Novel alkali free bioactive fluorapatite glass ceramics

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ABSTRACT

Alkali free bioactive glasses with the presence of Ca/SrF$_2$ were synthesized and then characterised by Differential Scanning Calorimetry, X-ray Diffraction, Fourier Transform Infrared Spectroscopy and Magic Angle Spinning–Nuclear Magnetic Resonance Spectroscopy. The crystallisation of the glasses was explored by heat treatment. An increased crystallisation tendency of the as quenched glasses was evident with an increase in the Ca/SrF$_2$ content, where Ca$_{10}$(PO$_4$)$_6$F$_2$ (fluorapatite), Ca$_4$Si$_2$O$_7$F$_2$ (cuspidine) and CaF$_2$ crystallise in sequence for the Ca-containing system, and Sr$_{10}$(PO$_4$)$_6$F$_2$, SrSiO$_3$ and SrF$_2$ for the Sr-containing system. Upon heat treatment, Ca$_{10}$(PO$_4$)$_6$F$_2$ or Sr$_{10}$(PO$_4$)$_6$F$_2$, which is mainly nucleated from bulk is the primary crystalline phase. Although partially crystallised these sodium free fluorapatite glass ceramics are proposed to have enhanced bioactivity comparable to bioactive glasses.

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1. Introduction

Bioactive glasses and glass ceramics with the ability to form apatite-like phases on heat treatment or on being exposed in physiological solution have been used extensively in medicine and dentistry [1,2]. Apatite glass ceramics are attractive as bone fillers and implant materials, as a result of their favourable biocompatibility and osteoconductivity arising from the presence of apatite [3,4]. Kokubo et al. [5] developed an apatite wollastonite (AW) glass ceramics system, which has high mechanical strength and shows good chemical bonding with living tissue. However, as this system surface nucleates, it has to be sintered and then machined to shape, which is unattractive commercially. In addition, the extremely low CaF$_2$ content (<1 mol%) used in AW formulations results in a restricted amount of fluoride substitution in apatite and mixed oxy-fluorapatite crystals formation [3].

The castable apatite mullite (AM) glass ceramics based on the CaO–Al$_2$O$_3$–SiO$_2$–P$_2$O$_5$–CaF$_2$ system synthesized by Rafferty et al. [6] predominantly bulk nucleate and crystallise to fluorapatite (FAP) and mullite crystals. These bioactive glass ceramics can have high fracture toughness and strength and as a consequence of exhibiting bulk nucleation can be readily cast to shape. Nevertheless, the possibility of toxicity caused by the release of aluminium in vivo is perceived as being problematic for AM glass ceramics.

Brauer and co-workers [7,8] successfully developed two glass ceramic series with different amounts of P$_2$O$_5$ in the system of Na$_2$O–CaO–SiO$_2$–

P$_2$O$_5$–CaF$_2$. Mixed sodium calcium fluoride phosphate, FAP, and combeite (Na$_2$Ca$_2$Si$_3$O$_9$) were found as the main crystalline phases in the glasses with high P$_2$O$_5$ content (>4.7 mol%) [7], whilst no FAP crystallised from low P$_2$O$_5$ (<1.1 mol%) containing glasses [8]. Brauer et al. also found that a sodium free high P$_2$O$_5$ containing bioactive glass composition crystallised to FAP. Thus, it is clear that the crystallisation of apatite from glass is strongly influenced by the phosphate content. The presence of sodium is often considered to be essential for bioactive glasses to achieve bioactivity. However, recently, apatite formation in simulated body fluid was also found for glass and glass ceramics that contain no sodium [9–11]. Furthermore, sodium free formulations of bioactive sol–gel glasses have been known for a long time [12] in addition to recently developed hybrid materials [13]. This suggests that sodium is not an essential component for bioactive glasses and glass ceramics [14–16]. In fact high sodium content can cause undesirable rapid rise in pH and a cytotoxic effect.

Fluorapatite (Ca$_{10}$(PO$_4$)$_6$F$_2$) is analogous to hydroxyapatite (Ca$_{10}$(PO$_4$)$_6$(OH)$_2$; HAP), which is close to the main mineral component of bones and teeth [17,18]. However, FAP is much more stable in acidic environment (pH < 4) compared to HAP, this is extremely favourable in dentistry.

