Sol–gel synthesis, structure and bioactivity of Polycaprolactone/CaO • SiO_2 hybrid material

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A method has been developed to cast novel organic/inorganic polymer hybrids from multicomponent solutions containing tetramethyl orthosilicate, calcium nitrate tetrahydrate, polycaprolactone, water, and methylethyketone via sol–gel process. The existence of the hydrogen bonds between organic and inorganic components of the hybrid and hydroxyapatite formation on the surface was proved by Fourier transform infrared analysis. The morphology of the hybrid material was studied by scanning electron microscopy. The structure of a molecular level dispersion was disclosed by atomic force microscopy, pore size distribution, and surface measurements. The infrared spectra of the hybrid relative to sample soaked in a fluid simulating the composition of human blood plasma suggests that polycaprolactone/CaO • SiO_2 hybrid material synthesised via sol–gel process is bioactive as well as the CaO • SiO_2 gel glass.

1. Introduction

The sol–gel process has proved to be versatile and has been widely used in the preparation of organic/inorganic hybrid materials [1–3], nonlinear optical materials [4–7], and mesomorphic materials [8, 9]. The sol–gel chemistry is based on the hydrolysis and polycondensation of metal alkoxides $M(OR)_x$, where $M =$ Si, Sn, Ti, Al, Mo, V, W, Ce, etc. The following sequence of reactivity is usually founds $(OR)_4 \ll Sn(OR)_4 = Ti(OR)_4 < Zr(OR)_4 = Ce(OR)_4$ [3]. Because silicon alkoxides are not very reactive, the sol–gel process with silicon alkoxides is slow and easy to control in order to produce a transparent gel. There is considerable interest in organic–inorganic hybrid/composite materials prepared via the sol–gel process. A variety of organic polymers have been introduced into inorganic networks to yield hybrid or composite materials with or without covalent bonds between the polymer and inorganic components. The sol–gel reactions are known to be affected by many synthetic parameters such as structure and concentration of the reagents, solvents, and catalysts as well as reaction temperature and rate of removal of by-products and solvents [10–12]. In particular, the presence of organic components, modifies the morphology and physical properties of the sol–gel products. For example, the base-catalysed sol–gel reaction usually results in translucent or opaque products with visible organic–inorganic phase separation. Under acid catalysis and carefully controlled reaction conditions, transparent and monolithic hybrid/composite materials can be obtained.

Recently, a family of monolithic and transparent hybrid materials have been synthesised via the acid- or photo-acid-catalysed sol–gel reactions of an inorganic precursor, such as tetraethyl orthosilicate (TEOS), with polymer precursors that contain reactive alkoxysilyl groups [13–17]. A key issue that remains unresolved in these organic-modified materials is the degree of mixing of the organic–inorganic components, that is, the phase homogeneity. The high optical transparency to visible light indicates that the organic–inorganic phase separation, if any, is on a scale of ≤ 400 nm. Many conventional methods for analysing composite materials have not proved to be effective. For example, the changes in and disappearance of a well-defined glass transition of the polymer component as measured by differential scanning calorimetry (DSC) or dynamic mechanical analysis (DMA) suggest the diminution of phase separation but offer little quantitative information [18–21]. Transmission electron microscopy (TEM) often fails to provide useful morphological data because of weak contrast [18]. Recently, there have been several reports with encouraging examples of applying atomic force microscopy (AFM) in the analysis of sol–gel materials [18–22].

Recently, the study of organic–inorganic nanocomposites' networks and gel became an expanding field of investigation [23–25]. At first glance, these materials are

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considered as biphasic materials, where the organic and inorganic phases are mixed at the nm to sub-μm scales. Nevertheless, it is obvious that the properties of these materials are not just the sum of the individual contributions from both phases; the role of the inner interfaces could be predominant.

It is known that $CaO \bullet SiO_2$ glasses are bioactive, that is, they are able to bond to living bone [26]. As reported in the literature [26, 27], the essential condition for glasses and glass–ceramics to bond to living bone is the formation of a bone-like apatite layer on the surfaces. ''*In vitro*'' studies are performed [26, 27] by soaking the glasses in a simulated body fluid (SBF) to study hydroxyapatite formation on the surface.

