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## Review

# A fundamental review on composite materials and some of their applications in biomedical engineering

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#### ABSTRACT

Composites or composite materials are engineered materials that consist of two or more constituent materials with wide discrepancies in their physical, chemical, and mechanical properties. The characteristic properties of these composite are as a result of the individual properties of their constituent parts and their respective volume fractions and arrangements in the material system. Depending on the intended application, composites can be designed to satisfy specific geometrical, structural, mechanical, chemical, and sometimes aesthetic requirements. Areas of application of these synthetic materials includes construction such as in buildings and bridges, automotive industry such as in car bodies, aeronautic, naval (e.g., ships and boats), and in the biomedical fields. Although metallic, polymeric and ceramic biomaterials have been in use for medical treatments such as tissue repairs and replacements for decades, composites are just coming to light. Therefore, the main purpose of this paper is to introduce composite materials and discuss their current and potential use in the biomedical field. © 2020 The Author. Production and hosting by Elsevier B.V. on behalf of King Saud University. This is an

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# 1. Introduction

The fabrication and the use of composite materials by the human race dates back to over 6000 years ago when the first recorded composite, wattle and daub, were used as building materials for wall construction Shaffer (1993). In recent century, this

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construction material has since been replaced by another composite, concrete, which is composed of cement and reinforcements such as gravel (aggregates) commonly known as loose stones, and the production capacity per annum has been reported to be in millions of tons worldwide. Some of the mechanical properties of concrete are high compression strength and low tensile strength Bazant and Murphy (1995); Shaffer (1993). Steel reinforcements are usually incorporated during concrete casting to enhance its tensile strength and consequently prevents it from failure under tensile loading Park and Paulay (1975). Another widely known composite is the Fiber-Reinforced Composite (FRP).

The two common types of FRP are the Carbon Fiber-Reinforced Composite (CFRC) and Glass Reinforced Plastic (GRP). Just as the names imply, the fiber materials (or inclusion) used in the fabrication of the CFRC and GRP are carbon and glass, respectively, and epoxy resin which is a thermoplastic, is often a general choice of matrix, also known as a binder. Other types of composites include composite wood which are primarily thin layers or "plies" of wooden boards glued together, Ceramic Matrix Composite (CMC), metal matrix composite (MMC), Polymer Matrix Composite (PMC) and the materials known as advanced composites (ACM). The inclusions used in CMC, MMC, and PMC are ceramic, metallic and polymeric materials, respectively, and these composites are collectively known as conventional composites. The ACMs have higher strengths, stiffness and modulus of elasticity and lower densities than the conventional composites due to the use high strength low density fibers in their fabrication. These materials are also characterized by their ease of manufacture, chemical, temperature and creep resistance. Fig. 1 shows the classification of materials using the Venn diagram.

In general, composite materials find applications in different areas of the human society such as in construction industry (e.g., buildings and bridges), automotive industry (e.g., automobile parts such as car bodies), aeronautics where materials with a property combination of high strength and low density is required, manufacture of housing and industrial parts such as storage tanks, bathtubs, washing sinks, and shower stalls, and in medical field as biomaterials for tissue repairs and replacements Al-Salloum and Almusallam (2003); Khan et al. (2017); Punyamurthy et al. (2017).

Biomaterials engineering which is a multidisciplinary field that seeks to use engineered materials (biomaterials) for medical therapeutic and/or diagnostic purposes Enderle and Bronzino (2012). This materials science and engineering entity work hand-in-hand with biomedical engineering which is another multidisciplinary field that applies concepts of engineering principles and design standards to medical biology for the purpose of advancing human health Enderle and Bronzino (2012). Both areas rely on the knowledge of the human anatomy and physiology in order to come up



Fig. 1. Classification of materials using the Venn diagram.

with biomaterial designs that when manufactured and integrated into the human body, either to facilitate tissue repair/healing or as a complete tissue replacement, would provide the intended functions without harming their immediate surrounding tissues or the whole body system Williams (2008). Biomaterials are tailored to suit their intended applications, which is the reason behind their classifications. Composite biomaterials which is one of such classifications is among the most widely used, both in vitro and in vivo, because of their high figure of merit. These multiphase materials can be easily manufactured to have unusual combination of properties and shapes Durowaye et al. (2019); Edoziuno et al. (2020). Specific material properties can be manufactured with high accuracy with the simplest of manipulations of such parameters as the constituents' volume ratios, fiber particle size, geometry, orientation and distribution, matrix type, and so on. As a result, composite materials have design flexibility and can easily be tailored to have almost any desired property combinations, unlike the metallic, polymeric, and ceramic biomaterials. The aim of this paper is to introduce the composite biomaterials, discuss their functions as repair and replacement parts, and the recent trends in their applications. The advantages over other biomaterials such as metallic, polymeric, and ceramics are also reviewed.