The Sr^{2+} cation is chemically similar to the Ca^{2+} cation but slightly larger in size (effective ionic radius: 1.16 vs 0.94 Å), and therefore it can potentially replace Ca^{2+} in the apatite crystal lattice to form strontium fluoride apatite (Sr$_{10}$(PO$_4$)$_6$F$_2$) [19]. Strontium has the capacity to facilitate enamel remineralisation [20], and the incorporation of strontium into bioactive glasses was reported to promote osteoblast proliferation and reduce osteoclast resorbtion [21,22]. Hence, the strontium containing bioactive glasses are attractive for dental remineralisation and bone regeneration.

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To minimize the disadvantages caused by the presence of sodium and also leverage the benefits by introducing fluoride into glasses, the aim of this paper is to investigate the influence of CaF_2 and SrF_2 content on the crystallisation behaviour of the novel sodium free, high phosphate content bioactive glasses.

2. Materials and methods

2.1. Glass synthesis

Novel sodium free fluoride containing bioactive glasses were designed by introducing CaF_2/SrF_2 into the SiO_2–P_2O_5–CaO ternary glass system (Table 1). Glasses were synthesized by a melt–quench method with analytical grade silica (Prince Minerals Ltd., Stoke-on-Trent, UK), calcium carbonate, phosphorus pentoxide and calcium fluoride or strontium fluoride (all Sigma-Aldrich, Gillingham, UK). A 200 g batch was melted in a 300 ml platinum/rhodium crucible for 1 h in an electrical furnace (EHF 17/3, Lenton, UK). The melting temperature was 1550 °C for glasses with 0 and 3 mol% CaF_2 and 1500 °C for the rest. The melted glasses were quenched into cold deionised water to suppress crystallisation. The as quenched granular glass frit was dried overnight and ground into powder by a vibratory mill (Gyro mill, Glen Creston, UK) for 14 min. The resultant powder was sieved through a 45 μm test sieve (Endecotts Ltd, UK) to obtain fine powder.

2.2. Glass characterisation

2.2.1. X-ray diffraction (XRD)

The amorphous state of the glasses synthesised in the present study was characterised by an X'Pert Pro X-ray diffractometer (PANalytical, The Netherlands) with a copper (Ni-filtered Cu-Kα) X-ray source. The XRD patterns of the glasses were recorded between 5 and 70° 2θ with a step size of 0.0334° and a step time of 200.03 s. Phase identification was carried out by using X'Pert HighScore Plus (v2.0, PANalytical, The Netherlands) in conjunction with the ICDD PDF-4 database.

2.2.2. Fourier Transform Infrared Spectroscopy (FTIR)

Attenuated Total Reflectance–Fourier Transform Infrared Spectroscopy (Spectrum GX, Perkin-Elmer, USA) was used to analyse the chemical bonding in the glass powder and heat treated samples. Ten scans were performed for each sample, and the data were collected for wavenumbers from 500 to 1600 cm^{-1}.

2.2.3. Magic Angle Spinning–Nuclear Magnetic Resonance (MAS–NMR)

^{31}P and ^{19}F MAS–NMR were employed to investigate glass structure and crystalline phases by using a 600 MHz (14.1T) Bruker solid state NMR Spectrometer. Experiments were carried out at spinning rates of 18 or 21 kHz and resonance frequencies of 242.9 and 564.7 MHz for ^{31}P and ^{19}F MAS–NMR, respectively. Recycle delay time was 60 s for ^{31}P and 30 s for ^{19}F. Typically 16 or 32 scans were used for ^{31}P, whilst 32 or 64 scans were adopted for ^{19}F MAS–NMR. Chemical shift for ^{31}P and ^{19}F was referenced by using 85% H_3PO_4 and 1 M NaF solution; the latter signal was adjusted to –120 ppm relative to $CFCl_3$.

2.2.4. Differential Scanning Calorimetry (DSC)

Differential Scanning Calorimetry (DSC) was used to characterise the thermal properties of the glasses. Glass frit or fine powder (50 ± 1 mg) were heated under Nitrogen (60 ml/min^{-1}) at a rate of 20 °C/min from room temperature up to 1100 °C against alumina using a differential scanning calorimeter (DSC 1500 Stanton Redcroft, Rheometric Scientific, UK). Glass transition temperature (T_g) and crystallisation peak temperatures (T_p) of each glasses were then obtained from the recorded DSC trace. The accuracy of all characteristic temperatures obtained and further presented in figures and tables was ± 5 °C.

