Effect of rock sugar as a pore-forming material on the physical and mechanical properties of hydroxyapatite scaffold

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Abstract. Hydroxyapatite (HA) ceramic scaffold had been made using the pressureless sintering method for bone scaffold applications. Micron- and nano-sized HA as the primary material with the addition of polyvinyl alcohol (PVA) as a binder and rock sugar (RS) sized 298-420 µm as pore-forming material had been prepared. RS was applied to produce interconnecting pores in the HA scaffold. The green body was made by uniaxial pressing method at a pressure of 200 MPa. Preheating was carried out at a temperature of 700°C with a holding time of 1 h, aimed at eliminating PVA and RS, and then the temperature was increased to 1200°C with a holding time of 2 h. During the sintering process, the heating rate and cooling rate were maintained at 3°C/min. Physical and mechanical properties were tested respectively, including porosity and compressive strength testing. The results showed that the 23.0% porosity obtained a compressive strength value of 15.6 MPa at a ratio of HA:RS of 65:35 wt%. The highest porosity of 48.4% was obtained with a compressive strength of 4.9 MPa at a ratio of 55:45 wt%. In this study, the maximum addition of RS was only at 45 wt%, while the addition of RS reaching 50 wt% or more could affect the tangential bonding between HA powders during the sintering process.

1. Introduction

Ceramic-based products, such as bioceramics as implant materials, have been widely applied. Hydroxyapatite (HA) is a bioceramic material that has the potential to be used as an implant material for its biocompatible properties and similarity to human bone elements [1–9]. One of the implant applications being developed is the bone scaffold, which functions to replace cancellous bone.

Ideally, a scaffold has a level of strength which is comparable to the mechanical strength of bone. A bone’s biomechanical system consists of cortical bone, which has a solid and hard surface with a compressive strength of 100-200 MPa, and cancellous bone with pores inside having a compressive strength of 2-20 MPa. The sizes of scaffold range from 100 to 400 µm to facilitate adherence of cells for bone growth [10,11] and approximately 70% porosity [12]. For this reason, a scaffold design that is accurate and has properties that match the original bone is required.

Some conflicting properties are still problematic in many studies conducted to make bone scaffold a cancellous bone replacement implant. Bone scaffold requires high porosity, which is approximately 70%, and relatively large pore size, namely 100-400 µm. At the same time, it also requires a relatively high compressive strength of 2-20 MPa. The results of the study mapping showed that when the
physical properties (pore size and percentage of porosity) meet the requirements, the mechanical properties (compressive strength) do not; and vice versa.

Many ways have been developed in the manufacture of bone scaffolds, such as the method of soaking polymer foam made in the form of slurry by mixing it in a PVA solution [13,14], the polymer sponge moulding method [15,16], the 3D printing method [17–19], as well as uniaxial pressing and isostatic pressing methods [20,21]. Bone scaffold manufacturing needs a particular material to make pores, to produce an appropriate level of porosity. Sodium chloride (NaCl) [20], polymethyl methacrylic (PMMA)[21–23], and other pore-forming materials have been developed. The main requirement of the pore-making materials is that they can melt during the sintering process, resulting in pores in the scaffold produced. Rock sugar (RS) has the potential as a pore-forming material. It can be made accordingly to the needs of both shape and size. Besides, its hardness helps it withstand the pressure when making a green body.

In this study, the primary material for making bone scaffold was micron- and nano-sized HA powder. PVA was also used as a binder. RS grains were added variously to obtain porosity on the bone scaffold. The powder metallurgy method using uniaxial pressing at a pressure of 200 MPa was applied for the manufacture of the green body. The sintering process was carried out in an air environment to obtain bone scaffold targeted.

2. Materials and method

2.1. Materials

The bioceramics used were analytical commercial HA sized 2.5 µm and 200 nm and obtained from Sigma-Aldrich Co, USA. The binder material was technical PVA, with alcohol as a diluent, obtained from LQ Lab, Indonesia. All materials were used as they were in their initial conditions without any preliminary treatment. Pure water (distilled water) used throughout the research process was obtained from Brataco, Indonesia.

