

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/251670062>

# Evaluation of the flexural properties and bioactivity of bioresorbable PLLA/PBSL/CNT and PLLA/PBSL/TiO<sub>2</sub> nanocomposites

Article in *Composites Part B Engineering* · April 2012

DOI: 10.1016/j.compositesb.2011.11.023

CITATIONS

19

READS

66

3 authors, including:



Mariatti Jaafar

Universiti Sains Malaysia

303 PUBLICATIONS 3,293 CITATIONS

[SEE PROFILE](#)



Srimala Sreekantan

Universiti Sains Malaysia

202 PUBLICATIONS 2,043 CITATIONS

[SEE PROFILE](#)

Some of the authors of this publication are also working on these related projects:



Electrical conductive composites [View project](#)



Polymer composites for cable insulator [View project](#)



## Evaluation of the flexural properties and bioactivity of bioresorbable PLLA/PBSL/CNT and PLLA/PBSL/TiO<sub>2</sub> nanocomposites

P.M. Chou, M. Mariatti\*, A. Zulkifli, S. Sreekantan

School of Materials and Mineral Resources Engineering, Engineering Campus, Universiti Sains Malaysia, 14300 Nibong Tebal, Pulau Pinang, Malaysia

### ARTICLE INFO

#### Article history:

Received 14 May 2011

Received in revised form 30 September 2011

Accepted 1 November 2011

Available online 10 November 2011

#### Keywords:

A. Polymer–matrix composites (PMCs)

B. Strength

D. Electron microscopy

Bioresorbable

### ABSTRACT

Bioresorbable nanocomposites made from PLLA/PBSL blended with varying contents of carbon nanotubes (CNTs) and titanium dioxide (TiO<sub>2</sub>) nanotubes were prepared through melt compounding followed by compression molding. The resulting flexural properties were investigated by flexural test and the bioactive behavior was assessed by FESEM and EDX. A higher flexural modulus value was obtained with the addition of nanofillers. The formation of a bone-like apatite layer was observed on the surface of the nanocomposite containing TiO<sub>2</sub> nanotubes after soaking in simulated body fluid (SBF) for 7 days. An increase in the water uptake of the PLLA/PBSL/TiO<sub>2</sub> nanocomposite occurred with increased filler loading. The nanocomposite containing CNT exhibited an increasing trend of water absorption similar to the PLLA/PBSL blend. With prolonged immersion in SBF, the pH value of the SBF reduced slightly and weight loss of the samples increased.

© 2011 Elsevier Ltd. All rights reserved.

### 1. Introduction

In recent years, environmental friendly biodegradable polymers have become substitutes for petroleum-based plastics, owing to their biodegradability that could reduce plastic waste pollution. Apart from that, limited fossil resources and increasing oil price have accelerated the development of biodegradable polymers derived from renewable resources. In this context, poly(L-lactic acid) (PLLA) is considered as one of the most attractive biodegradable polymer of strength and stiffness comparable to those of commodity plastics [1]. PLLA is a linear aliphatic thermoplastic polyester produced from agricultural resources such as wheat, corn, and sugar beets [2]. It has been extensively applied in biomedical applications such as bone fixation devices, sutures, scaffolds, and drug delivery systems due to its biodegradability, biocompatibility, and nontoxic degradation products [3]. However, its low toughness, low crystallization rate, and heat distortion temperature are major drawbacks that limit its applications [4]. One of the most common and versatile methods to improve these is blending PLLA with other flexible polymers such as poly(butylene succinate) (PBS) [5], poly(butylene succinate-co-L-lactate) (PBSL) [6], and poly( $\epsilon$ -caprolactone) (PCL) [7]. Vilay et al. [6] reports that the elongation at break and toughness of the blends were improved upon addition of PBSL. Furthermore, a previous study has shown that blending PLLA with 25 wt.% PBSL results in an increment of about 284% elongation at break compared with neat PLLA [8]. Although

these PLLA blends have improved elongation at break or toughness, almost all blends were accompanied by a remarkable decrease in modulus value. In addition, the lack of bioactivity hinders PLLA from being used as a biomaterial which is able to induce the desired bone cell regeneration [9]. The incorporation of bioactive fillers has been reported to improve the mechanical properties as well as the bioactivity of PLLA [10–12].

Over the past decade, nanocomposites comprising bioresorbable polymers and nanoparticles of grain size less than 100 nm have gained attention for their use in the biomedical field owing to their novel functional and size-dependent properties [13]. Previous investigations have confirmed that nanoscale bioceramics such as alumina (Al<sub>2</sub>O<sub>3</sub>), titania (TiO<sub>2</sub>), and zirconia (ZrO<sub>2</sub>) exhibit better cell adhesion and enhanced cellular behavior than conventional micro-sized bioceramics [14,15]. TiO<sub>2</sub> has been extensively studied due to its excellent mechanical properties, photocatalytic effects, as well as anti-bacterial and anti-corrosive properties [16]. In addition, several studies have proven that TiO<sub>2</sub> is bioactive because some forms of TiO<sub>2</sub> exhibit strong interfacial bonding to living tissue through the formation of a biologically active hydroxyapatite layer on the material surface [17,18]. Numerous studies have confirmed that TiO<sub>2</sub> is a promising reinforcement widely used in biodegradable polymer matrices [19,20]. On the other hand, carbon nanotubes (CNTs) have become one of the most promising reinforcements for multifunctional nanocomposites because of unique characteristics such as extremely high tensile strength and elastic modulus, as well as excellent thermal and electrical conductivity [21,22]. Furthermore, the excellent biocompatibility of CNT with various cells has been proven by in vivo studies [23,24].

\* Corresponding author. Tel.: +60 4 5995262; fax: +60 4 5941011.

E-mail address: [mariatti@eng.usm.my](mailto:mariatti@eng.usm.my) (M. Mariatti).

Although it was mentioned that TiO<sub>2</sub> nanoparticles impart bioactivity on PLLA [25,26], a study of CNT and TiO<sub>2</sub> nanotube addition to the PLLA/PBSL binary blend is yet to be reported. This study uses CNT and TiO<sub>2</sub> nanotubes as reinforcements in the binary blend of PLLA and PBSL. The PLLA/PBSL blending ratio of 75/25 achieves the optimum properties. The objective of this study is to investigate the mechanical properties of the prepared nanocomposites and to determine the effect of CNT and TiO<sub>2</sub> nanotubes on PLLA/PBSL blend system bioactivity, characterized by the formation of a bone-like apatite upon simulated body fluid (SBF) immersion.