In this paper, polycaprolactone/$CaO \bullet SiO_2$ hybrid materials have been prepared via sol–gel process. The organic component was chosen taking into account the biodegradable and biocompatible nature of the polycaprolactone. Fourier transform infrared (FTIR) analysis proved the existence of hydrogen bonds between organic and inorganic components of the hybrid and hydroxyapatite formation on the surface. The homogeneity of the sample was studied using scanning electron microscopy (SEM) and atomic force microscopy (AFM).

2. Experimental

A hybrid inorganic/organic material was prepared by means of sol–gel process from analytical reagent grade tetra methyl orthosilicate (TMOS) (Sigma-Aldrich) calcium nitrate tetrahydrate and polycaprolactone (PCL $M_w = 65\,000$). Fig. 1 shows the flow chart of glass synthesis by the sol–gel method. Molar ratio of the starting materials is indicated in the figure. An alcoholic solution of TMOS was mixed under continuous stirring with $Ca(NO_3)_2 \bullet 4H_2O$ (Sigma-Aldrich) diluted in C_2H_5OH (Sigma-Aldrich) at room temperature. To this solution was added a homogeneous solution prepared PCL diluted in minimum quantity of methylethyketone (MEK) (Sigma-Aldrich) for polymer solubilisation. As can be seen, water was added with calcium nitrate. After gelation the gel was dried in air. A powder containing 6% of organic component have been thus obtained.

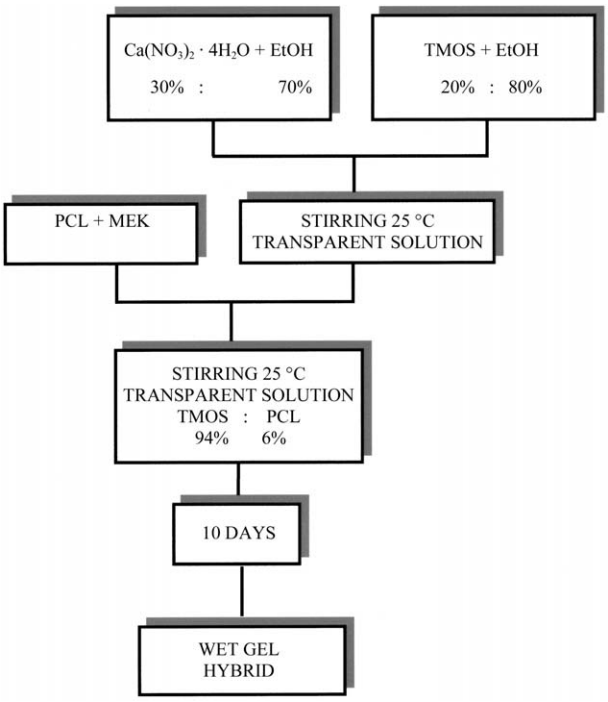


Figure 1 Flow chart of hybrid synthesis.

The microstructure of the synthesized gel was studied using a SEM, Cambridge model S-240, on pelletised discs previously coated with a thin Au film and by a Digital Instruments Multimode AFM in contact mode in air.

In order to study their bioactivity, samples of the studied hybrid materials were soaked in a (SBF) with ion concentrations nearly equal to those of the human blood plasma as reported elsewhere [27]. During soaking the temperature was kept fixed at 37 °C. The ability to form an apatite layer was studied by submitting the reacted samples to IR spectroscopy. Powers (170 × 230 mesh) were soaked in SBF and analysed in IR spectroscopy. Taking into account that [28–30] the ratio of the exposed surface to the solution volume influences the reaction, a constant ratio of $50\,mm^2ml^{-1}$ of solution was used, as in [27].

Fourier transform infrared transmittance spectra were recorded using a Mattson 5020 system, equipped with a DTGS KBr (Deuterated Triglycine Sulphate with potassium bromide windows) detector, with a resolution of $2\,cm^{-1}$ (20 scans). KBr pelletised discs containing 2 mg of sample and 200 mg KBr were made. The FTIR spectra were elaborated by means of a Mattson software (FTIR Macros).