2.2. Method

2.2.1. Sample preparation. HA powder was prepared in sizes of 2.5 µm and 200 nm at a ratio of 80:20 wt% [3]. Then, 10 wt% PVA [24] and alcohol twice the weight of HA were added. The materials were mixed for 2 h using a rotary mixer with an alumina ball mill in it. After the mixing process, HA was dried up for 48 h to remove the alcohol content. The HA powder grains were refined in a rotary mixer for 2 h with an alumina ball mill inside. To get the appropriate porosity for the targeted bone scaffold, RS was added variously to the HA powder with ratios of 65:35, 60:40, 55:45, and 50:50 wt%, respectively. Previously, the RS was prepared in sizes of 297-420 µm by sieving at 40 and 50 mesh. HA and RS at the mentioned ratios were mixed in a rotary mixer for 2 h to obtain a homogeneous mixture. The green body was made in the form of pellets with a diameter of 8mm and a thickness of 4mm with a uniaxial pressing process at a pressure of 200 MPa. In the sintering process, preheating was carried out at a temperature of 700°C with a holding time of 1 h to eliminate PVA and RS. The sintering was continued to a temperature of 1200°C with a holding time of 2 h. During the sintering process, the heating rate and cooling rate were maintained at 3°C/min.

2.2.2. Characterisation of sample. Linear shrinkage test was carried out in two ways, namely diameter shrinkage and weight shrinkage tests, by comparing the green body with the sintered body. The resulting porosity levels were tested for all variations of the addition of RS. Furthermore, the distribution of porosity was observed using scanning electron microscopy (SEM-Hitachi Horiba S-3400 N, Japan) and digital microscopy (DM-CMOS Controller 2MP AMCAP, China). Compressive strength testing on the bone scaffold was carried out using a compressive test tool (adinitp-UTM20kN, Indonesia), referring to ASTM-C1424 Standard for Monotonic Compressive Strength of Advanced Ceramics.
3. Results and discussion

3.1. Linear shrinkage

Figure 1 shows the linear shrinkage that occurred, where the test was carried out in two ways including diameter shrinkage and weight shrinkage tests. Linear shrinkage could only be observed in HA:RS variations with ratios of 65:35, 60:40, and 55:45 wt%, respectively. Meanwhile, the ratio of 50:50 wt% bone scaffold sample was not successful to observe (the sample broke after the sintering process) due to the high amount of the RS added. After testing separately to melt down RS in the furnace, RS showed the behaviour to produce bubbles before melting at temperatures above 200°C. This caused the tangential release of HA powder during the sintering process at the addition of 50 wt% RS. Figure 1 shows that the shrinkage diameter for the three ratios of the addition of RS ranged from 15-16%. No difference occurred because the diameter shrinkage was more dominantly influenced by the sintering temperature. Similar values of diameter shrinkage have also been reported in previous studies [25,26]. Weight shrinkage increased from 41.9% to 51.5% in the ratios of 65:35 and 55:45 wt%, respectively. The high weight shrinkage was due to RS and PVA, which completely melt at a temperature of 700°C, resulting in pores on the HA scaffold after sintering.

3.2. Porosity

Figure 2 shows the effect of the addition of RS as a pore-forming material on the porosity of the HA scaffold. The increased porosity was directly proportional to the addition of RS up to the highest ratio, namely 55:45 wt%. At a HA:RS ratio of 65:35 wt%, the porosity was 23% and continued to increase to 36.9% and 48.4% at ratios of 60:40 wt% and 55:45 wt%, respectively. Based on figure 2, increasing the amount of RS as a pore-making material was thought to increase the percentage of porosity, in accordance with the porosity standard of a bone scaffold product, i.e. 70% [27,28]. However, the addition of RS as a pore material can only be done at a maximum of 45 wt%. This is due to the behaviour of RS which produces bubbles when it melts, thus damaging the tangential bonds between the HA powders. At RS liquid temperature, around 200°C, HA has not yet undergone grain bonds, so it has the potential to release the tangential bonds that were generated during the making of the green body. The resulting pores already have interconnections, as shown in figure 3.