## 2. Experimental

### 2.1. Materials

PLLA pellets (Lacty 5000) with a weight-average molecular weight of  $1.45 \times 10^5$  were supplied by Shimadzu Co. Ltd. and the PBSL pellets with a weight-average molecular weight of  $1.47 \times 10^5$  were obtained from Mitsubishi Chemical Corp. Both the PLLA and PBSL pellets were used as-received. For the fillers, short multi-walled carbon nanotubes (S-MWCNT-4060) of external diameter 40–60 nm were purchased from Shenzhen Nanotech Port Co. Ltd. The nanotubes are more than 98 vol.% pure with a specific surface area of  $\sim 300$  m<sup>2</sup>/g. Titanium dioxide (TiO<sub>2</sub>) nanopowders containing 99.7% anatase were supplied by Sigma–Aldrich. The TiO<sub>2</sub> nanopowders have a mean particle size of 25 nm and a specific surface area of  $\sim 200$  m<sup>2</sup>/g. The TiO<sub>2</sub> nanopowders were further processed to obtain nanotube structures using a hydrothermal method. The details of the nanotube synthesis are reported by Sreekantan and Lai [27].

### 2.2. Preparation of nanocomposite

The PLLA/PBSL/CNT and PLLA/PBSL/TiO<sub>2</sub> nanocomposites were fabricated by melt-mixing using a Haake internal mixer. Filler loadings varying from 0 to 0.75 per hundreds weight of the blend resin (phr) were applied in this study. Prior to melt-mixing, PLLA and PBSL pellets were dried in a vacuum oven for 24 h at 80 °C to minimize hydrolytic degradation of the polymers due to moisture. The dried PLLA and PBSL pellets of weight ratio 75/25 were melt-mixed in an internal mixer set at 180 °C and a twin screw rotor speed of 50 rpm. After 3 min of mixing, the nanofillers were added into the mixing chamber for further compounding. The melt-mixing process completes when the recorded torque value becomes constant. The nanocomposite compounds were then taken out of the mixing chamber. Subsequently, compression molding was carried out using an electrically heated hydraulic press model GT-7014-A30C. The compounds were put into a 3 mm thick stainless steel mold and were preheated for 7 min at 180 °C. Subsequently, the compounds were hot pressed for 5 min under a pressure of 10 MPa at the same temperature. This was followed by 3 min of cooling to room temperature. The hot pressed samples were then sealed in plastic bags and kept in desiccators for subsequent characterization.

### 2.3. Flexural test

The three-point bending test was carried out using an Instron Universal Testing Machine Model 3366 at a cross-head speed of 10 mm/min and a span length of 50 mm. The specimens were cut into bars of rectangular cross-sections with dimensions of  $100 \times 12.7 \times 3$  mm, as recommended by ASTM D790-03 [28]. The flexural strength and modulus were computed based on the average of results for tests run on five specimens.

### 2.4. In vitro bioactivity test

The in vitro bioactivity test was conducted on the nanocomposites with filler loading 0.25 and 0.75 phr using SBF with ion concentrations nearly equal to those of human blood plasma. SBF was prepared using nine types of reagents in the sequence described by Kokubo and Takadama [29].

The specimens were cut into  $10 \times 10$  mm squares and specimen weight was measured in triplicates before and after soaking in SBF for 7, 14, 21, and 28 days at 37 °C. The pH value of SBF was measured every week. Used SBF was replaced by fresh SBF at the end of each week to ensure a constant liquid composition. After the particular immersion time, the specimens were removed from the SBF and gently wiped with a dry cloth. The wet weight of the specimens was then recorded. The wet specimens were put in a vacuum oven for drying overnight at room temperature. After 24 h of drying, the dry weight was measured. The water uptake (WU) and weight change (WC) of the in vitro bioactivity test specimens were computed using Eqs. (1) and (2), respectively.

$$WU = \frac{(W_w - W_d)}{W_d} \times 100 \quad (1)$$

where WU is the water uptake by the specimen, %;  $W_w$ , the wet weight of the specimen after removal from SBF, g; and  $W_d$  is the dry weight of the specimen after drying for 24 h, g.

$$WC = \frac{W_d - W_o}{W_o} \times 100 \quad (2)$$

where WC is the weight change of the specimen, %;  $W_d$ , the dry weight of the specimen after drying for 24 h, g; and  $W_o$  is the original weight of the specimen before SBF immersion, g.

### 2.5. Energy dispersive X-ray spectroscopy (EDX)

The chemical compositions of selected specimens after soaking in SBF for a certain period of time were characterized by EDX. Any apatite layer formed on the surface of the nanocomposites was determined from the EDX analysis.

### 2.6. Morphology observations

The nanofiller distribution in the polymer blend matrix and the nanocomposite phase morphology were examined using a Supra 35 VP Zeiss field emission scanning electron microscope (FESEM). Cryofractured surface specimens were prepared by immersing the flexural test specimens in liquid nitrogen for about 30 min. FESEM was also employed to inspect the possible formation of a bone-like apatite layer on the surface of the specimens soaked in SBF. All specimens were mounted on stubs using adhesive carbon tapes before FESEM observation. Since the specimens do not have adequate inherent electrical conductivity, gold sputtering was carried out to prevent the accumulation of electrostatic charge during electron irradiation [30].

## 3. Results and discussion

### 3.1. Flexural properties

The variation in flexural strength and modulus of the PLLA/PBSL-based nanocomposites as a function of filler content is displayed in Fig. 1. Flexural strength of the PLLA/PBSL/CNT nanocomposite increased slightly with the addition of up to 0.5 phr CNT. Further increasing the CNT filler loading resulted in a slight decrease of about 1% in flexural strength compared with the unmodified PLLA/PBSL blend. On the other hand, a gradual decrease in the flexural

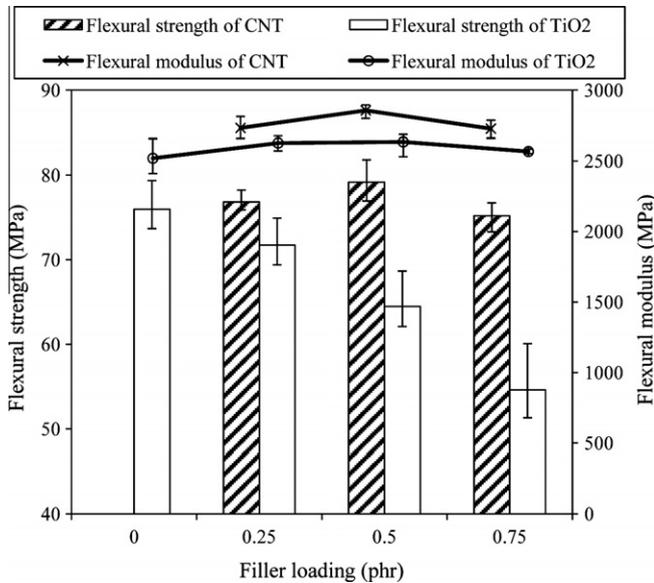


Fig. 1. Change in flexural strength and modulus of the PLLA/PBSL based nanocomposites as a function of filler loading.

