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Development and Analysis of Biomaterial Based on Calcium Sulfate Hemihydrate and Epoxy Resin

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Abstract

Bone deformation and the degradation of the joint are one of the most common problems faced around the world, especially after the age of 50. Materials like Allograft and Polymethyl-Methacrylate (PMMA) are used in traditional orthotics and prosthetics, and for bone grafting/filling procedures, however, these materials can be expensive. This research proposes, the fabrication of a novel material by utilizing Calcium-Sulfate Hemihydrate ($CaSO_4.\ 1/2H_2O$*), and epoxy resin, which can be used as a cost-effective orthotic and prosthetic material. The materials are already used as bone adhesives and bone grafts, hence, are compatible and non-toxic. The fabricated composite material possesses physical properties closest to the natural human bone and is also hydrophilic. Samples with different ratios of the constituents were fabricated and tested for their hardness, compression, and contact angle values using a Hardness tester, PASCO compression tester, and Image J software. The hardness test results indicate that sample 1 has the hardness value i.e.,* 29.5 ± 2.50 *HV in contrast the hardness value of a human bone is found to be* $33.3\ HV \pm 5.17$*, and values for the Young modulus are also within the range of human's Trabecular bone values. Moreover, all fabricated samples are also found to be hydrophilic having a contact angle of less than* $90°$*. Further, in-vivo tests can be done to assess the biological and other physical properties of the sample to solidify the claim that it can be used as a substitute orthotic and prosthetic material.*

Index Terms: *Bone Deformation, Bone Grafting/Filling, Calcium-Sulfate Hemihydrate, Epoxy Resin, Orthotics/Prosthetics.*

I. INTRODUCTION

One of the most common problems worldwide is bone and joint degeneration which can result from various factors such as aging, injury, or disease. For people at the age of 50 and above, these problems account for half the number of all chronic diseases experienced by them [1]. The remedy for these disorders often requires surgery and also includes total replacement of the joint in the event of natural joint deterioration. Numerous other disorders are required to be resolved by using biodegradable implants for scoliosis, back pain, different kinds of bone fractures, muscular problems, osteoporosis etcetera. The first and second generations of biomaterials focused on the development of biocompatible materials that could be tolerated by the body without causing harm or rejection [2]. The third generation of biomaterials laid the foundation for combining two or more materials to advance biocompatibility and tissue-regenerative properties to help heal the body [2]. We have now entered the fourth generation of biomaterials that focuses on creating biomaterials that can interact with the human body on a cellular level. The fourth generation of biomaterials is still in the early stages of development, but they hold great promise for advancing the field of regenerative medicine and personalized medicine. Biomaterials used in orthopedics are used as constituents that are designed to perform some specific biological functions by either performing the function of substitution or assisting the existing bone, ligament, cartilage, etc. Orthotics is one such device that provides support to a particular bone/area and assists in healing, pain-relieving, and corrective process [3]. Prosthetics, on the other hand, are artificial parts or features that are attached to a living being to make up for a missing body part. They can be surgically or non-surgically secured in place [4]. Conventionally, prosthetics and orthotics have been created using materials like Allografts, Polymethyl-Methacrylate, etc., which are quite expensive [5]. In underdeveloped and developing countries, these materials have to be imported. This adds up the duty, import, and taxes, making the material further expensive. To overcome these problems, this paper discusses the fabrication and testing of different ratio compositions of $CaSO_4.\ 1/2H_2O$ and epoxy resin material used as an alternate for bone adhesives and grafting.

