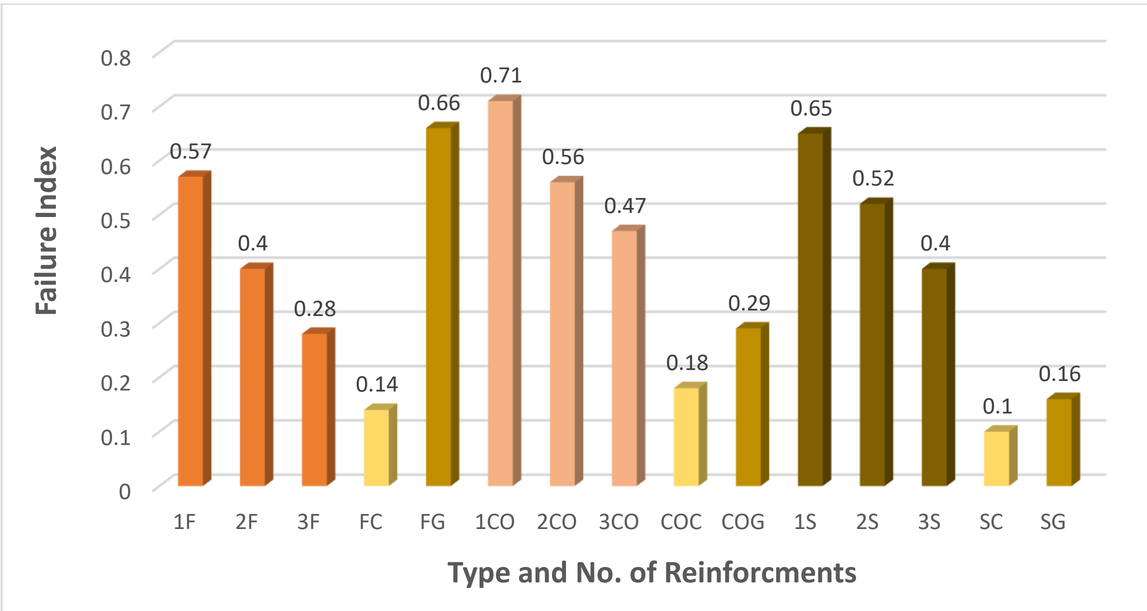


Figure (6.67): Theoretical failure index of different Prosthetic Composites.

6-5-2 Factor of Safety (SF):

For the goal of fully understanding the performance of the new projected materials, the theoretical safety factor of the composites was acquired as presented in figure (6.68) [173]. Both theoretical and numerical safety factors presented a great agreement for all laminations where the grouping of (flax carbon) fiber reinforcements exhibited the greatest results and that can be attributed to the remarkable characteristics of carbon fiber. While cotton reinforcement in lamination (1CO) had the lowest safety factor (1.4). A numerical and theoretical safety factor of lamination groups were presented in figure (6-2).

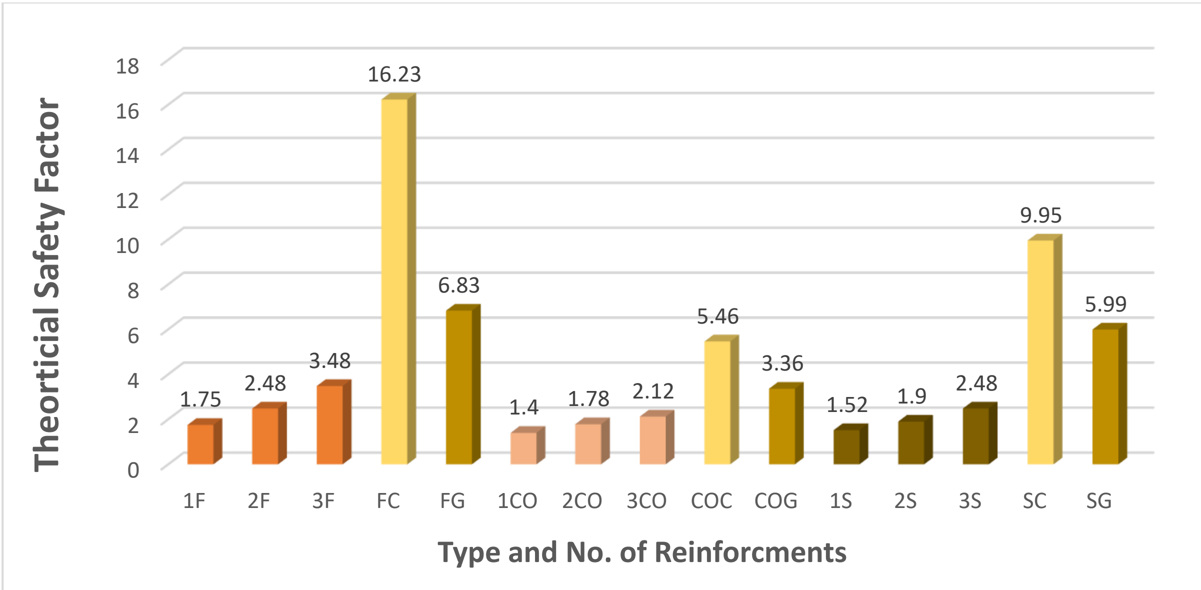


Figure (6.68): Theoretical Safety Factor of prosthetic socket lamination specimens.