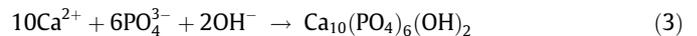
strength of PLLA/PBSL/TiO<sub>2</sub> with increasing filler loading was observed. The increase in flexural strength with small amounts of CNT is attributed to its high aspect ratio which increased the contact surface between CNT and the PLLA/PBSL matrix, thus improving the load transfer between the PLLA and the PBSL phases. The reduction in flexural strength of the nanocomposites may have been caused by poor nanofiller dispersion in the polymer matrix. Nano-sized fillers possess high surface energies that lead to agglomeration in the polymer matrix. At higher filler loading, the agglomerated fillers possibly acted as stress concentrators, causing the premature failure and the decrease in nanocomposite flexural strength [31]. Another factor that may have contributed to the reduction of tensile strength at high filler loading is the weak interfacial adhesion between the two polymer phases. A similar finding has been reported by Wu et al. [32] for the PCL/PLA blend containing MWCNT. The flexural strength result is corroborated by the FESEM micrographs of the cryofractured surface of PLLA/PBSL/CNT and PLLA/PBSL/TiO<sub>2</sub> nanocomposites with various filler loading (Fig. 2). It is observed that the entire compositions consist of two phases, namely the continuous PLLA phase and the dispersed spherical PBSL phase. This indicates that PLLA is not miscible with PBSL [6]. Comparing the phase morphology between the PLLA/PBSL/CNT and PLLA/PBSL/TiO<sub>2</sub> nanocomposites with filler loading up to 0.5 phr reveals that the fractured surface of PLLA/PBSL/CNT is smoother than that of PLLA/PBSL/TiO<sub>2</sub>. In addition, detachment of the PBSL domains from the PLLA matrix is more apparently in the PLLA/PBSL/TiO<sub>2</sub> nanocomposite. In consequence, poor interfacial bonding between PLLA and PBSL phases leads to the decrease in flexural strength of the nanocomposites.

The flexural modulus of both nanocomposites exhibited an increase as the filler loading increased up to 0.5 phr. The improvement in flexural modulus upon addition of a small amount of either CNT or TiO<sub>2</sub> is attributed to the higher stiffness value of the rigid fillers compared to the polymer blend. However, there was a slight decrease in flexural modulus upon further addition of filler loading until 0.75 phr. This is probably caused by the agglomeration of nanofillers in the polymer matrix. This observation is in agreement with the previous study conducted by Hasook et al. [33]. Overall, the flexural modulus of PLLA/PBSL/CNT is higher than that of PLLA/PBSL/TiO<sub>2</sub> at the same filler loading. This is due to

the fact that CNT possesses a higher value of flexural modulus than TiO<sub>2</sub>.

### 3.2. In vitro bioactivity

The in vitro bioactivity test is commonly conducted to investigate the ability of a material to form apatite crystals on the surface exposed to SBF. The apatite crystals which possess a chemical composition similar to the human bone are able to stimulate bone regeneration [34]. The bone-like apatite growth on the PLLA/PBSL-based nanocomposites was determined by EDX elemental analysis. Figs. 3 and 4 present the EDX spectra of the PLLA/PBSL/CNT and PLLA/PBSL/TiO<sub>2</sub> nanocomposites associated with their respective chemical compositions after soaking in SBF at 37 °C for 7 days. Only two elements, namely carbon (C) and oxygen (O), are present in the unmodified PLLA/PBSL blend in Fig. 3a. This indicates no apatite growth on the polymer blend after immersion in SBF. As observed in Fig. 3b and c, the compositions of PLLA/PBSL/CNT nanocomposites are similar to the unmodified PLLA/PBSL blend. Sodium (Na) and chlorine (Cl) found in the nanocomposite containing 0.75 phr of CNT is probably from SBF residue due to improper washing of the specimen after soaking. In contrast, the PLLA/PBSL/TiO<sub>2</sub> nanocomposites contain phosphorus and calcium. This implies that the addition of TiO<sub>2</sub> to the blend induced bone-like apatite formation after SBF immersion for 7 days. This is in agreement with a previous study carried out by Song et al. [35] and Nakayama and Hayashi [36]. Upon immersion in SBF, the TiO<sub>2</sub> filler of the nanocomposite tends to adsorb water at its surface, leading to the formation of basic titanium hydroxide (Ti-OH) groups, components suggested to induce the nucleation of apatite. Eq. (3) shows the selective interaction between the negatively charged units on titania and the positively charged calcium ions (Ca<sup>2+</sup>) in SBF which contributes to the formation of bone-like apatite [37].



The EDX result is consistent with the FESEM micrographs of the PLLA/PBSL/CNT and PLLA/PBSL/TiO<sub>2</sub> nanocomposite surfaces after 7 days of SBF immersion (Fig. 5). For the PLLA/PBSL blend and the PLLA/PBSL/CNT nanocomposite, no inorganic deposition was observed on the surface of the samples immersed in SBF for 7 days. On the contrary, a small amount of apatite crystals deposited on the surface of PLLA/PBSL/TiO<sub>2</sub> nanocomposite containing 0.25 phr of TiO<sub>2</sub> nanofillers is revealed in Fig. 5. The surface of PLLA/PBSL/TiO<sub>2</sub> containing 0.75 phr of TiO<sub>2</sub> nanofillers is completely covered with the compact spheroids, which represent apatite deposits, judging from the EDX analysis. This suggests that the amount of apatite crystals formed is directly proportional to the amount of TiO<sub>2</sub> present in the nanocomposite.