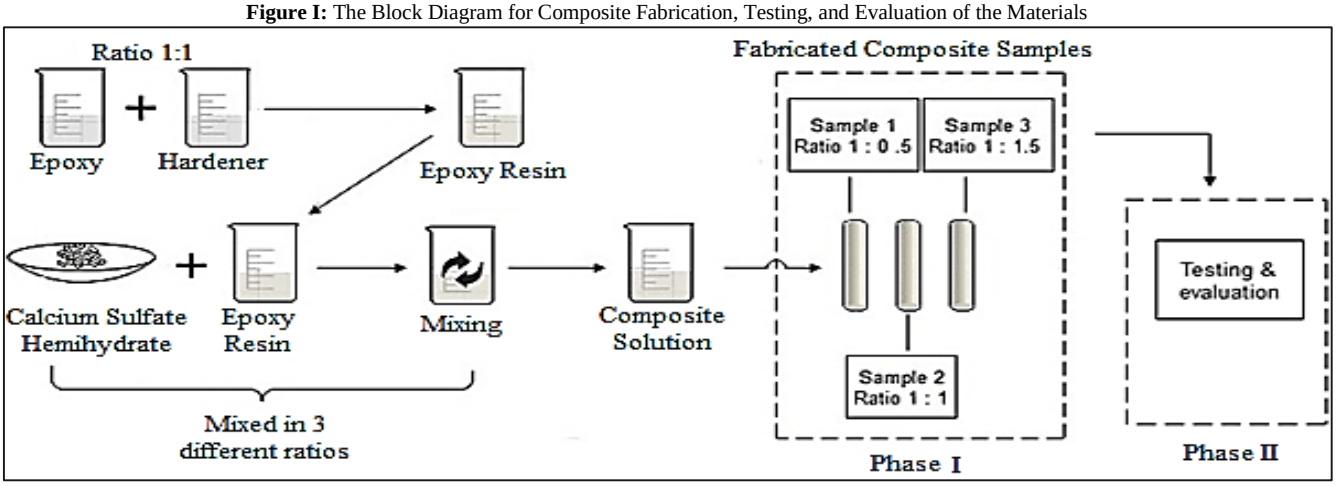
Bone grafting is one of the most commonly done orthopedic surgical procedures. This procedure repairs and rebuilds a damaged bone (either due to trauma, accident, or medical conditions such as osteoarthritis) using an artificial bone piece [5]. Approximately 2.2 million bone grafting procedures take place globally in a year [6]. Artificial bone is a material identical to the real bone that expresses properties similar to the bone being replaced. The material used is site-specific i.e., depends on the replacement site as the material chosen needs to have certain chemical and physical properties. While designing the orthotic or prosthetic, it is imperative to consider the

material's biocompatibility, density, stress-bearing ability, tensile strength, Young's modulus, etc.

There is a vast history of CaSO4. 1/2H2O being used as a bone filling and grafting material in dentistry [7] and implants due to its bio-inert properties [8]. CaSO4. 1/2H2O has been proven to be a strong building material as it has been used in construction for at least five thousand years. The first to report a study of 'Plaster of Paris' as an implantable material as a bone filling was Dreesman. Ever since the success of Dreesman there have been several groups that have researched and studied many different bioactive and bio-inert ceramics for bone filling as well as repair which include Calcium Silicate Hydrate (CSH), CSH-HA, CSH-polymers and many more [9].

In prior research it was deduced through clinical trials that reinforced carbon fiber and epoxy resin were potential substitutes for fracture fixation [10]. Epoxy resin belongs to a class of polymers that contain high adhesiveness to various substrates, have good heat and chemical resistance, and also contain excellent mechanical properties [11], and [12]. In addition, epoxy resin's shrinkage property is negligible which makes it an excellent material for the anatomical detail of prosthetics [13]. This paper aims to combine the separately used epoxy resin and CaSO4. 1/2H2O, as a composite, and to deduce its use as a prosthetic and orthotic material by comparing the properties of the fabricated composite to those of real bone.

Figure I: The Block Diagram for Composite Fabrication, Testing, and Evaluation of the Materials



II. METHODOLOGY

The following methodology was conducted in the Biomedical Engineering Department, Salim Habib University in 2022-23.

The methodology for this research is divided into two parts mainly:

1. Fabrication Phase: The Fabrication of the Samples of Different Ratios,
2. Testing Phase: Material Hardness Test, Material Compression Test, and Material Contact Angle Test.

A. Fabrication Phase

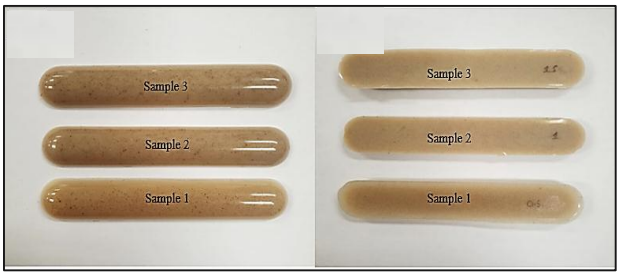
The constituents needed to fabricate the material included epoxy resin, hardener (4,4'-diaminodiphenyl sulfone), and CaSO4. 1/2H2O. The block diagram in figure I shows the process of fabrication of the composite. The exact amount of the constituents was collected and mixed using a beaker and weight balance. A plastic container was used to mix these with the help of a spatula. Epoxy resin and hardener were mixed using a wooden stirrer to mix them well and avoid lumps. While working with epoxy resin, rubber gloves were used to avoid contact with the skin.