#### 2. Classifications and properties of composites

Surprisingly, the future of technological advancement, in general, are dependent on composite materials Chawla (2012). These materials have unique advantages over other material types (metals, alloys, ceramics, and polymers) such as the ability to be manufactured to have predetermined physical, chemical, mechanical and thermal properties and characteristics. For instance, the aerospace industry is constantly looking for lightweight materials with properties that can only be found in heavy materials such as high mechanical strength and stiffness, abrasion and wear resistant and so on. These aerodynamic materials are also expected to be inert of corrosion attack, withstand high temperatures and easy to manufacture. Composite materials have been used, is still in use, and will continue to be used to satisfy the material demand of such industries, at least until a more sustainable alternative is invented or discovered. Fig. 2(a) shows the comparison between single phase monolithic materials with composite materials, while Fig. 2(b) shows the comparison between ceramics, polymers and composites.

The final properties of a manufactured composite material are dependent on the individual properties of the constituents and their relative amounts, geometry and distribution. The relative amounts of the constituent phases or materials can be expressed as mass fractions or volume fractions, however, the latter is predominantly used by material engineers. Most composite materials are composed to just two constituents; a matrix, which is usually a material with relatively high ductility and low fracture strength that surrounds the other constituent, often known as the inclusion or the dispersed phase. The final properties of the composite materials strongly depends on the geometry and distribution of the latter phase. The geometry of the dispersed phase refers their shapes and sizes while the distribution encompasses their positions and orientations in the matrix. The schematic representations of these geometrical and spatial characteristics of the particles of the inclusion in a matrix can be found in Fig. 3.

#### 2.1. Classifications of composite materials

Over the years, different authors have come up with different classifications of composite materials. These classifications can be



Fig. 2. Comparison between (a) pure metals and composite materials Chawla (2012) (b) ceramics, polymers and composites.



Fig. 3. Schematic descriptions of the various geometrical and spatial configurations of the particles of the inclusion of composites: (a) concentration (b) size (c) shape (d) distribution (e) orientation (Callister, 2007).

collectively lumped into three categories (see Fig. 4): particlereinforced composites which make use of inclusions that have uniform axes, fiber-reinforced composites which utilizes fiber-like inclusions, and structural composites which is a combination of composites and homogenous materials (Callister and Rethwisch, 2007). Therefore, the major difference between the first two groups is the dispersed phase particle geometry. The particles in the particle-type are usually spherical in shape while those of the fiber-type have irregular geometries, but with higher length-to-diameter ratios, just as natural fibers.



Both the particle- and fiber-reinforced composites can be grouped according to the type of matrix used. The three major groups are metal matrix composites, polymer matrix composites and ceramic matrix composites.

#### 2.1.1. Particle-reinforced composites

For the particle-reinforced composites, short particulates are used as reinforcements, and based on the average size of these reinforcements this composite type can be classified as either large particle or dispersion-strengthened composites (see Fig. 5). In the former, the large particles, which are millimeter sizes or more, are the major load bearers and tend to restrain the matrix deformation around their shared surfaces. These restrictions is the main strengthening mechanism in large particle composites. Dispersionstrengthening composites, on other hand, make use of nanometer size particles, and unlike the large-particle composites the matrix bears the major chunk of the load when subjected to a mechanical stress. The strengthening mechanism in this case happens in the atomic level and it involves the obstruction of the propagation of dislocation lines along the matrix by the dispersed particles.