### 3.3. Water uptake

Effects of filler loading and filler type on the water uptake of the nanocomposites as a function of soaking time is presented in Fig. 6. All samples exhibited an increase in water uptake with increasing soaking time in SBF. This is attributed to the accumulation of the hydrolytic degradation products of PLLA. A similar trend of water uptake has been reported by Mohn et al. [38]. However, water uptake of the binary blend reached a plateau beyond 21 days; insignificant change is observed in the water uptake of PLLA/PBSL/CNT compared with the unmodified PLLA/PBSL blend. On the other hand, PLLA/PBSL/TiO<sub>2</sub> water uptake is higher than that of the unmodified PLLA/PBSL blend. The water uptake of the PLLA/PBSL/TiO<sub>2</sub> nanocomposites increased with increasing filler loading. This is due to the hydrophilic nature of TiO<sub>2</sub> that tends to adsorb water

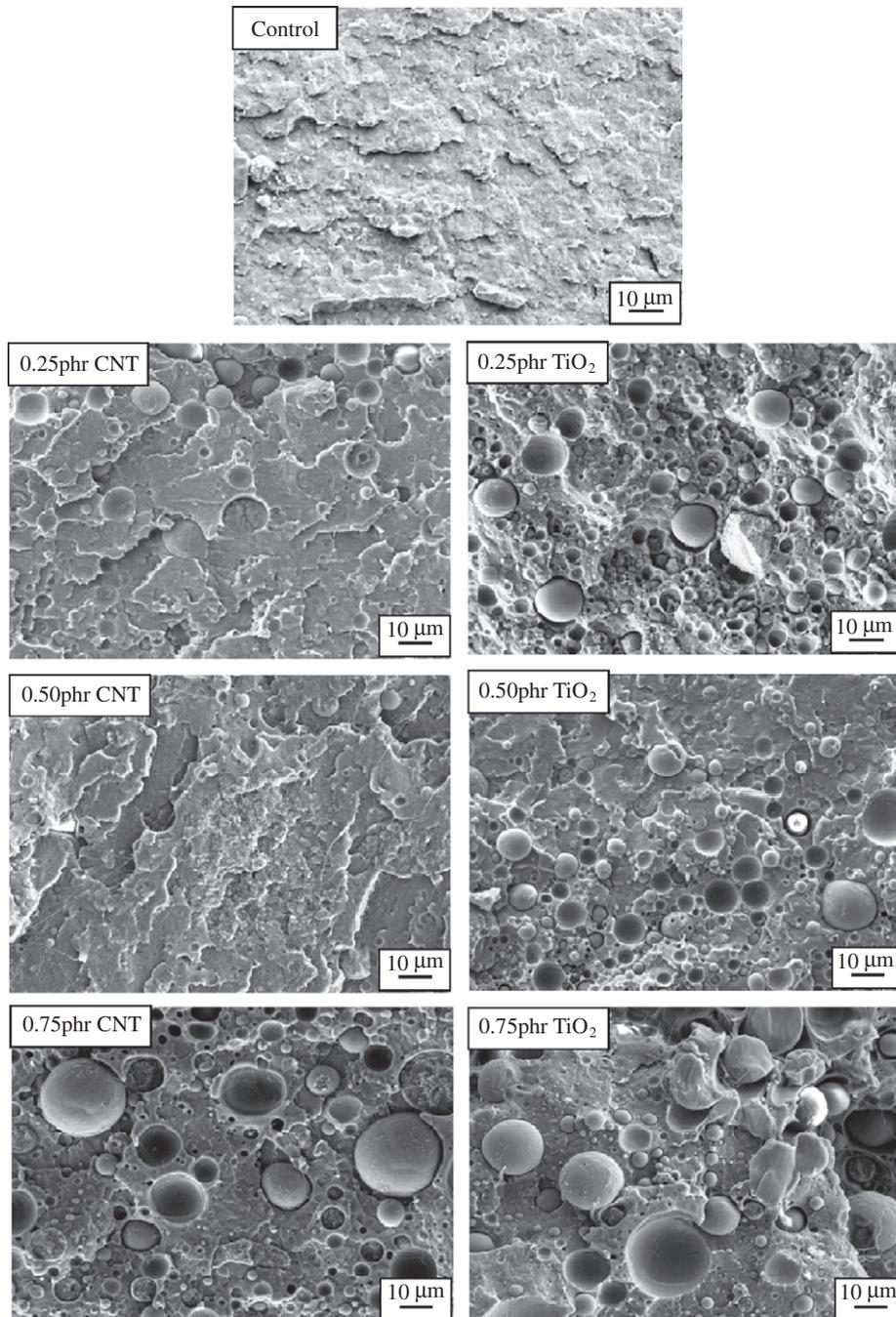


Fig. 2. FESEM micrographs of the cryofractured surface of PLLA/PBSL/CNT and PLLA/PBSL/TiO<sub>2</sub> nanocomposites with various filler loadings (500× magnification).

at the surface [39]. Thus, the addition of TiO<sub>2</sub> to the polymer blend results in an increase of water uptake. In contrast, CNT is hydrophobic in nature. Therefore, the water uptake of the PLLA/PBSL/CNT nanocomposites remains almost unchanged.

#### 3.4. pH measurement

Fig. 7 shows the change in pH of the SBF solutions with immersed PLLA/PBSL/CNT and PLLA/PBSL/TiO<sub>2</sub> nanocomposites of different filler loading throughout 28 days. The pH value of SBF decreased gradually with increasing soaking time. The decrease is caused by the release of the acidic degradation products of PLLA. Apart from that, nanocomposites with higher filler loading result in higher pH values of the SBF. The pH value of SBF with PLLA/PBSL/

TiO<sub>2</sub> is higher than that with PLLA/PBSL/CNT. This is attributed to the release of alkaline ions from the alkaline titanate layer into SBF and the ion exchange with H<sub>3</sub>O<sup>+</sup> ions in SBF which increases the pH of the surroundings [40].

