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ORIGINAL ARTICLE

Fabrication and mechanical properties of newly developed triphasic blocks composed of gypsum-brushite-monetite for bone graft applications

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KEYWORDS

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Monetite;
Mechanical properties

Abstract *Objective:* A triphasic bone graft block composed of gypsum, brushite, and monetite is expected to be better for regenerating bone than a gypsum-hydroxyapatite-tricalcium phosphate block. Therefore, the aim of this study was to fabricate and evaluate the mechanical properties of a newly developed triphasic block composed of gypsum, brushite, and monetite.

Materials and method: Triphasic blocks were prepared by mixing calcium sulfate hemihydrate, brushite, and monetite powders with distilled water at a powder-to-liquid ratio of 0.5. The content of calcium sulfate hemihydrate was fixed at 50%, and the contents of brushite and monetite powders were varied. After molding and setting, the obtained blocks were characterized, and their mechanical properties were evaluated.

Results: The triphasic blocks were prepared and could maintain their shape without collapsing. The XRD characterization of the obtained triphasic blocks showed that only three phases existed in the block. Calcium sulfate hemihydrate was transformed into its dihydrate form and provided mechanical strength to the block through a setting mechanism. The transformation of calcium sulfate hemihydrate into its dihydrate crystals formed an interlocked structure that was disrupted in triphasic blocks, as observed in SEM images. The disruption of the interlocked structure resulted

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in lower mechanical strength of the obtained triphasic blocks compared to the set gypsum control. The variation in brushite and monetite composition did not affect the mechanical properties of the triphasic blocks.

Conclusion: The triphasic gypsum-brushite-monetite block was successfully prepared, and no other crystal phases were found. The triphasic blocks could maintain their shape after setting. The addition of brushite and monetite powders disrupted the interlocked structure of the set gypsum crystal, resulting in a decrease in mechanical strength. Furthermore, the variation in brushite and monetite powders did not affect the mechanical properties of the triphasic blocks.

1. Introduction

Gypsum blocks have been widely used clinically as bone grafts due to their biocompatibility (Barone et al., 2020; Mohammed et al., 2021). Gypsum blocks have also been used to carry antibiotics to treat bone infection through a local delivery system (Li et al., 2017). Despite its good clinical outcome, the main drawback of gypsum is its fast resorption, which may induce inflammation (Sargolzaie et al., 2018).

To overcome the rapid dissolution of gypsum blocks, biphasic gypsum-calcium phosphate was developed. Hydroxyapatite and β-tricalcium phosphate are among the calcium phosphate ceramics that are often used to prepare biphasic blocks (Chang et al., 2021; Leventis et al., 2014). The addition of hydroxyapatite or β-tricalcium phosphate produces block bone grafts with reduced dissolution and enhanced bone formation properties. Although showing better clinical results, the performance of biphasic calcium sulfate–calcium phosphate still needs to be improved, especially the ability to promote the formation of new bone. Therefore, triphasic gypsum-calcium phosphate was later developed (Hill et al., 2017). These triphasic blocks are usually composed of gypsum, hydroxyapatite and β-tricalcium phosphate (Harris et al., 2018; Trost et al., 2020). However, slow resorption of hydroxyapatite may hinder further bone regeneration (Ayukawa et al., 2015).

Recently, monetite has emerged as an ideal candidate for bone grafts due to its ability to balance resorption and bone formation (Zhou et al., 2021). Furthermore, the ability of monetite to promote new bone formation was close to that of autografts, which are the gold standard (Torres et al., 2015). In addition to monetite, brushite was also proven to be a good bone graft. Its ability to facilitate new bone formation has been largely studied. Therefore, triphasic blocks made of gypsum, brushite and monetite would be expected to be more favorable for bone regeneration than triphasic gypsum-hydroxyapatite-β-tricalcium phosphate. In this study, for the first time, triphasic gypsum-brushite-monetite blocks are fabricated. The mechanical strength and microstructure of the newly developed triphasic blocks are evaluated.

2. Materials and methods

2.1. Sample preparation

Calcium sulfate hemihydrate powder (Sigma Aldrich) was mixed with brushite powder (Sigma Aldrich) and monetite powder (Labochemie) according to the ratios given in Table 1. Distilled water was then added to the powder mixture at a liquid-to-powder ratio of 2:1. The mixture was blended to make a paste and placed in a cylindrical mold. There were two sizes of cylindrical molds used in this study, 4 mm × 8 mm and 6 mm × 3 mm, for compressive strength and diametral tensile strength (DTS) measurements, respectively. After molding, the paste was allowed to set at room temperature for twenty-four hours. The set block was removed from the mold and used for characterization and mechanical tests.

