

# Manufacture and Characterisation of a Bioactive and Biodegradable Composite Developed for Bone Tissue Repair

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**Abstract**—A bioactive and biodegradable composite containing hydroxyapatite (HA) and polyhydroxybutyrate (PHB) was developed for bone tissue repair. A manufacturing process, which consisted of compounding, pelletising, drying, and injection moulding, was established for producing the composite. The HA/PHB composite containing 10, 20, 30 and 40% by volume of particulate HA was successfully made. The distribution of HA particles in the PHB matrix was examined using scanning electron microscopy (SEM). Differential scanning calorimetry (DSC) was employed to investigate the melting and crystallization behavior of both compounded and injection moulded HA/PHB composite.

## I. INTRODUCTION

BONE tissue repair normally requires temporal bone substitute to take over mechanical and other functions of the damaged bones, and to induce the growth of new bones. At the same time, the bone substitute degrades gradually to give way to the newly formed bones. All of these critical demands put biodegradable materials or bioactive composites with degradable polymer matrices into advantageous positions for bone tissue repair.

Polyhydroxybutyrate (PHB) is a naturally occurring  $\beta$ -hydroxyacid (a polyester). Its ability to degrade and resorb in the human body environment makes it a potential candidate as the matrix for bioactive and biodegradable composite implants that will guide tissue growth and be replaced eventually by newly grown tissue [1]. Being similar to the main inorganic component of natural bone and possessing osteoconductive properties, hydroxyapatite (HA) has become the favorite bioceramic to be used as a reinforcement in composites for medical implants [2, 3].

In the current investigation, to develop bioactive and biodegradable composites for bone tissue repair, particulate HA was incorporated into PHB to form HA/PHB composite with HA volume percentages up to 40%. To examine the quality of composite produced, the distribution of HA particles in the PHB matrix was studied. Thermal properties of PHB raw material and HA/PHB composite were also investigated after each thermal-mechanical production stage.

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## II. MATERIALS AND METHODS

### A. Raw materials

PHB homopolymer, in the form of small-size granules, was commercially available from Tianan Biologic Material Ltd., Ningbo, China.

HA, in the form of fine powder, was a high purity, crystalline, synthetic material and was purchased from Taihei Chemicals, Japan. The average particle size of HA was about 20 $\mu$ m and the particles had a spherical shape.

### B. Mixing of raw materials

Composite materials with five nominal compositions, i.e., HA/PHB composite containing 0, 10, 20, 30 and 40 vol.% of HA, respectively, were to be produced in the current investigation. In order to achieve the required nominal compositions, HA and PHB raw materials were mixed according to corresponding weight percentages, which were converted from constituents' volume percentages following the "Rule of Mixtures" [4], as listed in Table 1.

Table 1. HA content in the HA/PHB composite

Volume Percentage	Weight Percentage
10	21.93
20	38.73
30	52.00
40	62.76

### C. Manufacture of HA/PHB composite

A thermal-mechanical manufacturing route consisting of compounding, pelletising, drying and injection moulding was established to produce the composite (Fig.1).

A twin-screw extruder was used for the compounding process, and the processing parameters were strictly controlled, especially the temperatures of the barrel. According to the melting temperatures determined through DSC (refer to Section E), several production trials were conducted in order to optimize the compounding temperature for HA/PHB composite. The strands of compounded materials were then pelletised into granules through a cutting machine. The granules of HA/PHB composite were dried overnight in an oven and subsequently injection moulded into rectangular plates or dumbbell tensile specimens. Fig.2 shows the injection mould and an injection moulded HA/PHB plate. By using different mould inserts, either rectangular plates or dumbbell specimens could be moulded.

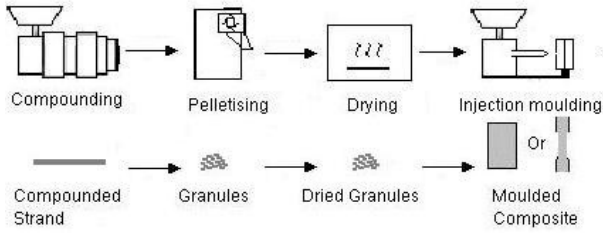


Fig. 1. Fabrication process of HA/PHB composite

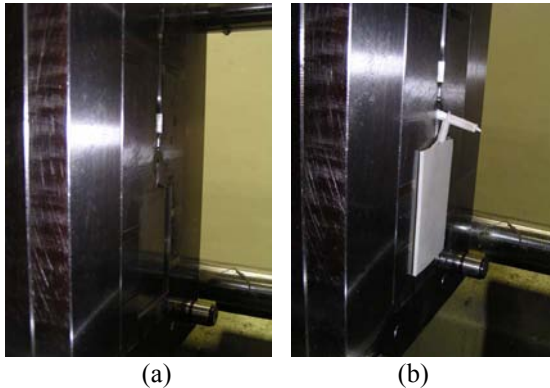


Fig. 2. Injection mould (a), and an injection moulded HA/PHB composite plate in the mould (b)