#### 3.5. Weight change

Weight change of the nanocomposites as a function of soaking time in SBF at 37 °C is depicted in Fig. 8. For the PLLA/PBSL blend, the weight loss of the sample increased with increasing soaking time in SBF. A similar trend was observed in the PLLA/PBSL/CNT nanocomposites. However, weight loss in the nanocomposites is lower than that in the polymer blend. This result is consistent with

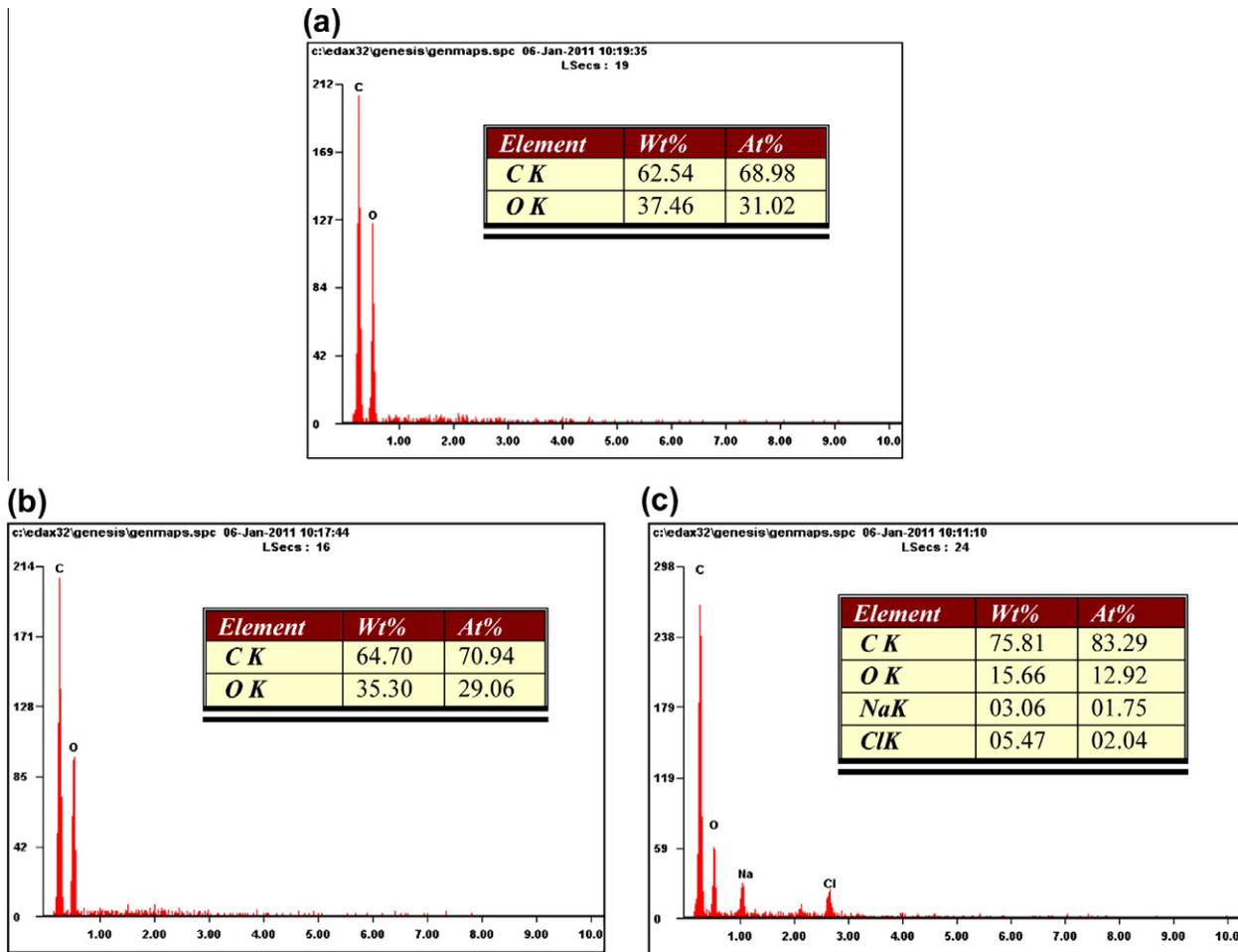


Fig. 3. EDX spectra of (a) PLLA/PBSL blend, (b) PLLA/PBSL/0.25 phr CNT nanocomposite and (c) PLLA/PBSL/0.75 phr CNT nanocomposite after soaking in SBF at 37 °C for 7 days.

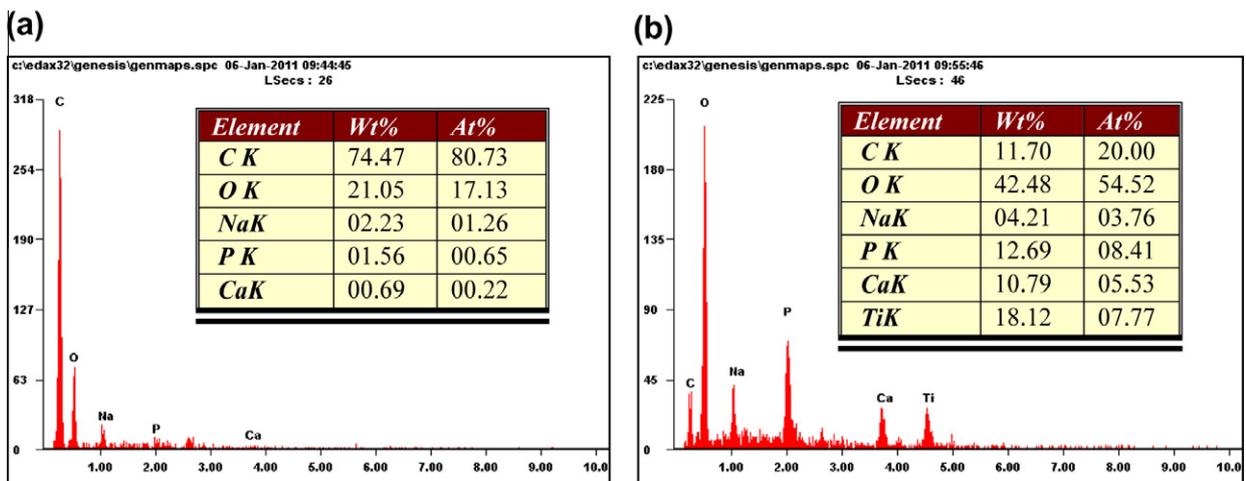


Fig. 4. EDX spectra of (a) PLLA/PBSL/0.25 phr TiO<sub>2</sub> nanocomposite and (b) PLLA/PBSL/0.75 phr TiO<sub>2</sub> nanocomposite after soaking in SBF at 37 °C for 7 days.

the pH measurement of the fluid. The weight loss of the samples resulted from the hydrolytic degradation of PLLA [3].