2.2. Material characterization

The gypsum-brushite-monetite block was crushed into powder and characterized using X-ray diffraction (XRD) (PANalytical). Cu-Kα radiation with a wavelength of 1.541 Ã... was used. XRD was performed at a voltage of 40 kV, a current of 30 mA, and a step size of 0.0167°. Phase identification was determined using HighScore Plus software. Scanning electron microscopy (SEM, Thermo Scientific Quanta 650) was used to evaluate the difference between the microstructure of triphasic blocks and the control set gypsum block.

2.3. Mechanical property measurements

Compressive strength and DTS measurements were performed using a Universal Testing Machine (Shimadzu AGX-S series) with a load cell and speed of 5000 N and 0.05 mm/minute, respectively. Compressive strength measurement was done by placing the specimen (4 mm in diameter and 8 mm in height) centrally between two bearing plates. The force was then applied (Fig. 1A). DTS measurement was performed by placing the specimen as illustrated in Fig. 1B. The force at which the sample started to break was recorded. The compressive strength and DTS were calculated based on Equations (1) and (2), respectively (Bresciani et al., 2004).

$$\sigma = \frac{F}{A} \quad (1)$$

Table 1 Composition of the gypsum-brushite-monetite block.

Sample name	$CaSO_4{\cdot}0.5H_2O$	Brushite	Monetite
Formula 1	5 gr	2.5 gr	2.5 gr
Formula 2	5 gr	1.25 gr	3.75 gr
Control	10 gr	0	0

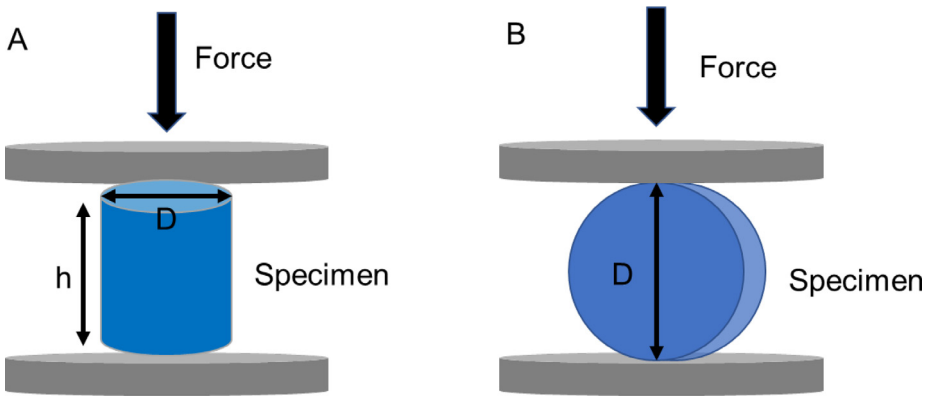

Fig. 1 Schematic of compressive strength (A) and DTS (B) measurements.

σ = Compressive strength
F = Force
A = Area (diametral plane)

$$DTS = \frac{2F}{\pi Dt} \quad (2)$$

DTS = Diametral tensile strength
F = Force
π = Phi (3.14)
D = Diameter
t = Thickness

2.4. Statistical analysis

Statistical analysis was performed for the compressive strength and DTS values. Three specimens were used for each group. The Shapiro-Wilk test followed by one-way ANOVA was performed for normality testing. A Bonferroni test was performed for post hoc, where a p value < 0.05 was considered statistically significant.

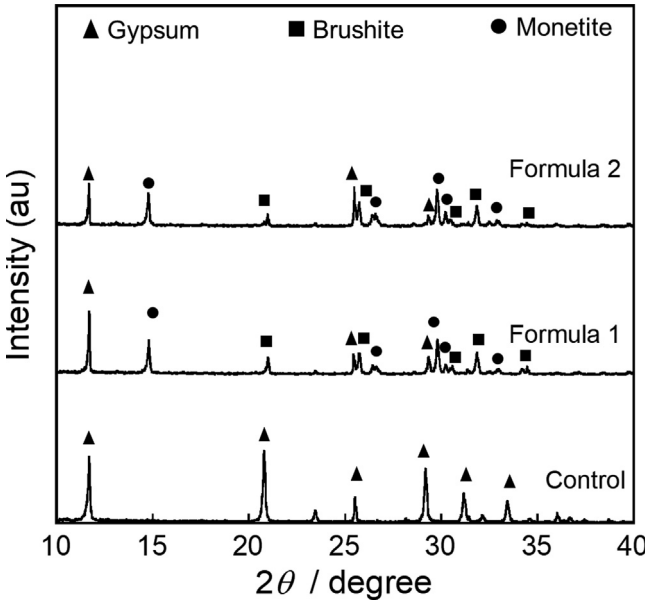

Fig. 3 XRD patterns of control gypsum and triphasic blocks.