The FTIR was also used to prove the existence of hydrogen bonds between the organic and inorganic components of the hybrid material.

The XRD measurements have been carried out on PCL/$CaO \bullet SiO_2$ and $CaO \bullet SiO_2$ gel powders using a Philips diffractometer. Powders of each sample were scanned in $2\Theta = 5$–$60°$ range using Cu Kα radiation.

3. Result and discussion

Gelation is the result of hydrolysis and condensation reactions according to the following reactions

$$-Si(OCH_3)_4 + nH_2O \Rightarrow Si(OCH_3)_{4-n}(OH)_n + nCH_3OH \quad (1)$$

$$-SiOH + CH_3O-Si- \Rightarrow -Si-O-Si- + CH_3OH \quad (2)$$

$$-Si-OH + OH-Si \Rightarrow -Si-O-Si- + H_2O \quad (3)$$

The reaction mechanism is not known in detail; however, it is generally accepted that they proceed through a second order nucleophilic substitution [31]. The interaction between the electrophilic agent (TMOS) and the nucleophilic agent (H_2O or $C_2H_5O^-$) gives rise to addition reaction (Equation 1). C_2H_5OH acts as the mutual solvent (TMOS and $Ca(NO_3)_2 \bullet 4H_2O$). MEK was chosen to dissolve PCL, owing the good solubility of the polymer in this solvent. The main problem in MEK use is its toxicity, therefore it is employed in a very small amount. Moreover the good volatility of the MEK allows its removal during the drying of gel.

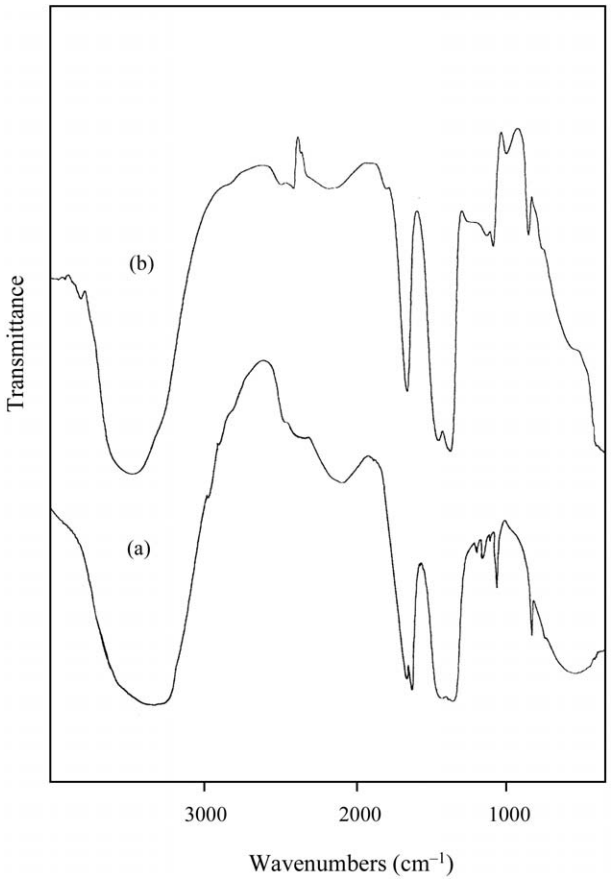
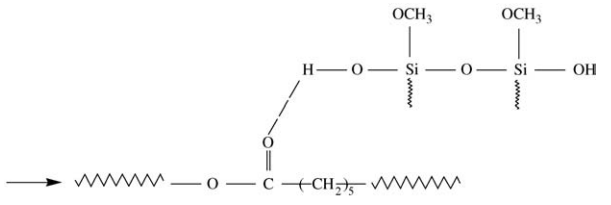


Figure 2 FTIR of (a) hybrid and (b) $CaO \bullet SiO_2$ recorded in 400-4000 cm^{-1} region.