An increment in weight gain with increasing soaking time in SBF up to 14 days was found in the PLLA/PBSL/TiO<sub>2</sub> nanocomposites. In addition, the percentage of weight gain is higher in the PLLA/PBSL/TiO<sub>2</sub> nanocomposites with higher filler loading. This is attributed to the greater amount of apatite deposited on the

nanocomposite containing a higher amount of TiO<sub>2</sub> fillers. However, weight gain reduced after soaking in SBF for 21 days or more. This is probably due to the increase in the biodegradation of PLLA with soaking time, consequently increasing the weight loss of the samples. According to Pitt [41], PLLA undergoes hydrolytic degradation upon incubation in an aqueous medium, leading to hydrolytic cleavage of ester bonds. The cleavage of an ester bond

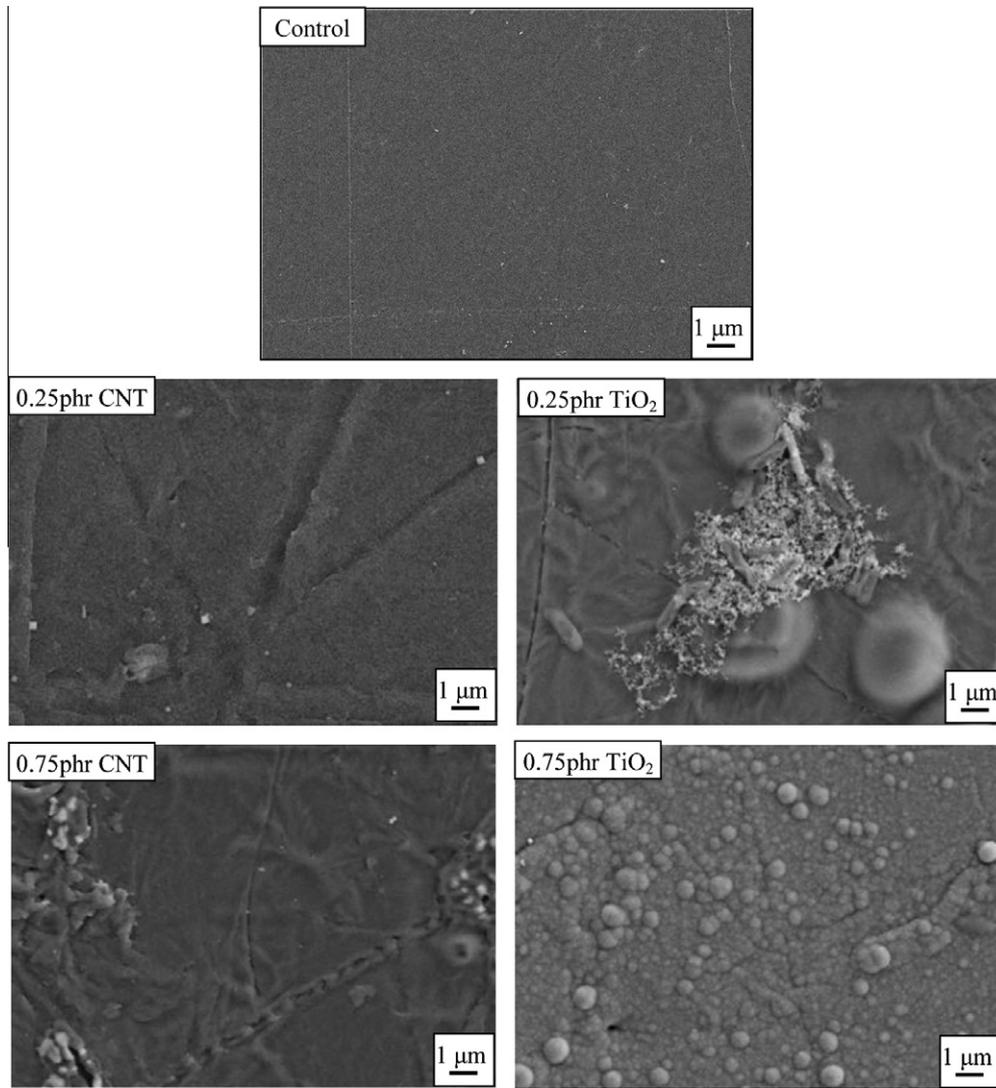


Fig. 5. FESEM micrographs of the PLLA/PBSL/CNT and PLLA/PBSL/TiO<sub>2</sub> nanocomposites' surfaces after soaking in SBF for 7 days.

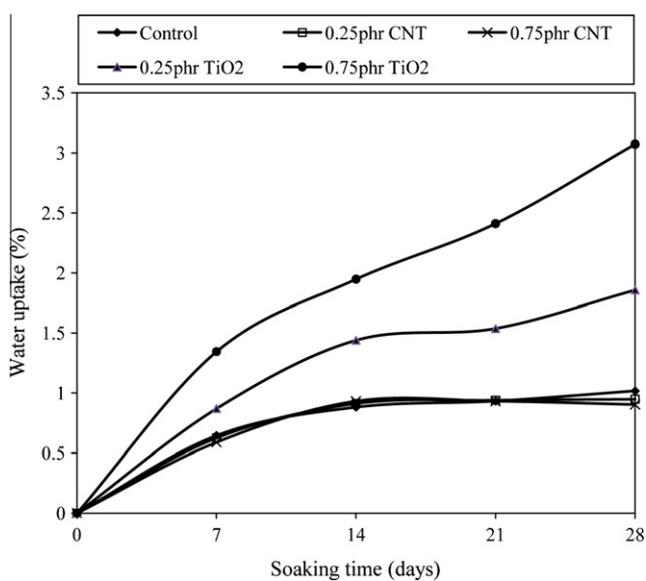


Fig. 6. Variation in water uptake of the nanocomposites as a function of soaking time in SBF.