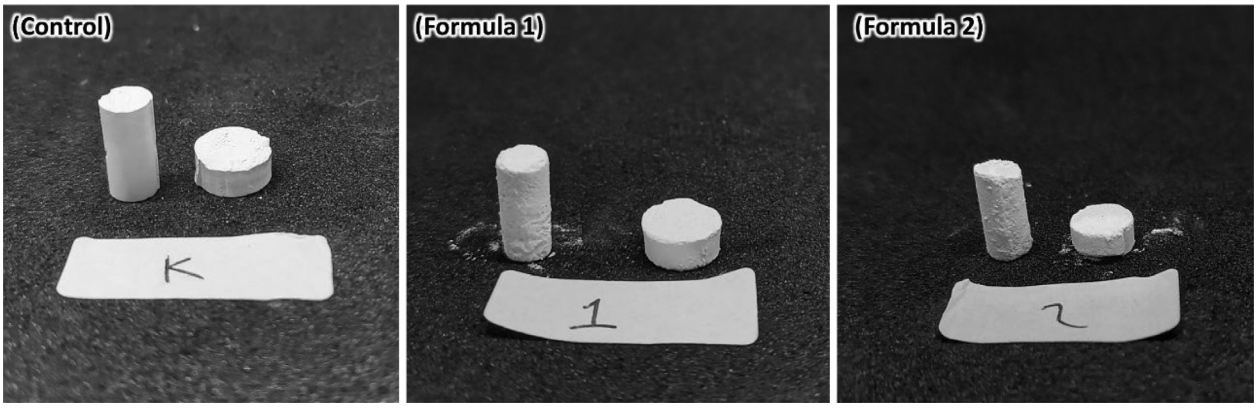

Fig. 2 Photograph of control gypsum and triphasic blocks with different sizes.

3. Results

Fig. 2 shows photographs of the set gypsum (control) and triphasic blocks of two different sizes in every case. After mixing and setting for 24 h, the triphasic block did not collapse and maintained its shape.

The XRD patterns that show the crystal phases of the blocks are presented in Fig. 3. All the formulas contain gypsum, brushite, and monetite. The control sample was a set gypsum block ($CaSO_4{\cdot}2H_2O$). Formulas 1 and 2 generated peaks at 2θ values of 11.7°, 23.4°, 25.5°, 29.2°, 31.2°, and 33.4° which belong to gypsum peaks (Crystallography Open Database (COD) reference code: 96–101-1075). In addition, peaks were also generated at 14.8°, 26.5°, 26.5°, 30.2°, 30.5°, and 32.9°, which belong to monetite (COD reference code: 96–900-7620), and 20.9°, 25.8°, 30.5°, 31.8°, and 34.2°, which belong to brushite (COD reference code: 96–900-7307).

The microstructure of the triphasic blocks and set gypsum control are presented in Fig. 4. Entangled needle-like gypsum crystals are observed in the set gypsum control block, forming interlocking structures (Fig. 4A and 4B). Interlocking structures were not observed in the triphasic blocks made with either Formula 1 or Formula 2 (Fig. 4C-4F).

The compressive strength of the triphasic blocks obtained from the two different formulations is shown in Fig. 5. The set gypsum block control has an average compressive strength value of 15.47 ± 0.76 MPa. Triphasic blocks have average compressive strengths of 0.20 ± 0.06 MPa and 0.67 ± 0.51 MPa for Formulas 1 and 2, respectively. The difference between the average compressive strength of the set gypsum