Table (6-2): Numerical and theoretical safety factors of lamination groups

Lamination	Theoretical safety factor	Numerical safety factor
Lamination 1	1.21	1.21
Lamination 2	1.59	1.59
Lamination 3	1.93	1.93
Lamination 4	5.34	5.34
Lamination 5	3.24	3.24
Lamination 6	1.56	1.56
Lamination 7	2.29	2.29
Lamination 8	3.29	3.29
Lamination 9	16.12	15
Lamination 10	6.71	6.71
Lamination 11	1.34	1.34
Lamination 12	1.71	1.71
Lamination 13	2.29	2.29
Lamination 14	9.84	9.84
Lamination 15	5.87	5.87

Chapter Seven
Conclusions and Recommendations

7-1 Conclusions:

Variable materials produced from PMMA as matrix and reinforcing layers (natural or natural) fibers at different numbers and orientations are investigated experimentally and numerically. The following conclusions can be divided into two categories:

A- According to the results of the experiment part:

1. Varying the number and type of reinforcements had a significant impact on all lamination groups' mechanical, physical, and numerical characteristics. The optimum value of these characteristics is noticed in specimens of hybrid (natural and synthetic) fiber layers.
2. PMMA specimens that have flax fibers added to them are lighter.
3. When evaluating the mechanical characteristics of laminated composites, a hybrid lamination consisting of three layers of flax fiber with layers of carbon fiber had the best tensile strength, Young's modulus, compression strength, and hardness with (423 MPa, 5.6 GPa, 119 MPa, and 86 Shore-D).
4. The group consisting of three layers of sisal plus two carbon fiber layers exhibited the greatest flexural strength, flexural modulus, and maximum shear stress when all lamination groups were compared with (225 MPa, 7.2GPa, and 13.8 MPa).
5. The impact strength of hybrid (Cotton plus Carbon) lamination improved as the number of reinforcing layers grew; the impact strength of hybrid (Cotton plus Carbon) lamination is the greatest of all lamination groups.
6. As the number of layers rises, the percentage of elongation reduces. Lower values of these characteristics are observed in specimens of lamination 8 (1F), which equals 2.1 %.
7. As the volume fraction of fiber increases, water absorption values fall, with the lowest water absorption values reported when flax fibers are hybridized with glass with 0.6187%.
8. The surface roughness reached its highest point in lamination (4) (COC) (3.095 mm) and its lowest point in lamination 6 (1F)(3.095 μm)

9. UV irradiation and water cycles significantly reduced various property values, such as ultimate tensile strength and modulus of elasticity, flexural strength, flexural modulus, and compressive strength.
10. The FTIR data revealed no new peak appeared; this behavior pertains to the physical bond between both the matrix and the reinforcing material, and no new material was generated.

B- According to the numerical results:

1. The cotton fiber-reinforced lamination had the maximum total deformation (9.05 mm), whereas the lamination composite reinforced by flax and carbon fibers had the lowest (2.72 mm).
2. The highest value of equivalent stress (Von Mises stress) for sisal-reinforced laminated composite prosthetic sockets was 26.83 MPa.
3. For cotton fiber-reinforced laminated composites prosthetic sockets had the highest value of the equivalent elastic strain (0.016).
4. The lowest value of the minimal numerical safety factors was 1.21 for cotton fiber-reinforced laminated composites, while the highest value was 15 for laminations reinforced by flax and carbon fibers.
5. Most of the experimental results matched the numerical results of the F.E.A.

7-2 Recommendations for future studies:

This study can be expanded by:

1. Investigating other features such as fatigue, wear, creep, varying temperatures, and dynamic fracture toughness on these natural fiber-reinforced composites in use in prosthetic socket fabrication.
2. A comparative investigation of the influence of various matrix materials with different types of these reinforcing materials such as (natural fibers or/and synthetics) at various weight fractions can be employed as the main choice for this application.
3. Determine the effect of a chemical coupling agent on fibers' bonding strength to PMMA, as well as their physical and mechanical properties, using a pullout test and scanning electron microscopy.