The constituents were mixed in different proportions, i.e., the same quantity of epoxy resin but different quantities of CaSO4. 1/2H2O, to be able to carry out a comparative study. Each of the mixtures was poured into a mold and allowed to be set for 24 hours in a cool and dry place.

The material was extracted from the mold after 24 hours. Figure II shows the end product of the fabrication (the top and bottom view of the samples). Each of the samples was marked as 0.5, 1, and 1.5, based on the ratio of epoxy resin to CaSO4. 1/2H2O, as given in table I. The lowermost sample in figure II (a) and figure II 2(b) are of the three samples created i.e., Sample 1 (ratio 1: 0.5), the middle one is Sample 2 (ratio 1:1), and the top most being Sample 3 (ratio 1:1.5).

Table I: Quantities for the Fabrication of Composite Samples

Sample No.	$CaSO_4 \cdot \frac{1}{2}H_2O$ (g)	Epoxy Resin (ml)	Hardener (ml)	Ratio (Epoxy Resin + Hardener: $CaSO_4 \cdot \frac{1}{2}H_2O$)
1.	2.3	2.3	2.3	1.0:0.5
2.	4.6	2.3	2.3	1.0:1.0
3.	6.9	2.3	2.3	1.0:1.5



(a) (b)

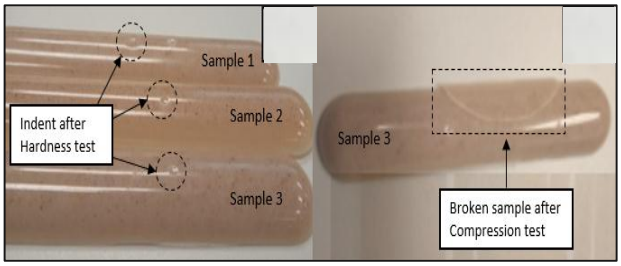
Figure II: View of Fabricated Materials; (a) Top View of the Fabricated Materials, (b) Bottom View of the Fabricated Materials

B. Testing Phase

Once the material was successfully fabricated; the material's strength was tested by performing 'Rockwell's Hardness Test' on the samples using the 'HBRV-187.5 Hardness Tester' as shown in figure III(a). The material was also tested for its compression bearing ability by performing compression testing on them by using 'PASCO's Compression Tester' [14] as represented in figure III(b). Figure IV displays the materials after the compression and hardness tests were performed on the samples. An indentation can be seen on all three samples in figure IV(a) due to the Rockwell Hardness Test. Figure IV(b) shows an evident breakage on Sample 3 after the compression test was carried out. Furthermore, contact angle test was performed to analyze the wettability of the samples.

(a) (b)

Figure III: Testing of Material's Properties using; (a) Rockwell's Hardness, (b) Compression Testing of Materials



(a) (b)

Figure IV: Material After Performing; (a) Hardness Test, (b) Compression Test

a) Material Hardness Test:

The Rockwell hardness test was performed on the fabricated specimens using HBRV 187.5 Hardness Tester. The initial test force of 98.07 N (10 Kg) is applied for 5 seconds. This is repeated for all the 3 samples and their values are noted down.

b) Material Compression Test:

The compression test is performed by placing the fabricated samples in the middle of the circular load anvil in the PASCO Universal Material Tester. The crank of the tester is then turned at a uniform speed until the force of 10N is reached. The compression curve is then observed and the gradient of the elastic region is determined.

c) Material Contact Angle Test:

Contact Angle Test was performed as hydrophilicity is important in bone filling as surface hydrophilicity increases the adhesion and proliferation of osteoblasts [15]. Bone cement and implant materials are designed in a way that mimics the inherent surface roughness, hydrophilicity, and, chemistry of native bone. Soft tissue attachment and cell adhesion are facilitated by hydrophilic surfaces [16]. The test was performed on the fabricated specimens using 'Image J software' via the Drop Shape Analysis plugin. Droplet images on samples were acquired using a digital camera. The images were then converted into binary for further analysis. The "Shape Descriptor" function was used to determine the droplet's shape parameters, including the contact angle.