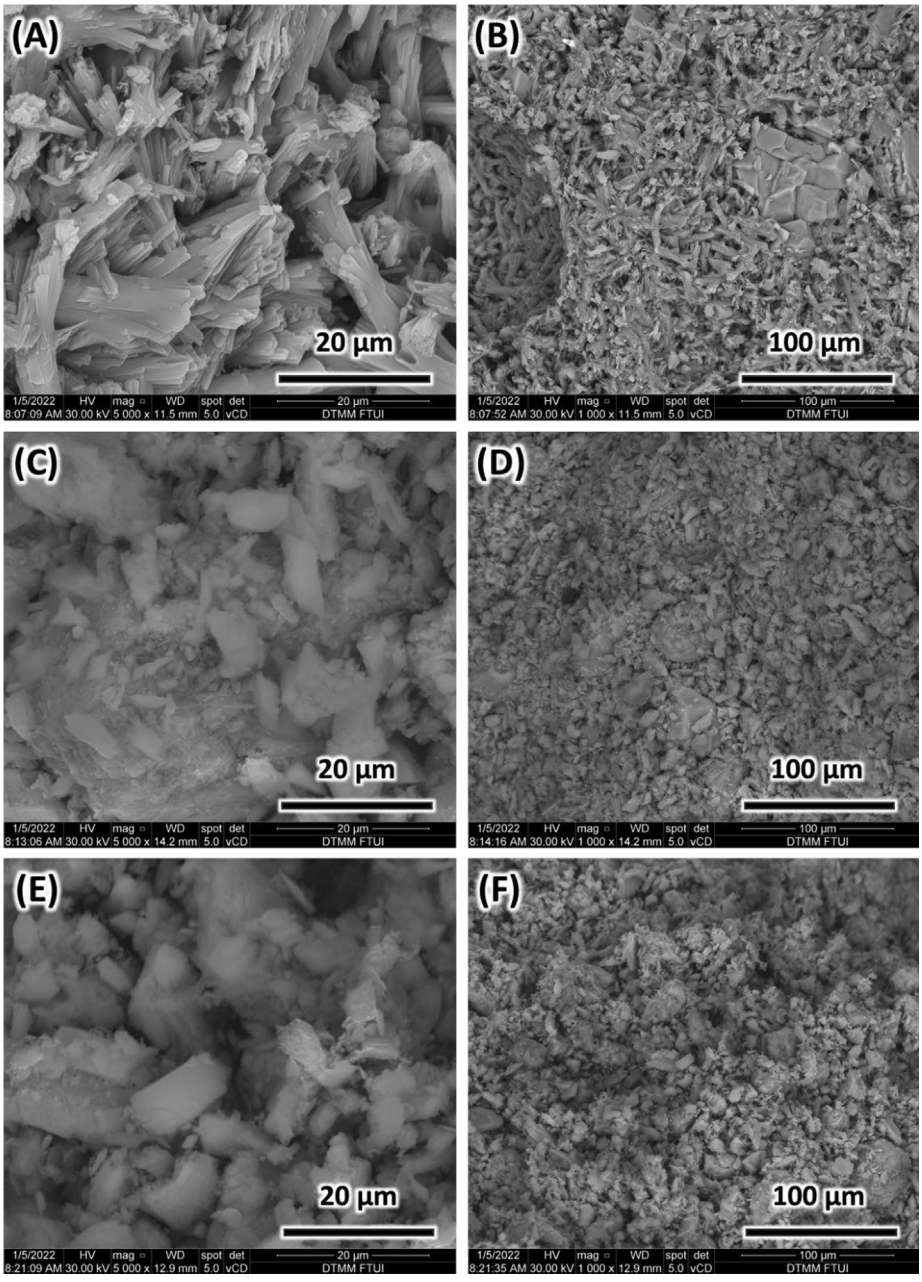

Fig. 4 SEM images of control gypsum (A and B) and triphasic blocks Formula 1 (C and D) and Formula 2 (E and F).

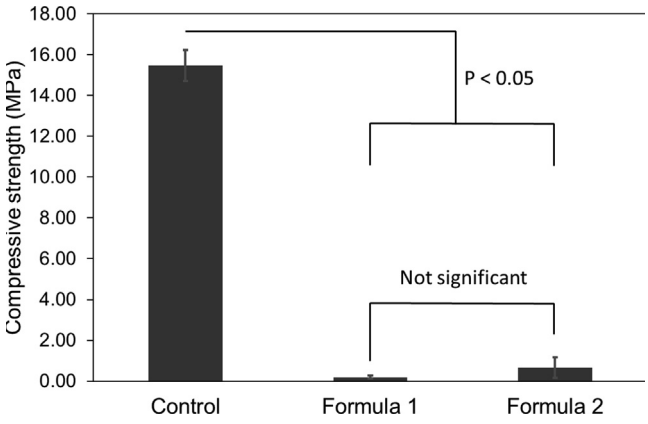

Fig. 5 Compressive strength of control gypsum and triphasic blocks.