The range of values of the mechanical properties of a composite such as modulus of elasticity can be found by employing a fundamental principle known as the rule of mixtures. This rule states that the mechanical property of a composite material falls between the estimated theoretical lower and the upper bounds of the mechanical property in question. This estimate is calculated using the individual mechanical properties of the composite's constituent materials and their volume fractions. The assumption that the property of a composite is the weighted average of the properties of its constituent parts on a volume basis.

$$E = E_m V_m + E_i V_i \quad (\text{Upper bound}) \tag{1}$$

$$E = \frac{E_m E_i}{E_m V_i + E_i V_m} \quad \text{(Lower bound)}$$
(2)

where E and V denote the modulus of elasticity and volume fraction respectively. The sub-scripts m and i represent matrix and inclusion or particulate phases, respectively. Since the size, shape, and distribution of inclusions as well as their interfacial adhesion with the surrounding matrix play a huge role in the mechanical properties of a composite, the margins of deviation of the rule of mixtures are huge Ahmed and Jones (1990). This limitation has led to the development of different theoretical and experimental models for



**Fig. 6.** Theoretical models of the modulus of elasticity of composites. Curves 3, 5 and 4, 6 are the approximate lower and upper bounds, respectively, of the models developed by different authors Ahmed and Jones (1990).

predicting the mechanical properties of particulate-filled composites Ahmed and Jones, 1990; Ishai and Cohen, 1967; Paul, 1959; Hashin, n.d., Fig. 6 shows different theoretical models, including the lower and upper bound derived from the law of mixtures.

Experimental results usually vary with the theoretical models due to the limitations of the manufacturing processes.

#### 2.1.2. Fiber-reinforced composites

This is the most widely known, fabricated and used type of composite material system. The sys-tem is put together by surrounding fibrous materials with high mechanical properties such as strength and modulus of elasticity, with a matrix, such as a metal, polymer or ceramic. The resulting strength and stiffness of a composite depends, not only on the individual properties of the constituent materials, but on a dimensionless quantity known as the length to diameter ratio, of the fibrous phase Fu and Lauke (1996). Depending on this ratio and the fiber orientations, fiber-reinforced composites has been classified into three main groups: continuous or long and aligned, discontinuous or short and aligned, and discontinuous and randomly oriented (see Fig. 7).

As mentioned earlier, the fiber length-to-diameter ratio is one of the critical factor that determines the final strength and stiffness of the resulting composite. The minimum length required for effective strengthening and stiffening of composites is known as the critical length, and this quantity has been found to be strongly related to the ultimate tensile strength of the fibrous material  $\sigma_f$ and the degree of bonding between the fiber and the matrix  $\tau_c$  as well as the diameter of the fiber as given in Eq. (3).



Fig. 5. Types of particle reinforced composites (a) Large particle (b) Dispersion – strengthened.



Fig. 7. Schematic diagram of fiber reinforced composites (a) continuous and aligned (b) discontinuous and aligned (c) discontinuous and randomly oriented.



**Fig. 8.** Schematic diagram of the stress-strain curve of a continuous aligned fiberreinforced composite subjected to a longitudinal load. The stress-strain curves for a brittle fiber and a ductile matrix is also shown.

$$l_c = \frac{\sigma_f^* d}{2\tau_c} \tag{3}$$

where  $l_c$  is the critical fiber length and d is the fiber diameter. Experimental studies have shown that for continuous fiber type composites, this critical value is less than the actual fiber lengths and that the reverse is the case for discontinuous fiber types (Callister and Rethwisch, 2007; Fu and Lauke (1996); Petersen (2005); Takagi and Ichihara (2004).

In terms of the behavior of composites under tensile load, the stress-strain relationship is dependent on the direction of the load relative to the longitudinal axis of the fiber. This is only the case for a continuous and aligned fiber composites. Discontinuous and randomly oriented fiber type behaves differently. The stress strain diagram for fiber, matrix and composite is shown in Fig. 8. The failure strength (stiffness) of the fiber material is usually many order of magnitude higher than that if the matrix. However, the matrix has higher ductility and therefore higher failure strain than the fiber. Because of these, the failure strength and strain of fiber-reinforced composites are located between those of their respective fibers and matrices.

#### 2.1.3. Structural composites

Just as the name implies, a structural composite is a system of composites carefully arranged and held together with a homogenous adhesive material Chawla (2012). The final properties, especially the mechanical and structural integrity of a structural composite, depends on the properties of the individual compositions of each of the constituents as well as on the geometrical designs such as shape and size of the bulker structural elements Tsai (2018). Two main types of structural composites exist: laminar composites and sandwich panels (see Fig. 9). A laminar composite is made from two dimensional sheets with different preferred high strength directions stalked and laminated by an adhesive. The term 'two dimensional' is used because the large surface cross-sectional area to thickness ratios of the individual sheets. These sheets are often continuous and aligned fiberreinforced composites. Unlike the laminar composites, sandwich panels are made of a high strength exterior and a relatively soft core. A laminating agent is used to hold the two parts together. The outer sheets are made of materials with high strength and stiffness such as laminar composites (e.g., plywood), metals (e.g., steel and titanium) and fiber-reinforced plastics (Callister and Rethwisch, 2007). Wood, honeycomb, and thermosets (e.g., epoxy and phenolic), on the other hand, are the preferred materials for the core (Callister and Rethwisch, 2007).