![Figure 1. Effect of adding RS on linear shrinkage of HA scaffold](image-url)
Figure 2. Effect of adding RS on porosity of HA scaffold

Figure 3. DM image of HA scaffold with variations of HA:RS (a) 65:35 wt%, (b) 60:40 wt%, (c) 55:45 wt%.
3.3. **Macrostructural characteristics**

Figure 4 shows the macrostructure and shape of the pores produced from the variations of the amounts of RS added as a pore-making material. Figure 4 (a1,2) indicates the HA scaffold with the addition of 35 wt% RS. SEM image shows the shape of the pores with total porosity of 23%. The figure also indicates the presence of interconnecting pores but in a small number. Figure 4 (b1,2) shows the HA scaffold with the addition of 40 wt% RS. The number of pores increased with the porosity of 36.9%. The interconnection between the pores also increased. Figure 4 (c1,2) shows the HA scaffold with the addition of 45 wt% RS. The porosity reached 48.4%. The interconnections between the pores could be seen more than others. Overall, the shape of the pores was not uniform, and some even had sharp corners. This form possibly had high-stress concentration when given a compressive load. A pore-making agent is necessary to prepare with a shape that has no angle or with a shape close to round. The interconnection between pores is also shown in Figure 3. The DM image was carried out by providing light on the bottom of the HA scaffold. The light seemed to penetrate the HA scaffold, which attested to the interconnection between the pores.

3.4. **Compressive strength**
One of the main mechanical properties of HA scaffold testing is compressive strength, where the minimum requirement is 2 MPa. Figure 5 shows the compressive strength value of the HA scaffold with the various amounts of the RS added. The compressive strength of the HA scaffold is inversely proportional to the amount of the RS added. At the addition of 35 wt% RS, the compressive strength value was 15.6 MPa and continued to decrease significantly to 4.9 MPa with the addition of 45 wt% RS.

Figure 4. SEM image of HA scaffold with variations of HA:RS (a₁,₂) 65:35 wt%, (b₁,₂) 60:40 wt%, (c₁,₂) 55:45 wt%.

Theoretically, the lowest compressive strength in this study met the minimum standard of a scaffold, i.e. 2 MPa [29]. However, according to the data in figure 2, the resulting porosity only reached 48.4%, still below the porosity requirement of 70% [28]. Figure 6 shows the relationship between compressive strength and porosity. Compressive strength decreased as RS decreased, and,
vice versa, porosity increased as RS increased. From the overall results of this study, it is necessary to consider the selection of other materials as pore-making materials. It is required that pore-forming materials, when melting, do not affect the tangential bonds between the HA powders. As a comparison, another study using a spherical pore material obtained a compressive strength value in nano-sized HA scaffold of about 31.4 MPa at 50% porosity [21] and 1.1 MPa at a porosity above 80% [30]. A summary of the physical and mechanical properties of the HA scaffold can be seen in Table 1.

Table 1. Summary of physical and mechanical properties of HA scaffold

| Ratio of HA:RS (wt%) | Linear shrinkage (%) | Porosity (%) | Compressive strength (MPa) |
|---------------------|----------------------|--------------|--------------------------|
|                     | Diameter             | Weigh        |                          |
| 65:35               | 15.81 ±0.14          | 41.9 ±2.42   | 23.0 ±1.82               | 15.6 ±1.3 |
| 60:40               | 16.75 ±0.19          | 47.8 ±3.08   | 36.9 ±2.40               | 11.5 ±0.7 |
| 55:45               | 15.50 ±0.20          | 51.5 ±2.19   | 48.4 ±3.59               | 4.9 ±0.2  |

Figure 5. Effect of adding RS on compressive strength of HA scaffold

Figure 6. Effect of adding RS on compressive strength and porosity of HA scaffold

4. Conclusion
The addition of RS as a pore-forming material to manufacture HA scaffold has succeeded in obtaining pores with total porosity of 48.4% with a compressive strength value of 4.9 MPa. The maximum amount of the RS added should be 45 wt%. The addition of RS as much as 50 wt% or more can affect the tangential bond between HA powders during the sintering process.

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