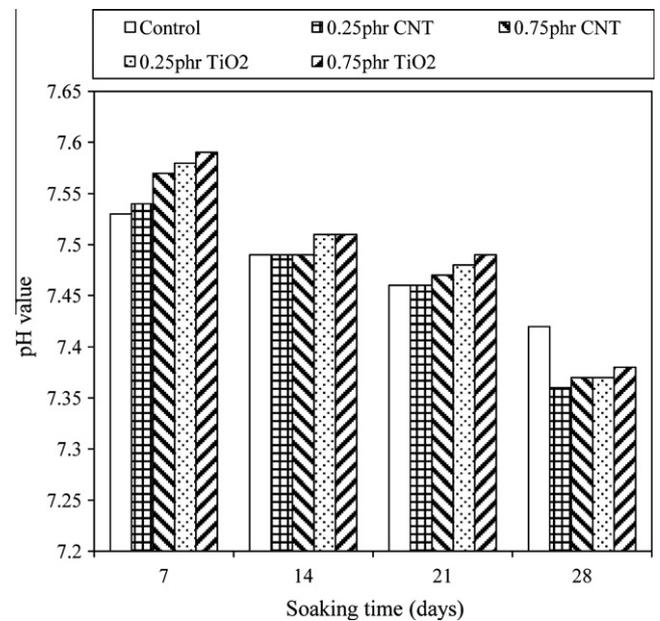


Fig. 7. Effect of filler type and loading on the pH value of the SBF as a function of soaking time.

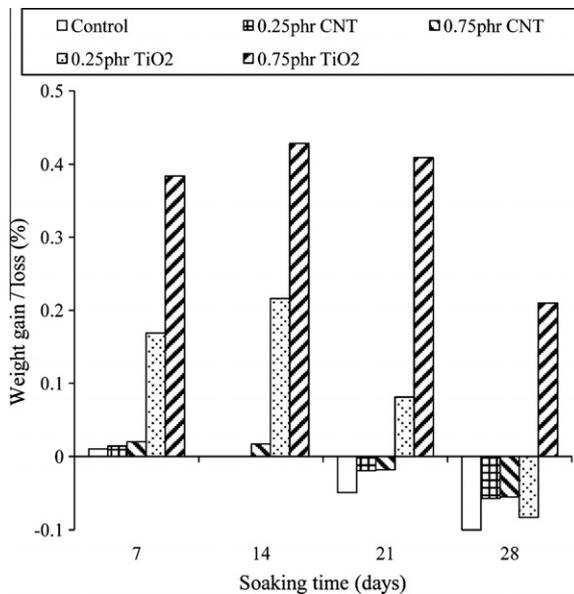


Fig. 8. Weight change of the PLLA/PBSL blends containing different filler loading of CNT and TiO<sub>2</sub> as a function of soaking time in SBF at 37 °C.

yields a carboxyl end group that is capable of catalyzing hydrolysis of the other ester bonds. As a result, the hydrolytic reaction of the remaining ester bonds is accelerated.

#### 4. Conclusion

PLLA/PBSL-based nanocomposites containing different filler loadings of CNT and TiO<sub>2</sub> nanotubes were developed by melt compounding. The PLLA/PBSL/CNT nanocomposites exhibit higher flexural strength and modulus compared to the PLLA/PBSL/TiO<sub>2</sub> nanocomposites at the same filler loading. However, the addition of TiO<sub>2</sub> nanofillers improves the bioactivity of the PLLA/PBSL blend by forming bone-like apatite particles on the surface of the nanocomposite after 7 days of SBF immersion. On the contrary, the addition of CNT did not give any positive effect on the in vitro bioactivity of PLLA/PBSL. Water uptake of the nanocomposites containing TiO<sub>2</sub> nanotubes increased with increasing filler loading, whereas the incorporation of CNT showed no significant change in the water uptake of the binary blend. A slight decrease in the pH value of SBF and a rise in the weight loss of the samples with prolonged immersion time in SBF were also observed.

#### Acknowledgment

The authors would like to acknowledge the Ministry of Higher Education Malaysia and Universiti Sains Malaysia for the USM-RU-PRGS research Grant (No. 8043044), USM Fellowship, and research facilities.

#### References

- Drumright RE, Gruber RE, Henton DE. Polylactic acid technology. *Adv Mater* 2000;12(23):1841–6.
- Lunt J. Large-scale production, properties and commercial applications of polylactic acid polymers. *Polym Degrad Stab* 1998;59:145.
- Ikada Y, Tsuji H. Biodegradable polyesters for medical and ecological applications. *Macromol Rapid Commun* 2000;21:117.
- Auras R, Harte B, Selke S. An overview of polylactides as packaging materials. *Macromol Biosci* 2004;4:835.
- Park JW, Im SS. Phase behavior and morphology in blends of poly(L-lactic acid) and poly(butylene succinate). *J Appl Polym Sci* 2002;86:647–55.
- Vilay V, Mariatti M, Zulkifli A, Todo M. Characterization of the mechanical and thermal properties and morphological behavior of biodegradable poly(L-