#### D. Microstructural analysis

After injection moulding, SEM was employed to examine the microstructure of HA/PHB composite, i.e., to analyse the distribution of HA particles in the PHB matrix. Small specimens were cut from each group of injection moulded plates, and the specimen preparation procedure included mounting, grinding, polishing, ultrasonic bath cleaning and drying. These specimens were gold-coated for the SEM.

#### E. Analysis of thermal properties

DSC analyses (using a Perkin-Elmer Pyris 6 system) were conducted through a standard thermal cycle, heating from 30°C to 200°C which was followed by cooling from 200°C to 30°C, to determine thermal properties of the PHB raw material, compounded materials, and injection moulded composite. A heating/cooling rate of 10°C/min and a sample weight of ~10mg were maintained for all DSC analyses.

The degree of crystallinity of the PHB raw material and PHB matrix of the composite after compounding and injection moulding was calculated using the following equation [5]:

$$\chi_c = \frac{\Delta H_m / \phi_{PHB}}{\Delta H_m^0} \times 100\% \quad (1)$$

where  $\Delta H_m$  is the apparent fusion enthalpy of the PHB raw material or matrix PHB in the composite specimens,  $\Delta H_m^0$  is the fusion enthalpy of the theoretically 100% crystalline PHB polymer which has been reported to be 146J/g [4], and  $\phi_{PHB}$

is the matrix PHB weight content in the composite.

### III. RESULTS AND DISCUSSION

HA/PHB composite plates of the dimensions 80x50x2mm<sup>3</sup> and containing up to 40vol% HA were successfully produced (Fig.3). All these plates were crack-free and voids-free through visual inspection. This result is significant and can contribute to the success of HA/PHB composite as an implant material. Previous attempts in producing HA/PHB composite through the compression moulding route had resulted in cracked plates due to prolonged heating time during compression moulding [4]. Even though the subsequent structural, mechanical and biological tests after composite fabrication could use non-perfect composite plates for research purposes, defect-free and crack-free plates are preferred. Furthermore, injection moulding uses far less time at the elevated composite processing temperature than compression moulding, which significantly reduces the degree of oxidation of the polymer matrix, especially for heat-sensitive polymers such as PHB.

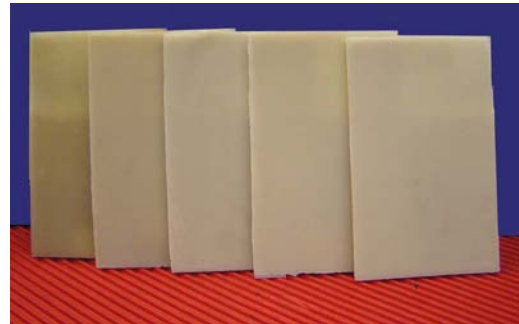


Fig. 3. Injection moulded HA/PHB composite plates (from left to right: plates containing 0, 10, 20, 30, 40% HA)

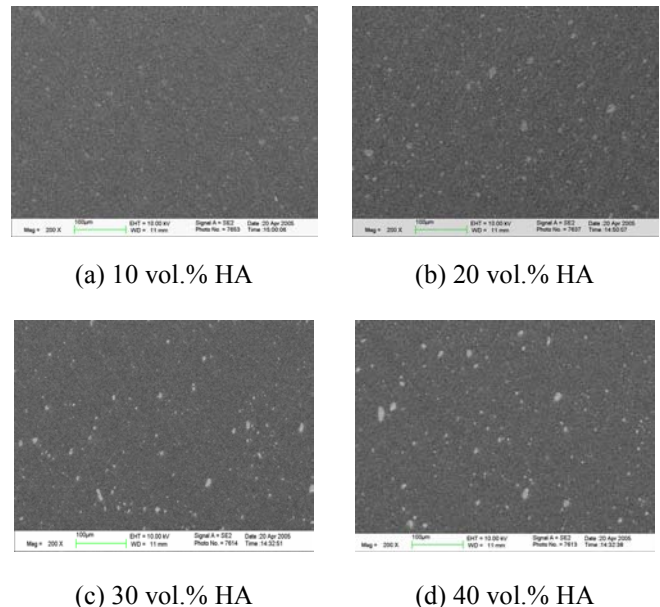


Fig. 4. SEM micrographs of injection moulded HA/PHB composite

The microstructure of HA/PHB composite is shown in

Fig.4. From Fig.4, it can be seen that for all the nominal compositions of the HA/PHB composite, HA particles were well dispersed in the PHB matrix, indicating that the compounding and injection moulding route was successful. This homogeneous distribution of HA particles would lead to good mechanical properties of the composite.