FTIR measurements were employed to ascertain the nature of the synthesised hybrid material. The nature of the interface has been used recently to divide these materials into two distinct classes [32]. In class I, organic and inorganic compounds are embedded and only weak bonds (hydrogen, van der Waals, or ionic bonds) give the cohesion to the whole structure. They result from much research work emerging from sol–gel and polymer chemists and these materials will present a large diversity in their structures and final properties. In class II materials, the phases are linked together through strong chemical bond (covalent or ionic–covalent bonds).

Fig. 2 shows the infrared spectrum of (a) the hybrid and (b) a $CaO \bullet SiO_2$ gel. In Fig. 2(b) the bands at 3400 and 1600 cm^{-1} are attributed to water [33, 34]. The 1400 cm^{-1} band is due to NO_3^- stretching modes [33]. The bands at 1080 and 470 cm^{-1} are due to the stretching and bending modes of SiO_4 tetrahedra [35, 36]. In Fig. 2(a) the bands at 2950 and 2853 cm^{-1} are attributed to the symmetric stretching of $-CH_2-$ of polycaprolactone. The band at 1715 cm^{-1} is due to the characteristic carboxylic group shifted to low wave numbers, the broad band at 3200 cm^{-1} is the characteristic O–H group of hydrogen bonds.



(4)

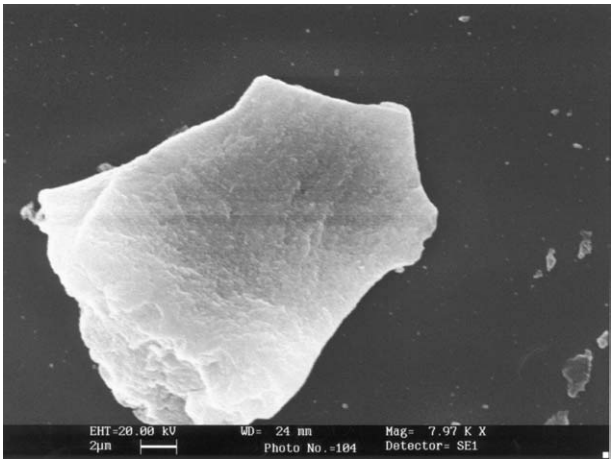


Figure 3 SEM micrograph of $CaO \bullet SiO_2$.

Reaction (4) shows the hydrogen bonds presumed to occur between the carboxylic groups of organic polymer and the hydroxyl groups of inorganic matrix.

The microstructure of the PCL/$CaO \bullet SiO_2$ hybrid material was studied by SEM and AFM.

Scanning electron microscopy micrographs of a $CaO \bullet SiO_2$ gel sample and of PCL/$CaO \bullet SiO_2$ gel sample are shown in Figs. 3 and 4. A marked difference can be observed between the morphology of the two crystalline materials. This result indicates that PCL plays an essential role in the crystallisation of the $CaO \bullet SiO_2$ system, the nature of the crystallising phase is strongly affected by the presence of the polymeric component as can be detect by the XRD patterns of Fig. 5. Moreover this result, according with those obtained by FTIR measurements, suggests the formation of links (hydrogen bonds) between the polymeric component and the growing $CaO \bullet SiO_2$ nuclei during the sol–gel synthesis.

The degree of mixing of the organic–inorganic components, that is, the phase homogeneity has been ascertained by applying the AFM in the analysis of the sol–gel hybrid material. The AFM contact mode image can be measured in the height mode or in the force mode. Force images (z range in nN) have the advantage that they appear sharper and richer in contrast and that the contours of the nanostructure elements are clearer. In contrast, height images (z range in nm) show a more exact reproduction of the height itself [37]. In this work

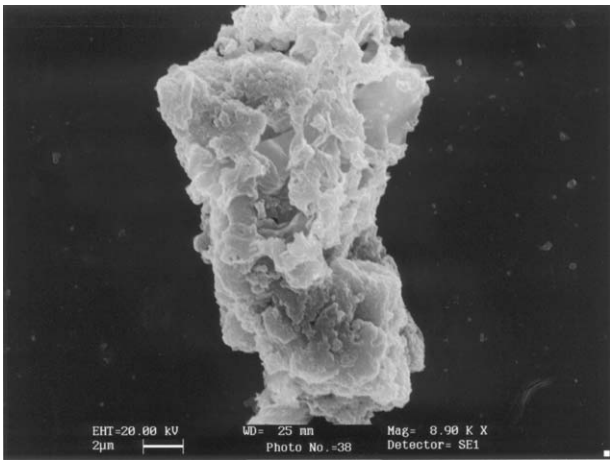


Figure 4 SEM micrograph of hybrid.