- lactide)/poly( $\epsilon$ -caprolactone) and poly(L-lactide)/poly(butylene succinate-co-L-lactate) polymeric blends. *J Appl Polym Sci* 2009;114:1784–92.
- Aslan S, Calandrelli L, Laurienzo P, Malinconico M, Migliarese C. Poly(D,L-lactic acid)/poly(caprolactone) blend membranes: preparation and morphological characterization. *J Mater Sci* 2000;35:1615–22.
- Chou PM, Mariatti M, Zulkifli A, Todo M. Changes in the crystallinity and mechanical properties of poly(L-lactic acid)/poly(butylene succinate-co-L-lactate) (PLLA/PBSL) blend with annealing process. *Polym Bull* 2011;67(5):815–30.
- Hench LL, Polak JM. Third-generation biomedical materials. *Science* 2002;295(5557):1014.
- Kasaga T, Yoshio O, Masayuki N, Yoshihiro A. Preparation and mechanical properties of polylactide acid composites containing hydroxyapatite fibres. *Biomaterials* 2001;22:9–23.
- Bleach NC, Nazhat SN, Tanner KE, Kellomaki M, Tormala P. Effect of filler content on mechanical and dynamic mechanical properties of particulate biphasic calcium phosphate polylactide composites. *Biomaterials* 2002;23:1579–85.
- Zhang K, Wang Y, Hillmayer MA, Francis LF. Processing and properties of porous poly(L-lactide)/bioactive glass composites. *Biomaterials* 2004;25:248–500.
- Siegel RW. Creating nanophase materials. *Sci Am* 1996;275:42–7.
- Temenoff JS, Lu L, Mikos AG, Daveis JE. Bone engineering. *EM Squared: Toronto*; 2000. p. 445–73.
- Ramires PA, Romito A, Cosentino F, Milella E. The influence of titania/hydroxyapatite composite coatings on in vitro osteoblasts behaviour. *Biomaterials* 2001;22:1467–74.
- Fujishima A, Rao TN, Tryk DA. Titanium dioxide photocatalysis. *J Photochem Photobiol C* 2000;1:1.
- Moritz N, Jokinen M, Peltola T, Areva S, Yli-Urpo A. Local induction of calcium phosphate formation on TiO<sub>2</sub> coatings on titanium via surface treatment with a CO<sub>2</sub> laser. *J Biomed Mater Res* 2003;65A:9.
- Areva S, Paldan H, Peltola T, Nürhi T, Jokinen M, Lindén M. Use of sol-gel-derived titania coating for direct soft tissue attachment. *J Biomed Mater Res* 2004;70A:169.
- Dalby MJ, McCloy D, Robertson M, Wilkinson CDW, Oreffo RC. Osteoprogenitor response to defined topographies with nanoscale depths. *Biomaterials* 2006;27(8):1306–15.
- Torres FG, Nazhat SN, Sheikh SH, Fadzullah MD, Maquet V, Boccaccini AR. Mechanical properties and bioactivity of porous PLGA/TiO<sub>2</sub> nanoparticle-filled composites for tissue engineering scaffolds. *Compos Sci Technol* 2007;67:1139–47.
- Correa-Duarte MA, Wagner N, Rojas-Chapana J, Morszczek C, Thie M, Giersig M. Fabrication and biocompatibility of carbon nanotube-based 3D networks as scaffolds for cell seeding and growth. *Nano Lett* 2004;4(11):2233–6.
- Gheith MK, Sinani VA, Wicksted JP, Matts RL, Kotov NA. Single-walled carbon nanotube polyelectrolyte multilayers and freestanding films as a biocompatible platform for neuroprosthetic implants. *Adv Mater* 2005;17(22):2663–70.
- Shi XF, Hudson JL, Spicer PS, Tour JM, Krishnamoorti RM, Mikos AG. Injectable nanocomposites of single-walled carbon nanotubes and biodegradable polymers for bone tissue engineering. *Biomacromolecules* 2006;7(7):2237–42.
- Mei F, Zhong JS, Yang XP, Ouyang XY, Zhang S, Hu XY, et al. Improved biological characteristics of poly(L-lactic acid) electrospun membrane by incorporation of multiwalled carbon nanotubes/hydroxyapatite nanoparticles. *Biomacromolecules* 2007;8:3729–35.
- Gerhardt LC, Jell GMR, Boccaccini AR. Titanium dioxide (TiO<sub>2</sub>) nanoparticles filled poly(D,L lactid acid) (PDLLA) matrix composites for bone tissue engineering. *J Mater Sci Mater Med* 2007;18:1287–98.
- Wei J, Chen QZ, Stevens MM, Roether JA, Boccaccini AR. Biocompatibility and bioactivity of PDLLA/TiO<sub>2</sub> and PDLLA/TiO<sub>2</sub>/Bioglass® nanocomposites. *Mater Sci Eng C* 2008;28:1–10.
- Sreekantan S, Lai CW. Study on the formation and photocatalytic activity of titanate nanotubes synthesized via hydrothermal method. *J Alloys Compd* 2010;490:436–42.
- ASTM D790-03 standard test method for flexural properties of unreinforced and reinforced plastics and electrical insulating materials. Philadelphia: The American Society for Testing and Materials, Annual Book of ASTM Standards; 2005. p. 149–59.
- Kokubo T, Takadama H. How useful is SBF in predicting in vivo bone bioactivity? *Biomaterials* 2006;27:2907–15.
- Watt IM. The principles and practice of electron microscopy. 2nd ed. Cambridge: Cambridge University Press; 1997.
- Ou BL, Li DX. The effect of functionalized-TiO<sub>2</sub> on the mechanical properties of PP/PA6/functionalized-TiO<sub>2</sub> nanocomposites prepared by reactive compatibilization technology. *J Compos Mater* 2009;43:1361.
- Wu DF, Zhang YS, Zhang M, Yu W. Selective localization of multiwalled carbon nanotubes in poly( $\epsilon$ -caprolactone)/polylactide blend. *Biomacromolecules* 2009;10:417–24.
- Hasook A, Muramatsu H, Tanoue S, Iemoto Y, Unryu T. Preparation of nanocomposites by melt compounding polylactic acid/polyamide 12/organoclay at different screw rotating speeds using a twin screw extruder. *Polym Compos* 2008;29:1–8.
- Hench LL. Bioceramics. *J Am Ceram Soc* 1998;81:1705–28.

- [35] Song M, Pan C, Li JY, Wang XM, Gu ZZ. Electrochemical study on synergistic effect of the blending of nano TiO<sub>2</sub> and PLA polymer on the interaction of antitumor drug with DNA. *Electroanalysis* 2006;18:1995–2000.
- [36] Nakayama N, Hayashi T. Preparation and characterization of poly (L-lactic acid)/TiO<sub>2</sub> nanoparticle nanocomposite films with high transparency and efficient photodegradability. *Polym Degrad Stab* 2007;92:1255–64.
- [37] Boehm HP. Acidic and basic properties of hydroxylated metal oxide surface. *Discuss Faraday Soc* 1971;52:264–75.
- [38] Mohn D, Ege D, Feldman K, Schneider OD, Imfeld T, Boccaccini AR, et al. Spherical calcium phosphate nanoparticle fillers allow polymer processing of bone fixation devices with high bioactivity. *Polym Eng Sci* 2010;50:952–60.
- [39] Wang R, Hashimoto K, Akira Fujishima A, Chikuni M, Kojima E, Kitamura A, et al. Photogeneration of highly amphiphilic TiO<sub>2</sub> Surfaces. *Adv Mater* 1998;10(2):135–8.
- [40] Gil FJ, Padrós A, Manero JM, Aparicio C, Nilsson M, Planell JA. Growth of bioactive surfaces on titanium and its alloys for orthopaedic and dental implants. *Mater Sci Eng C* 2002;22:53–60.
- [41] Pitt CG. Non-microbial degradation of polyesters: mechanisms and modifications. In: Vert M, Feijen J, Albertsson A, Scott G, Chiellini E, editors. *Biodegradable polymers and plastics*. London: Royal Society of Chemistry; 1992. p. 7–19.