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(54) Title: BIOACTIVE GLASS COMPOSITION

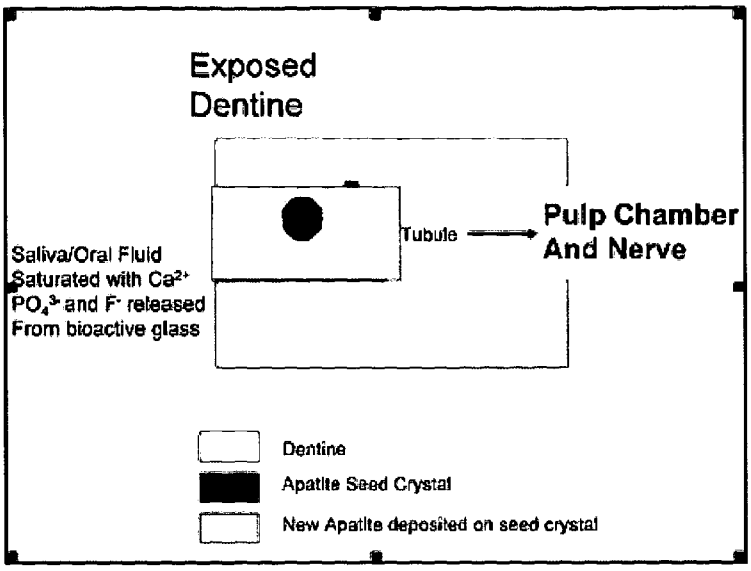

Figure 1

(57) Abstract: A bioactive glass composition comprising one or more glasses comprising Si02, P205 and a fluoride, the Si02 content being less than 40 mole %, the P205 content being at least 4 mole %, and the fluoride content being greater than 1 mole %. The bioactive glass or glass - ceramic can be used in a number of medical applications, including dental applications such as toothpaste.

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Bioactive Glass Composition

The present invention relates to a bioactive glass composition.

A biologically active (or bioactive) material is one which, when implanted into living tissue, induces formation of an interfacial bond between the material and the surrounding tissue. Bioactive glasses are a group of surface-reactive glasses, which exhibit bioactivity. The bioactivity of these glasses is the result of complex reactions which take place on the surface of the glass under physiological conditions, and which result in the formation of hydroxycarbonated apatite (HCA) on the surface of the glass. The term "bioactive glass" as used herein is intended to encompass bioactive glass-ceramics as well as bioactive glasses. Bioactive glass-ceramics are similar to bioactive glasses but contain a crystalline phase in addition to the glass phase.

Because of the ability of bioactive glasses to bond with living tissue, and in particular bone, they are used in a number of medical applications, including dental applications such as toothpaste.

For many applications, and in particular for toothpastes, it is preferable that the glass phase should release fluoride and form fluorapatite (FAP), instead of HCA. This is because FAP is more resistant to acid dissolution in oral fluids than HCA and aids in the prevention of dental caries. Moreover, fluoride ions are known to aid apatite formation and stimulate the cell division of osteoblasts, the bone forming cells. For these reasons, fluoride may be incorporated into bioactive glasses.

While it is desirable to incorporate a fluoride in a bioactive glass, it has been found that, if the fluoride content of a glass is too high, it will result in the formation of fluorite (CaF_2) at the expense of fluorapatite when the glass is immersed in a body fluid.

Another problem that has been found with existing bioactive glasses is that they are very abrasive towards enamel and can result in excessive and undesirable wear of

enamel. This is because the known glasses are harder than enamel. The common bioactive glass (45S5) used currently has a measured hardness Of 4.58GPa compared to enamel at approximately 3.5GPa.

It is an object of the invention to seek to mitigate these problems which have been found with existing bioactive glasses.

The invention provides a bioactive glass composition comprising one or more glasses/glass-ceramics comprising SiO_2, P_2O_5 and a fluoride, the SiO_2 content being less than 40 mole %, the P_2O_5 content being at least 4 mole %, and the fluoride content being greater than 1 mole %.

The applicant has found that the tendency of FAP formation to be suppressed at higher concentrations of fluoride is reduced in glasses with a relatively low SiO_2 content and a relatively high phosphate content.

In addition, the applicants have found that glasses with a relatively low SiO_2 content and a relatively high phosphate and fluoride content have lower hardness values and so are softer and less abrasive towards enamel.

Moreover, the applicants have found that such glasses form apatite not only in simulated body fluid (SBF), but also readily in Tris buffer at pH 7.25.

The bioactivity of bioactive glasses is usually studied using an ISO Standard, ISO 23317. Under this standard, the glass is immersed in SBF, a saturated calcium and phosphate solution that mimics the ionic concentrations found in body fluids/blood plasma. If the glass results in the formation of HCA within the time period designated under the standard, then it is termed bioactive. For the purposes of the present patent we extend this definition to include the formation of fluorapatite.

Although bioactivity is usually studied using ISO Standard, ISO 23317, this standard is not particularly suitable for studying bioactivity within the mouth. The reason for this is that saliva is somewhat diluted after taking in liquids and is often no longer

saturated with regard to Ca^{2+} and PO_4^{3-}. For this reason, bioactivity may also be investigated using Tris buffer, a simple buffer solution at pH=7.25 which contains no Ca^{2+} and PO_4^{3-}. This represents a far more severe test of bioactivity.