2.3. Crystallisation behaviour

1 g of fine powder (<45 μm) was compacted into a disc, placed on a platinum foil and heated up at a rate of 20 °C/min from 400 °C to the heat treatment temperature (T_{HT}) in a porcelain furnace (CeramPress, NEY Dental International, USA) without holding. According to the width of the crystallisation peak from the DSC traces, T_{HT} was T_p or approximately 10 °C above T_p. After heat treatment, samples were immediately withdrawn from the furnace and air quenched.

The resulting sintered glass ceramics were then ground into powder and characterised by using XRD, FTIR and NMR. In order to investigate the morphology of the crystalline phases, the heat treated glass ceramics were embedded in resin, polished with a series of silicon carbide grinding paper and finished with 0.3 μm diamond paste (Met Prep Ltd., UK). The polished specimens were gold coated and viewed under a scanning electron microscope (FEI Inspect F, Oxford Instruments, UK) using back-scatter and secondary electron imaging modes.

3. Results

3.1. Glass formation

The XRD patterns of the as quenched sodium free Ca- and Sr-containing glasses are given in Fig. 1a and b. Amorphous halos at 30° 2θ were found in glasses with low CaF_2 content (less than 9.3 mol%), whereas clear diffraction peaks were noticed for higher CaF_2 containing glasses. With an increase in the CaF_2 content (up to 9.3 mol%), additional small features at 25.86°, 32.23° and 33.07° 2θ were evident. These peaks were matched to the major apatite (FAP: 00-034-0011) diffraction lines. However, a minor peak at 31.89° 2θ was seen for glasses with 4.5 and 6.0 mol% CaF_2. A further increase in the CaF_2 content up to 17.8 mol% resulted in the crystallisation of cuspidine ($Ca_4Si_2O_7F_2$, 00-011-0075) with diffraction lines at 26.5° and 29.1°. At the same time, additional lines at 28.28° and 47° 2θ corresponding to fluorite (CaF_2, 00-004-0864) were also found.

The SrF_2-based series demonstrated similar patterns (Fig. 1b). Amorphous halos were exhibited at 29° 2θ in the glass with SrF_2 contents less than 4.5 mol%, and sharp peaks at 26.5°, 27.85°, 30.5° and 31.7° 2θ were observed for glasses with SrF_2 content greater than 4.5 mol%, which were identified with the main diffraction lines of $Sr_{10}(PO_4)_6F_2$ (00-050-1744). With increasing SrF_2 content up to 13.6 mol%, peaks corresponding to $SrSiO_3$ (00-034-0099) appeared at 24.95° and 43.9° 2θ. Furthermore, additional peaks at 43.19° and 52.23° in the XRD patterns of 17.8 and 25.5 mol% SrF_2 glasses were matched to the characteristic diffraction peaks of SrF_2 (00-001-0644). The crystalline phases identified in both glass series are summarised in Table 2.

FTIR spectra of the as quenched CaF_2 containing glasses (Fig. 2a) show the typical non-bridging oxygen band and Si–O–Si stretch band at 920 and 1030 cm^{-1} for the whole series. In addition, a small band around 600 cm^{-1} was noticed in the glasses with CaF_2 content lower

Table 1
Glass compositions in mol%. GF is used for CaO/CaF_2 series and SF for SrO/SrF_2 series.

Glass code	SiO_2	CaO/SrO	P_2O_5	CaF_2/SrF_2
GF/SF 0.0	38.1	55.5	6.3	0.0
GF/SF 3.0	37.0	53.9	6.1	3.0
GF/SF 4.5	36.4	53.0	6.0	4.5
GF/SF 6.0	35.9	52.2	5.9	6.0
GF/SF 9.3	34.6	50.4	5.7	9.3
GF/SF 13.6	32.9	48.0	5.5	13.6
GF/SF 17.8	31.4	45.7	5.2	17.8
GF/SF 25.5	28.4	41.4	4.7	25.5