The DSC curves of PHB raw material are shown in Fig.5. From the melting scan, the melting temperature ( $T_m$ , 173.9°C) and enthalpy of fusion ( $\Delta H_m$ , 102.6J/g) were determined. From the cooling scan, the crystallization temperature (86.2°C) and onset of crystallization temperature (92.3°C) were also obtained.

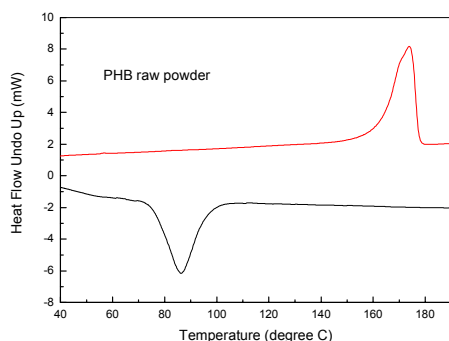


Fig. 5. DSC curves for PHB raw material

As PHB is very sensitive to heat and suffers thermal degradation at temperatures just around the melting temperature [6], the compounding temperature of PHB with HA must be carefully chosen, and theoretically, the lower the temperature the better. According to the melting temperature obtained from Fig.5, a number of compounding temperatures which were below the melting temperature were tried and it appeared that 163°C was the lowest temperature to compound PHB with HA smoothly. The DSC curves of PHB compounded at 163°C and at a higher temperature of 168°C as a control are shown in Fig.6, and the corresponding melting temperature, enthalpy value and crystallinity can be found in Table 2, which also includes those of the PHB raw material.

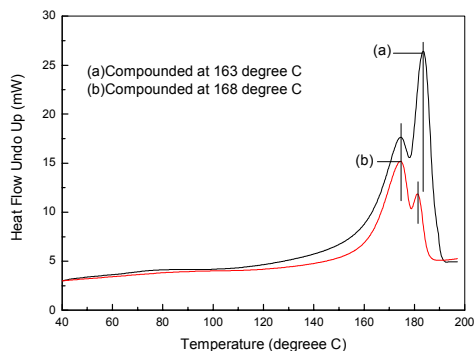


Fig. 6. DSC curves of compounded PHB

It can be seen from Fig.6 that both melting scans had double peaks. For the material compounded at 163°C, the

melting temperature was 183.5°C, and the lower peak appeared on the lower temperature side of the main peak. For the material compounded at 168°C, the melting temperature was 174.4°C, and the lower peak appeared on the higher temperature side of the main peak. Interestingly, the melting peak in one curve and the lower peak in the other curve appeared at about the same temperatures.

For both DSC curves in Fig.6, the first melting peak is due to the formation of primary crystals during the cooling process and the second melting peak is caused by the recrystallisation process during the DSC heating. The double or multiple melting behavior is not uncommon for PHB and is usually proposed to link either to the process of partial melting and recrystallisation and remelting or to melting of crystal with different lamellar thickness and/or different crystal structures [6].

For the material compounded at 163°C, the area of the secondary crystal melting peak was much larger than the primary crystal melting peak, while for the material compounded at 168°C, the area of the secondary crystal melting peak was smaller than the primary crystal melting peak, indicating that the degree of recrystallisation of PHB was much higher when it was compounded at a lower temperature.

Table 2. Thermal properties of PHB raw material and PHB compounded at different temperatures

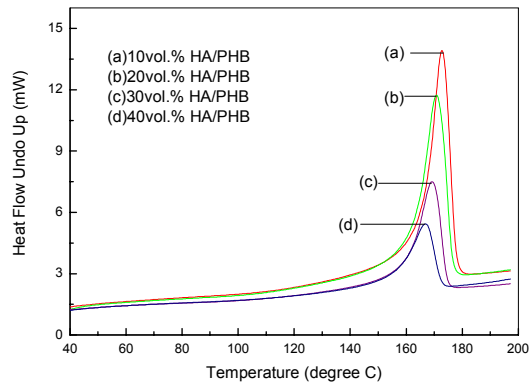
Material	$T_m$	$\Delta H_m$	$\chi_c$
Raw material	173.9	102.6	76.2
Compounded at 163°C	183.5	109.3	74.9
Compounded at 168°C	174.4	81.8	56.0