A well-designed sandwich panel should be able to withstand both compressive, tensile and shear stresses without failure. High temperature resistant adhesives are often employed to prevent delamination in high temperature applications.

#### 2.2. Properties of composite materials

As previously mentioned, composites with different property combinations exit due to the unique flexibility in their design and manufacture. Therefore, unlike traditional materials such as steel, there are no fixed values for the properties of composites. However, one characteristic property that is common with most composites is low weight-to-strength ratio. This attribute is the reason for their wide applications in biomedical, automobile and aerospace industries. In general, composites are designed to have a predetermined specific load-bearing capacity and other performance characteristics superior to other materials. Such properties include:

- High corrosion resistance
- High fatigue resistance
- High impact strength
- Low weight-to-strength ratio
- Low thermal and electrical conductivity
- High wear resistance
- Creep resistant

#### 3. Composite biomaterials and their applications

These are composite materials used in the medical field. Their application in the medical field ranges from handling biologicals to diagnoses and treatment of different diseases and injuries. When properly designed, composite biomaterials can be used to as direct substitutes or integral functions of organs that had been damaged by traumatic or pathological incidents Salernitano and Migliaresi (2003). The possibility of manufacturing composite biomaterials to have precise predetermined specific physical, chemical and mechanical properties for peculiar applications is one of the major reason they are currently the most widely used in the medical field. Other types of biomaterials, both natural and artifi-



Fig. 9. Schematic diagrams of the structural composites (a) laminar composite (b) sandwich panel.

cial, have been used for decades but composites have revolutionized the biomedical engineering field. The continued improvement of these materials and the breakthrough in the invention of other sophisticated medical devices have seen an increase in accident and disease survival rates, quality of life and life expectancy Salernitano and Migliaresi (2003). Like the composites materials that find applications in other field such as in construction and manufacturing, composite biomaterials are characterized based on their constituent parts: particle-reinforced, fiber reinforced and structural type composite biomate-rial. Again, a typical composite biomaterial usually exhibit performance properties that are different from those of its constituent parts (matrix and inclusions). The various constituent parts of composite biomaterials is shown in Fig. 10.

#### 3.1. Cardiovascular applications

The cardiovascular system commonly known as the circulatory system is one of the main control systems in a human body. This physiological system which is composed of the heart, the blood vessels, and the blood ensures that nutrients are transported to various organs located throughout the entire body system. Metabolic wastes are also removed simultaneously as the heart pumps and the blood vessels circulates the blood. Surgical treatments are often required to take care of congenital or acquired diseases of the heart such as the coronary artery disease (CAD) and arrhythmias (Fig. 11(d)). Physical injuries to the cardio system also required the surgical repair or replacement of some parts. The stent and the pacemaker are two popular biomaterials used in cardio related treatments. Stents are biomaterials used to open up or prevent disease-induced constrictions such as thrombosis (blood clot) in

flow channels such as in the heart, peripheral arteries, veins, throat, and digestive systems Serruys et al. (2006), a surgical procedure known as angioplasty (Fig. 11(b) and (c)). These materials are also used temporarily during surgical operations to keep such channels open. The commonly used materials for stents are stainless steel and other alloys of iron, titanium and its alloys, magnesium alloys, cobalt alloys, and plastics, however, composite biomaterials such as metal and polymer matrix composites are beginning to serve as better alternatives Serruys et al. (2006). This is because of the flexibility composites brings in stent designs as well as their low cost, biodegradability, and manufacturability. Modern composite stents have the short-term structural integrity to support channel vessels and the ability to be fully absorbed by the surrounding tissues on the long term Erne et al. (2006). These materials also have reduced vascular tissue irritation because their biocompatibility is achieved through design that is based on the knowledge of the interaction between the surface of the stent material and the surrounding biological tissues.