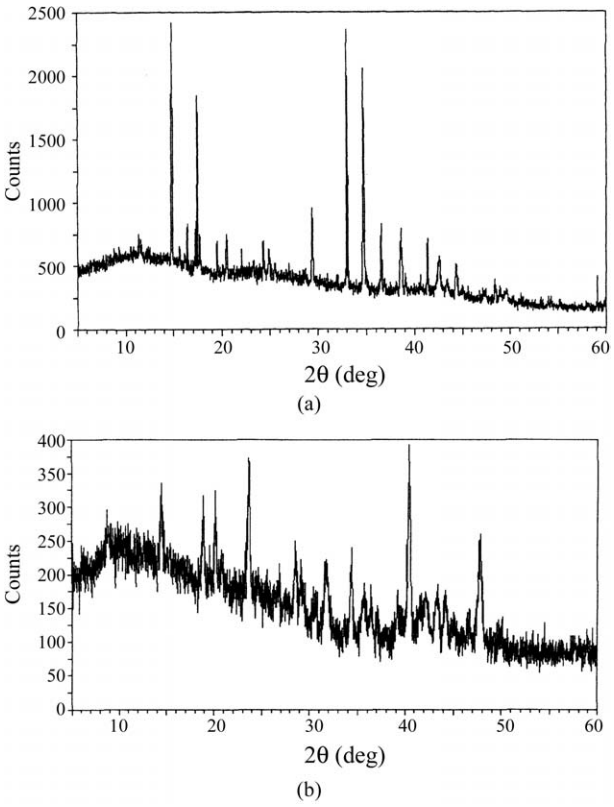


Figure 5 XRD patterns of (a) $CaO \bullet SiO_2$ gel; (b) $PCL/CaO \bullet SiO_2$ hybrid.

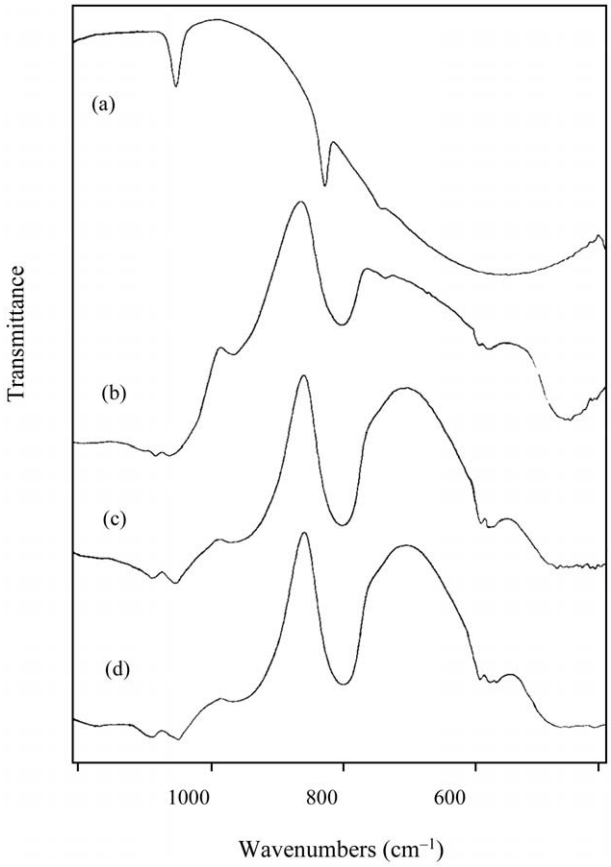


Figure 7 FTIR spectra of hybrid after different times of exposed (a) not exposed; (b) 7 days, (c) 14 days, (d) 21 days recorded in 400–1200 cm^{-1} region.

the height mode has been adopted to evaluate the degree of homogeneity of the hybrid material. The AFM topographic images of $PCL/CaO \bullet SiO_2$ gel samples is shown in Fig. 6. As can be observed, the average domain is less than 400 nm. This result confirm that the $PCL/CaO \bullet SiO_2$ gel synthesised can be considered an organic/inorganic hybrid material as suggested by literature data [38].