The degree of crystallinity has a profound effect on the mechanical properties of the polymer matrix and hence the composites. It also affects the biodegradation behaviour and rate of the composite. In the current investigation, the lower compounding temperature which was 163°C was finally chosen for a higher degree of crystallinity and lower possibility to oxidation-led thermal degradation during the compounding process. Similar work was done in optimizing the injection moulding process, and a temperature of 160°C was chosen for injection moulding. Thermal properties of as-produced HA/PHB composite after compounding and injection moulding are shown as DSC curves in Fig.7, which also indicates the effect of HA amount on thermal properties of the PHB matrix.

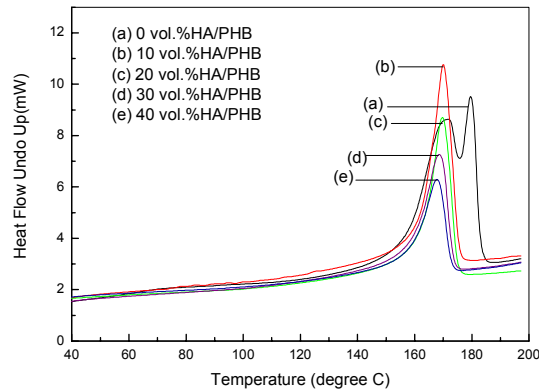
Corresponding melting temperature, enthalpy value and crystallinity of the PHB matrix for composite with different HA volume percentages are listed in Table 3.

It can be seen from Fig.7 and Table 3 that for PHB with no HA particles, the values of  $T_m$ ,  $\Delta H_m$  and  $\chi_c$  after injection moulding were lower than those after compounding, while for each HA/PHB composite, there were slight reductions in their thermal properties between the compounded and injection moulded specimens. For HA/PHB composite with different HA contents, the values of  $T_m$ ,  $\Delta H_m$  and  $\chi_c$  decreased with an increase in HA content.

The melting temperature decreased slowly with the increase in HA content, while the values of enthalpy and degree of crystallinity dropped more significantly when the HA content was changed to 30 vol.% and 40 vol.%.



(a) after compounding



(b) after injection moulding

Fig. 7. DSC curves of HA/PHB composite

Table 3. Thermal properties of HA/PHB composite after compounding (C) and injection moulding (IM)

HA Content	$T_m$		$\Delta H_m$		$\chi_c$	
	C	IM	C	IM	C	IM
0	183.5	179.5	109.3	103.5	74.9	70.9
10%	172.8	170.0	76.6	78.6	67.3	69.0
20%	170.8	169.7	64.7	62.9	72.6	70.6
30%	169.3	168.6	39.8	37.7	56.7	53.8
40%	166.8	167.3	28.4	28.1	52.6	52.0

The degree of crystallinity of injection moulded PHB decreased more obviously as compared to that of the compounded PHB, due to the effect of thermal processing during the composite manufacturing process. The incorporation of HA into PHB tended to decrease the degree of crystallinity of the polymer matrix. However, when the HA content was low, such as 10 and 20 vol.%, the HA particles acted as nucleating agent which would enhance the nucleation of crystallites in the polymer and thus improve the crystallinity of the polymer matrix. As a result, although the

content of PHB in the composite was reduced, its degree of crystallinity was still about the same as that of PHB without HA particles. When the HA content increased to a higher level, such as 30 vol.% and above, its role as nucleating agent diminished, leading to the decrease of the degree of crystallinity.

#### IV. CONCLUSIONS

Bioactive and biodegradable HA/PHB composite with HA content up to 40 vol.% was successfully produced. A manufacturing route employing injection moulding was established for this composite. It was shown that processing parameters of the composite could be optimized through thermal analysis of the composite produced.

SEM examination of polished HA/PHB composite specimens indicated a homogeneous distribution of HA particles in the PHB matrix which would ensure good mechanical and biological properties of the composite for bone tissue repair.

Thermal properties of as-produced HA/PHB composite were systematically evaluated. The degrees of crystallinity of 10 vol.% HA/PHB and 20 vol.% HA/PHB were almost the same as that of PHB without HA, because HA particles served as the nucleating agent in the PHB polymer, whereas the incorporation of HA particles at a higher level of 30 vol.% and above into PHB polymer reduced the degree of crystallinity of PHB matrix in the composite.

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