The pacemaker, arguably, is one of the most important heart support systems ever to be invented by the biomedical engineers. This lightweight electrochemical system is used to maintain the proper pumping and circulation of the blood in the heart by monitoring and controlling the heart rhythms. Fig. 12 shows the electrical system and signal of a normal human heart. The four main parts of the pacemaker are the connector block, lithium ion battery, lead, and the case. The case houses pulse generator which houses the battery and the connector block and is surgically place above the top layers of the skin located below the collarbone (Fig. 12(b)). The conductive tip of the lead is placed in the appropriate chamber of the heart and then connected to the connecting block through the subclavian vein. Before now, alloys such as platinum alloy were



Fig. 10. Constituents of composite biomaterials.

the main component parts of the pacemaker, nowadays, composites are beginning to serve as more sustainable alternatives. For instance, composites have replaced the metal case of pacemakers because of their light weight. The former is also more corrosion resistant than the latter, and this has reduced the number of reported pacemaker related skin reaction cases.

#### 3.2. Dental applications

In order to swallow food, the human teeth, which are classified as incisors, canines, premolars and molars, have to cut and crush the food into smaller particles. The incisors which are the eight middle teeth are responsible for cutting, the canines which are the four pointed-shaped teeth adjacent to the incisors are responsible for tearing, while the premolars and molars are responsible for crushing. The human dental systems is also important in speech or sound making. Like every other part of the human body, the dental system can be defective or damaged due to birth defects, diseases or injury. The results of genetic mutations include missing dentition and abnormal tooth growth. Plague and caries (cavities), also known as tooth decay, are the most common diseases of the teeth. The former is an accumulated biofilm that is totally made of bacteria. These bacteria populate and spread by feeding on food particles that are left in and around the teeth, and in the absence of oxygen they produce lactic acid which depletes the phosphorous and calcium in the enamel, making them susceptible to infections. Phosphorus and calcium are important tooth minerals, and continuous depletion can lead to complete tooth destruction. Caries or cavities, on the other hand, are diet related and are currently prevalent in children. Dental injuries from physical accidents can cause permanent physical dental damage or increase the chances of teeth infestation. In recent years, the number of accidents and violence have increased in the last century, consequently increasing the number of head injuries that often times affect the dental system. Since the enamel and dentine are composed of calcium phosphates and collagen, composite biomaterials such as polymer matrix composites are currently used to fill up cavities, to restore fractured teeth and for dental implants for teeth replacement or aesthetic purposes Salernitano and Migliaresi (2003). These materials are more biocompatible than the traditional dental metallic biomaterials such as silver amalgam. Silver-mercury amalgam filling have very high toxicity and acrylic resins possess low mechanical strength and stiffness for use as artificial posterior teeth. Fig. 13(a) shows the natural tooth and an artificial implant. To replace a fractured or missing tooth, the flap is raised, exposing the bone. A hole is made in the bone and a screw is fastened in the hole. The abutment, which contains the artificial tooth, is then fastened to the screw. Fig. 13(b) and (c) also shows the before and after the use of composite tooth filling. Detailed procedure for tooth replacement surgery is beyond the scope of this work but can be found in the literature.

Some dental prostheses are used in vivo (fixed bridges) while some are removable. Removable dental prostheses require intermittent use due to long-term discomfort to the patient. These materials are usually made of high corrosion resistant glass reinforced polycarbonates. Fixed bridges are manufactured mainly



Fig. 11. (a) Fully dilated absorbable stent Erne et al. (2006) (b) angioplasty (c) stent placement (d) comparison between the normal heart and the heart with CAD (https:// www.hopkinsmedicine.org/healthlibrary/test\_procedures/cardiovascular/angioplasty\_and\_stent\_placement\_for\_the\_heart\_92, p07981).



Fig. 12. (a) The electrical system of the heart (b) the pacemaker (https://www.hopkinsmedicine.org/healthlibrary/c onditions/cardiovascular\_diseases/overview\_of\_pacemakers\_and\_implantable\_cardioverter\_defibrillators\_icds\_85, P00234).

from ultra-high molecular weight polyethylene. More recently, a methacrylic matrix reinforced with fiber and inorganic particles has been found to have better mechanical and aesthetic properties than the conventional polymer matrix composites used in dental applications. Titanium-hydroxyapatite is another dental material that has received wide attention. Hydroxyapatite is used as the lower part of the implant because of its bioactive compatibility with the surrounding tissues while titanium which has high mechanical strength is used as the upper part Salernitano and Migliaresi (2003).