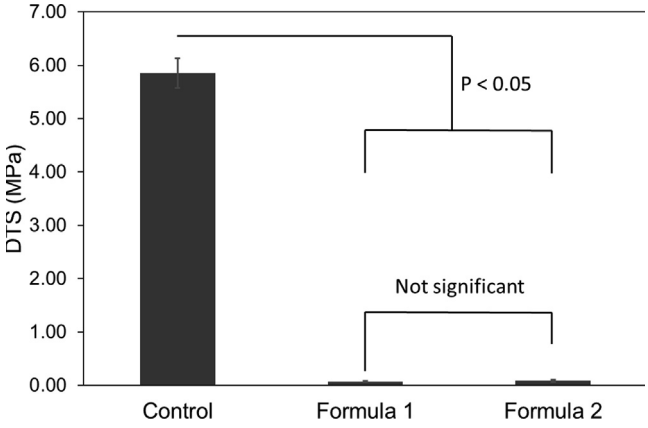

Fig. 6 DTS values of control gypsum and triphasic blocks.

block and every triphasic block is statistically significant ($p < 0.05$). Among the triphasic blocks, the differences in average compressive strength are not statistically significant.

The DTS values for the set gypsum and triphasic blocks are presented in Fig. 6. The average DTS value of set gypsum is 5.85 ± 0.28 MPa. For the triphasic blocks, the DTS values are 0.07 ± 0.01 MPa and 0.08 ± 0.02 MPa for Formulas 1 and 2, respectively. The DTS values of the set gypsum block and every triphasic block were significantly different ($p < 0.05$). Among triphasic blocks, the differences between average DTS values were not statistically significant.

4. Discussion

In this study, triphasic blocks composed of gypsum, brushite, and monetite were successfully fabricated using a simple method. The addition of brushite and monetite would be expected to decrease the solubility of gypsum blocks and promote new bone formation. It has been reported that monetite and brushite are 800- and 27-fold less soluble than gypsum, respectively (Sassoni, 2018). The mixture of calcium sulfate hemihydrate, monetite and brushite powder was blended with distilled water and hardened at room temperature to form a gypsum-brushite-monetite block. The reaction between calcium sulfate hemihydrate and water resulted in the formation of gypsum. The formation of the gypsum phase was confirmed in the XRD patterns generated from the obtained triphasic blocks (Fig. 3). The formation of gypsum and its setting mechanism provide mechanical strength to the gypsum-brushite-monetite blocks. Furthermore, no other setting mechanism occurred from either brushite or monetite during contact with water. This was confirmed from the XRD patterns, where no crystalline phases were detected other than gypsum, brushite and monetite. Therefore, the mechanical properties of gypsum-brushite-monetite blocks are solely provided by the setting mechanism of gypsum.

The mechanical strength of all triphasic blocks was significantly lower than that of the control gypsum block (Figs. 5 and 6). Both the compressive strength and DTS of the triphasic blocks are determined by the setting mechanism of gypsum, as confirmed by XRD. In this preliminary study, the amount of gypsum in the sample was set to 50 %. This 50 % composition was based on and close to the composition of a commercial biphasic gypsum-hydroxyapatite block (Geurts et al., 2021). Since the amount of gypsum phase was half the mass of the triphasic block, it is clear that the mechanical properties of triphasic blocks are lower than those of gypsum blocks; however, the mechanical strength of the triphasic blocks was drastically lower than that of gypsum blocks, a difference that was greater than anticipated. It is known that the setting strength of gypsum is due to the interlocking of entangled gypsum crystals when calcium sulfate hemihydrate reacts with water (Zhang et al., 2020). The interlocking mechanism might be disturbed as there are other powder crystals, thus lowering the mechanical strength. It is thought that monetite and brushite powders might disturb the interlocking structures of gypsum crystals. As a result, the mechanical strength of the triphasic blocks was drastically decreased compared to that of the control gypsum block. Microstructure observation confirmed the missing interlocking structures in the triphasic blocks (Fig. 4). Therefore, all three formulations still need further improvement of mechanical properties to reach values close to those of trabecular bone. Other formulations are required to achieve sufficient mechanical properties of triphasic blocks, such as the use of α-calcium sulfate hemihydrate as a precursor or by increasing the composition of calcium sulfate hemihydrate. It was reported that α-calcium sulfate hemihydrate demonstrated higher mechanical strength (Ishikawa, 2011; Ricci et al., 2008). Triphasic blocks composed of higher gypsum contents have also been reported. The content of gypsum used in previous experiments was as high as 75 % of the total powder content (Trost et al., 2020). The higher gypsum content would increase the mechanical strength due to less disruption of the interlocked structure after setting. Currently, research on more variations in gypsum is ongoing.

5. Conclusion

Triphasic blocks composed of gypsum, brushite, and monetite were successfully fabricated. The mechanical properties of the obtained triphasic blocks were much lower than those of the set gypsum block control. The lower strength of the triphasic blocks was caused by the disruption of the interlocking structure of the gypsum crystals, as found in the control block.

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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