The hybrid material was soaked in SBF, as suggested in Hench and Clark [28] for *in vitro* bioactivity tests. The results are reported in Fig. 7. In particular the IR spectra after different exposures to SBF, for 7, 14, and 21 days are shown. In Fig. 7 evidence of formation of a hydroxyapatite layer is given by the appearance of the 1116 and 1035 cm^{-1} bands, usually assigned to P–O stretching [36], and of the 580 cm^{-1} band usually assigned to the P–O bending mode [36]. The splitting, after only seven days soaking, of the 580 cm^{-1} band into two others at 610 and at 570 cm^{-1} can be attributed to formation of crystalline hydroxyapatite [34]. Finally the band at 800 cm^{-1} can be assigned to the Si–O–Si band vibration between two adjacent tetrahedra characteristic of silica gel [36]. This supports the hypothesis that a surface layer of silica gel forms as supposed in the mechanism proposed in the literature for hydroxyapatite deposition [27, 36].

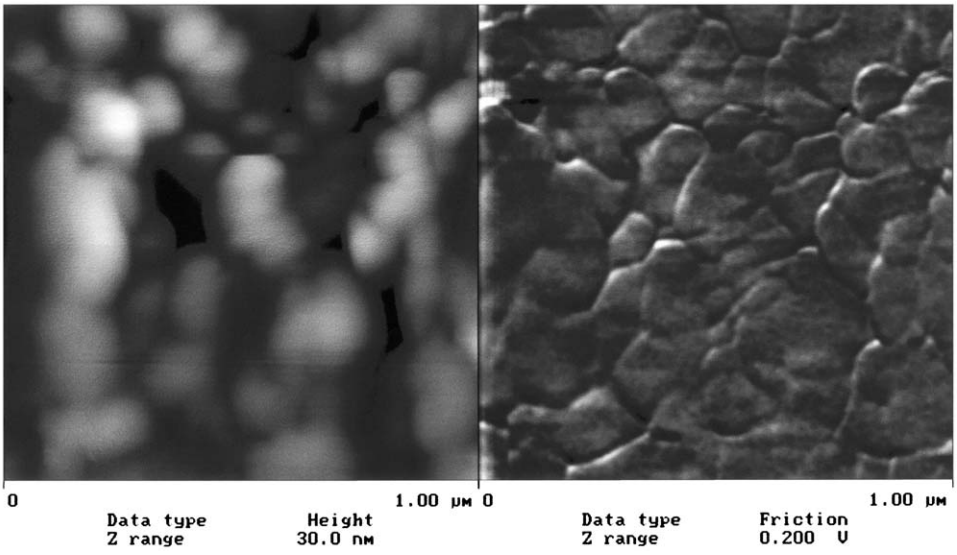


Figure 6 AFM images showing the morphology structure of $CaO \bullet SiO_2$ hybrid.

4. Conclusion

The PCL/CaO • SiO_2, prepared via sol–gel process, was found to be an organic/inorganic hybrid material. The polymer (PCL) was incorporated into network by hydrogen bond between the carboxylic group of organic polymer and the hydroxyl group of inorganic matrix. The formation of hydrogen bonds was ascertained by FTIR measurements. Moreover the AFM and SEM analysis confirm that the PCL/CaO • SiO_2 can be considered a homogeneous organic/inorganic hybrid material because the grains are less than 400 nm in size.

Finally the formation of a layer of hydroxyapatite on the surface when the sample was soaked in SBF showed by FTIR spectra indicates that the PCL/CaO • SiO_2 hybrid can be considered a bioactive material.

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