## 3.3. Artificial cartilage

Cartilage is a soft and slightly flexible bone structure that can be found in the joints, the nose, the rib cage, and in the ear. Its main function in an adult is to connect bones together. The majority of the skeletal tissues of an infant is made of this material, which are then gradually converted into the more rigid bone tissues as they grow. When absent since birth or damaged due to developmental diseases or physical injury, the cartilage can be replaced by polymeric composites such as poly [2-hydroxyethyl methacry-



Fig. 13. (a) Natural tooth and dental implant (https://www.efp.org/patients/dental-implants.html) (b) before tooth filling (c) after tooth filling (http://www.sksmiledental.com/services-provided/tooth-coloured-fillings-composite/).

late] (PHEMA) reinforced with polyethylene terephthalate (PET) synthetic fibers. By varying the volume fractions of either constituents of this biomaterial, properties similar to the natural cartilage can be obtained Salernitano and Migliaresi (2003). Another composite biomaterial used in the replacement of cartilage is the HA coated ultra-high molecular weight polyethylene. This material is widely used in the replacement of articular cartilage, intervertebral fibrocartilage and menisci due to their long-term performance Shikinami and Kawarada (1998). Failures in the use of artificial cartilage are mainly due to wear and fatigue due to cyclic loading. Improvements are constantly been made to address these issues. For instance, injectable hydrogels, which are polymeric biomaterial, are sometimes incorporated with composite biomaterials to reduce wear and to accelerate healing.

#### 3.4. Artificial ligament

Ligaments are fibrous tissues that connect or hold bones and cartilages together. Anterior Cruciate Ligament (ACL) injuries are one of the common, especially among athletes. Polymeric and composite biomaterials are used for the repair or for the complete replacement of this tissue in order to restore the proper functioning of the diseases infested or injured joints. Just as in the case of artificial cartilage, failure in the artificial ligament is primarily due to wear and cyclic loading. Long term failures are due to the weak abrasive resistance of the inclusions. low flexural and torsional strengths and the inflammation of the synovial membrane Salernitano and Migliaresi (2003). A biodegradable composite biomaterial that is made from polylactic acid and hyaluronic acid ester is used as a prosthetic ligament. The low wear rate of this prosthesis allows the natural healing of damaged ligament tissue. Kazanci et al. (2002) studied the fatigue behavior of UHMWPE reinforced ethylene-butene copolymers under cyclic loading and found that copolymer type/angle combination can yield very high fatigue resistant composites for biomedical applications. This fatigue resistant composite has since been used as ligament prosthesis. PET reinforced PHEMA, which is used as cartilage prosthesis, is also used in this application as well although experimental study has shown that they instigate synovitis Salernitano and Migliaresi (2003). To overcome this problem, a terephthalate polyester fiber and collagen matrix based composite with high fracture strength has been developed Huguet et al. (1997). This material showed no abnormal reaction with the surrounding tissues when tested in vivo for about six months, although less success was obtained in terms of the growth and penetration of fibrous tissues between the prosthesis and the surrounding bones Huguet et al. (1997).

#### 3.5. Joint prostheses

A joint is simply a region in the human body where two or more bones meet. These joints bears weight, and also allow voluntary activities such as movements. There are over 300 joints in a typical human body, the majority of which are constantly used to carry out some activities. As a result, the joints are susceptible to physical injuries such as dislocation and fracture or diseases such as inflammation, also known as arthritis. Sometimes, a joint can be restored to its healthy condition with medications and processes and encourage its healing, other times, a complete joint replacement is required, especially in severe cases of arthritis or physical damage. Fig. 14 shows the schematic diagrams of a badly diseases infested knee joint and an artificial replacement (OrthoInfo., 2019). The prosthetic femur and tibia components are attached to the femur and tibia, respectively, by drilling through them, and inserting the stems and exposing the heads. These parts are put together to have the same degree of freedom as a natural knee.

The hip joint works almost the same way as the knee joint. When damaged, the hip joint can be completely replaced with artificial parts. These biomedical devices are usually made of a combinations of metals, polymers, ceramics and composites. The schematic diagrams of a natural functioning hip joint and an arti-



Fig. 14. Schematic diagram of (a) damaged knee joint (b) knee joint completely replaced with biomaterials (https:// www.orthoinfo.org/en/treatment/knee-replacement-implants/).