III. RESULTS AND DISCUSSIONS

A. Material Hardness Testing

Table II represents the Rockwell Hardness for fabricated composites. It is quite visible from the results that as the CaSO4. 1/2H2O concentration is increased the hardness value is also increased.

Table II: Results for Rockwell's Hardness Testing

Sample No.	Scale	Indenter Type	Start Test Force (N)	Final Test Force (N)	Dwell Time (s)	Hardness Value
1.	HRC	Cone	10	60	5	27
	HRB	Ball	10	60	5	32
2.	HRC	Cone	10	60	5	61
	HRB	Ball	10	60	5	54
3.	HRC	Cone	10	60	5	78
	HRB	Ball	10	60	5	72

The hardness value of a real bone varies at the head from the range of 33.3 HV ± 5.17 to 43.82 HV ± 5.59 at the diaphysis. The shaft is recorded as the hardest part of the bone with a value of 48.11 ± 6.48 HV [14]. According to the results in table II, the hardness of Sample 1 was 29.5 ± 2.50 HV, Sample 2 was 57.5 ± 3.50 HV and Sample 3 was 75 ± 3.0 HV. Matching these with real hardness values of the radial bone, Sample 1 seems to be the closest.

In figure V, it can be seen that the value of sample 1, 29.5 ± 2.50 is the only sample that lies within the range of the hardness value of the real bone while the other samples do not. The dotted line in figure V, shows that the hardness value of Sample 1 lies within the range of that of real bone.

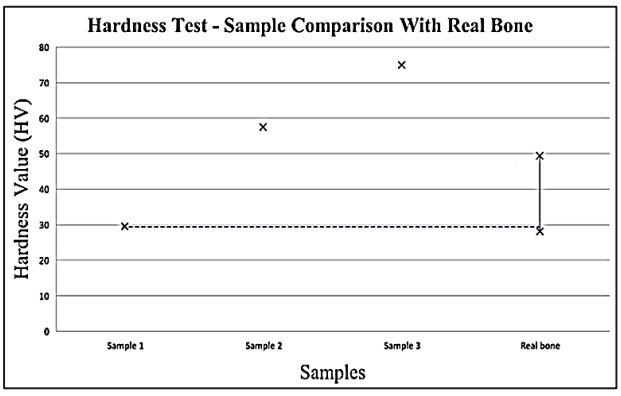


Figure V: Hardness Test Results Comparison with Real Bone Values

B. Material Compression Test

Table III shows the results for Young's Modulus for each of the samples. It is evident from the results that with the increase in CaSO4. 1/2H2O concentration, the

compressive strength or Young's Modulus of the specimens is decreased.

Table III: Results for Compression Testing

Sample No.	Force Applied (N)	Young's Modulus
1.	10	784
2.	10	621
3.	10	346

Human trabecular bone typically has Young's Modulus range between the values of 689-871 MPa, in a 55-year-old healthy male [16]. The results of all three samples' Young's Modulus is in table III, it can be observed that Sample 1 fall between the range of human trabecular bone's modulus i.e., (689-871 MPa), while the others do not.

Figure VI shows the Young's Modulus values of the samples fabricated, Sample 1 has a value (784 MPa) that lies between the range of the real bone (689-871 MPa), while the other two samples i.e., Sample 2 and Sample 3, do not have a Young's Modulus in the range of a real bone. The dotted line in figure VI, shows how Young's Modulus of Sample 1 lies within the range of that of real bone [16-18].

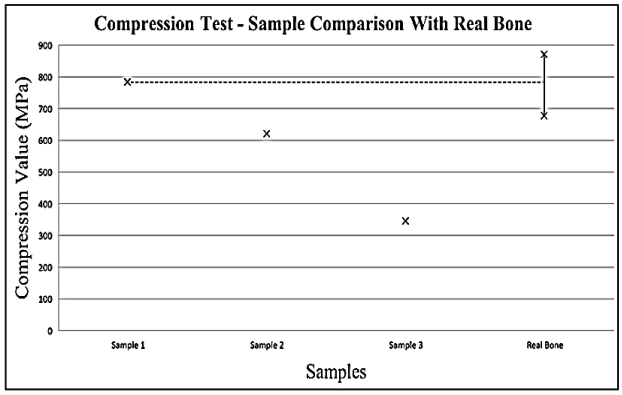


Figure VI: Compression Test Results Comparison with Real Bone Values

C. Material Contact Angle Test

Table IV represents the results for the contact angle test. Results obtained indicate that all three fabricated samples are hydrophilic having a contact angle less than 90°.

Table IV: Results for Contact Angle Test

Sample No.	Contact Angle
1.	43.1 ± 0.92°
2.	50.6 ± 2.4°
3.	51.1 ± 1.4°

Figure VII represents the analysis for contact angle measurement using 'Image J. Software' for each of the fabricated samples. The contact angle values for the Sample 1, Sample 2, and Sample 3 were 43.1±0.92°, 50.6±2.4°, and 51.1±1.4°, respectively. Results show that Sample 1 appears to be the most hydrophilic material. The results of this study suggest that our fabricated bone filling material is more hydrophilic than traditional PMMA-based bone filling material that has a contact angle value of 75.7±2.39° [19-22].

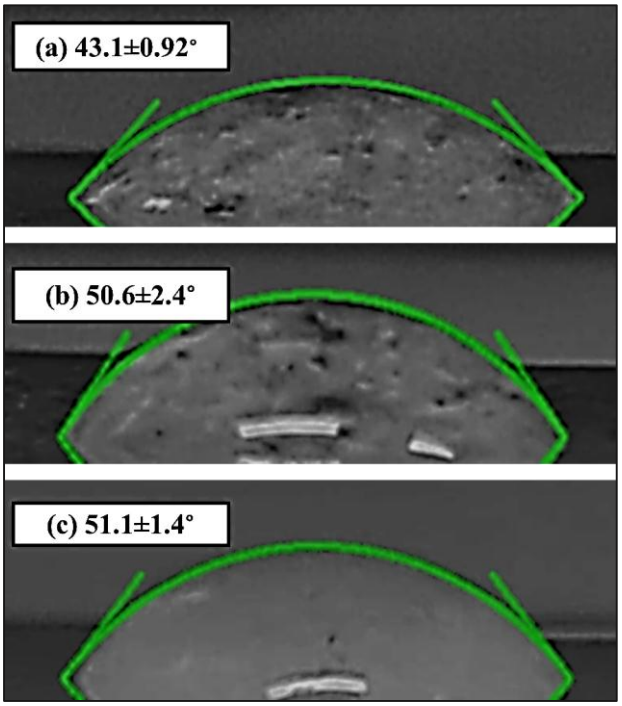


Figure VII: Contact Angle Image Analysis using Image J Software for; (a) Sample 1, (b) Sample 2, and (c) Sample 3

IV. CONCLUSION AND FUTURE WORKS

From the fabrication and testing carried out, it was successfully concluded that Sample 1 i.e., epoxy resin and hardener along with CaSO4. 1/2H2O (with a ratio of 1:0.5) is a good substitute to be used as bone cement or bone grafting material. The results from hardness and compression testing, on Sample 1, both proved to be similar to those of an original human bone value. Since epoxy resin is already in use as a bone adhesive, and CaSO4. 1/2H2O is being used for bone gap fillings, they impose a minimal threat to health as a biomaterial. Contact angle results suggest that the fabricated samples were more hydrophilic than PMMA, which is traditionally used as a bone-filling material. The obtained results indicate that, an increased concentration of CaSO4. 1/2H2O has a significant impact on the material properties, together these substances can be utilized as an efficient, cost-effective, and bio-inert material that mimics bone properties.

This work can be carried forward and more research can be done by comparing the properties of epoxy resin and CaSO4. 1/2H2O separately to see how they behave as a separate substance and together as a composite. Furthermore, fatigue testing can also be carried out on the samples to further strengthen the result of CaSO4. 1/2H2O and resin being suitable substitutes for PMMA as bone cement and grafting material.

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Authors Contributions

The contribution of the authors was as follows: Sadia Arshad's contribution to this study was the concept, technical implementation, and correspondence. The methodology to conduct this research work was proposed by Hafsa Aijaz. Data collection and supervision were performed by Muhammad Rizwan. Author Tooba Khan facilitated the data compilation and validation. Muhammad Zeeshan Ul Haque's contribution was project administration, and paper writing.

Conflict of Interest

The authors declare no conflict of interest and confirm that this work is original and not plagiarized from any other source, i.e., electronic or print media. The information obtained from all of the sources is properly recognized and cited below.

Data Availability Statement

The testing data is available in this paper.

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