Fig. 15. The schematic diagram of the hip joint (a) normal hip joint (b) artificial hip joint showing the stem and cup embedded in the femur and the pelvis, respectively Tuan et al. (2016).



**Fig. 16.** 16: (a) X-ray image of damaged hip joint recuperating under screws and plate (http://www.rapidmade.com/rapidmade-blog/2015/1/9/if-the-3d-screw-fits-wear-it), (b) comparison of the bending properties of materials used in bone plates (http://uon.technologypublisher.com/technology/17632).

ficial hip joint are shown in Fig. 15. The stem that is attached to the ball is embedded in the femur while the acetabular cup/shell is implanted to the pelvis with the help of a fixation agent. The stem is usually made of alloyed metals or metallic composites because of their high strength, both tensile and compression. The ball is now being manufactured from composite metals because of their high wear resistance compared to ceramic biomaterials.

When a patient is suffering from a minor hip injury, bone plates, screws and wires are used to facilitate the healing process. These parts are usually made of metallic biomaterial and/or composite biomaterial. Fig. 16(a) shows the x-ray image of a hip joint stitched together with the help of screws and a bone plate. Bone plates, when implanted, are subjected to high tensile, compressive and bending stresses and as a result materials which can withstand



Fig. 17. The use of bone cement as fillings for fractured skull (https://honestversion.com/bone-cement-market-20 19-2025-global-share-outlook-forecast/).

such stresses are used in their fabrication. A comparison of the bending properties of composites, polymers and metals used as bone plates is shown in Fig. 16(b).

#### 3.6. Bone repair

Composites have been shown to be useful in repairing bone fractures. This is again due to the fact that their composition mimics the structure and properties of bones. This makes them highly compatible osteoconductive materials that can provide support for healing bones until they regain their strength. In addition to acting as a frame, the composites are biodegradable, meaning they are not required to be removed after serving their purpose. Composite materials can also be used to make internal fixation devices. In the past, they have been made from metals. While metal devices boast high levels of strength and durability, they come with the problem of corrosion and stiffness higher than that of bone which can lead to discomfort. Using polymer based composites tackles these issues. A carbon fiber based polymer can be used to create a device with elasticity more comparable to the actual bone while still retaining its high strength necessary to support the healing bone. Given the type of material, the risk of corrosion is removed. Additionally, it is possible to use a biodegradable matrix mixed with drugs designed to dissolve the device as the bone heals and release medicine at the same time to aid recovery.

Bone cement is a material designed to bond bones to joint prostheses and repair fractures. As the name implies, it is applied in a way similar to regular cement. That is to say, it is applied as a highly viscous wet paste at the point of contact between bone and prostheses. It is allowed to fill the porous areas and then cured to complete the bond (see Fig. 17). Once polymerized, it forms a strong bond between the two components. Fiberglass and polyester fabrics can be used in combination with a polyurethane matrix to create casts that far surpass those made of traditional means of cotton and plaster. These composite based casts are better stronger, repel water better and allow for clearer X-rays. The one con being they are harder to remove, though the pros in this case far exceed this con. In addition to this method, recently 3-D printed composite casts have begun to see implementation. These casts include the same benefits as other composite casts while also offering the comfort of better ventilation due to its web-like design. They also allow for more comfortable ergonomic aesthetically pleasing designs custom made for each individual patient. As the technology and speed of 3-D printing continue to advance, this application is sure to see more use and possibly become the industry standard.

External prosthetics are quickly finding a lot of success in new composite based designs. Previously used materials such as wood, metal, and leather have now been replaced in favor of composite materials. Composites offer the perfect mix of properties that previously mentioned materials could not meet alone. They are lightweight, durable, and have a longer life span.

#### 4. Conclusion

The unique thing about composite materials in general is the fact that they can be tailored to suit specific applications. The biomedical industry has taken advantage of this multicomponent material in the design and manufacture of biomaterials that can be used for the repair or the complete replacement of different human tissues or organs. Composite biomaterials have numerous advantages over the traditional metallic and polymeric biomaterials in terms of their physical, mechanical and chemical properties. With advances in innovative technology, new composite materials such as the advanced composites are currently being looked into, and this has the potential to revolutionize the world of biomaterial science and engineering.

#### **Declaration of Competing Interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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