Accordingly, the fact that compositions according to the invention have been shown to rapidly form FAP following immersion in Tris buffer has particular relevance for dental applications such as toothpastes.

Not only do the compositions according to the invention form apatite in Tris buffer, they also form more apatite than existing bioactive glasses and they form apatite faster than existing bioactive glasses. Thus, in tests, glasses with a low SiO_2 content and a high phosphate content have shown very rapid formation of FAP in under six hours, following immersion in Tris buffer at pH=7.25.

The SiO_2 content of the glass composition is preferably less than 39 mole %, more preferably less than 38 mole % most preferably less than 35 mole %. The SiO_2 content is preferably more than 25 mole %.

The P_2O_5 content is preferably greater than 4.5 mole %, more preferably greater than 5 mole %. The P_2O_5 content is preferably less than 10 mole %, more preferably less than 7 mole %.

The applicant has found that incorporating fluoride in the glass composition aids FAP formation, provided that an excessive amount of fluoride is not used. The applicant has also found that higher fluoride contents reduce hardness, which correlates with the glass transition temperature, Tg. The glass composition should therefore preferably have the highest possible fluoride content which is consistent with forming FAP and no fluorite.

Accordingly, the fluoride content is preferably greater than 3 mole %, more preferably greater than 4 mole %, most preferably greater than 5 mole %. The fluoride content is preferably less than 25 mole %, more preferably less than 18 mole %.

Strontium may be used to replace calcium and is known to enhance bioactivity. Strontium has a well documented anti caries function and mixed calcium/strontium apatites have a lower solubility product than either the equivalent calcium or strontium apatites. Accordingly, the composition preferably comprises up to 57 mole % of CaO and SrO combined, more preferably up to 50 mole % of CaO and SrO combined.

In high-phosphate containing glasses, the lower charge to size ratio of the Sr^{2+} cation may result in the crystallisation of the glass, which is often undesirable as it reduces the solubility of the glass. Moreover sources of strontium are also much more expensive than sources of calcium which is important when the glasses are to be used in consumer health care products such as toothpaste. Accordingly, the composition preferably comprises less than 30 mole % SrO.

Potassium salts are often added to toothpaste formulations in order to treat dentine hypersensitivity and potassium may be used to replace sodium in the glass for this purpose. Accordingly, the composition may comprise up to 40 mole % K_2O.

It is important to note, however, that high K/Na ratios are potentially undesirable with regard to their effect on cells. For glasses used in medical applications such as bone substitutes and periodontal treatment a K/Na ratio close to that found in blood plasma of 0.04 is preferred.

Zinc may also be incorporated into the glass. Zinc inhibits apatite formation and is thought to block sites on the apatite crystal lattice and hinder apatite crystal growth. However zinc is often incorporated into toothpastes for its antibacterial and antigingivitis effects. Low zinc plasma levels which occur in many over sixty year olds are also often associated with poor wound healing rates and osteoporosis. Low zinc contents are attractive in glasses for both dental and medical applications for these reasons. Accordingly, the composition may comprise up to 5 mole % ZnO and ZnF_2 combined.

The composition may comprise up to 12 mole % of MgO and MgF_2 combined. Like zinc, magnesium acts to suppress apatite crystal growth.

One of the problems with bioactive glasses is that, whilst they dissolve rapidly and form amorphous phases rapidly, the crystallisation process to form an apatite is generally slow. Whilst fluoride speeds this process up, the applicant has found that adding an apatite further accelerates the process.

Accordingly, the composition may comprise an apatite. Preferably, the composition comprises at least 0.1wt% of an apatite. The apatite may be hydroxycarbonated apatite or it may be hydroxyl apatite, but it is preferably fluorapatite. Preferably, the apatite is crystallised, and the size of the crystals is in the range 30nm to 5 microns, preferably 30nm to 3 microns.

The apatite crystals are thought to act as seed nuclei for the formation of apatite and apatite nucleation is thought to be the slow step in the crystallisation of apatite from solution, whilst crystal growth is thought to be rapid. Thus adding an apatite reduces the time to form new apatite from solution.

Small crystals are preferred for this process with a large surface area and a large number density. However small crystals are also desirable as they can enter the dentinal tubules (which are typically 3-5 microns in diameter) and allow more apatite to form on them sealing and blocking the dentinal tubules. This process is shown schematically in Figure 1. A further advantage of using an apatite to seed the nucleation process is that larger bioactive glass particles may be used without the need to have a significant fraction of small (<5microns) bioactive glass particles in the particle size distribution. Such small particles are prone to dissolution and surface reaction with trace amounts of water in the suspending media such as glycerol used for forming the toothpaste.

As an alternative to adding seed apatite crystals to the composition, the glass(es) of the invention may be pre-treated so that they have crystallised to fluorapatite on

their surface. This fluorapatite may be a calcium fluorapatite or a mixed fluorapatite comprising strontium.

The surface fluorapatite may have a crystal size less than 5 microns, preferably less than 1 micron.

The pre-treatment may take the form of treatment with SBF or Tris buffer. Alternatively, in the case of fluorine-containing glasses with high phosphate content and low alkali metal content, the glasses may be heat treated at a temperature of between 400 and 850°C to selectively crystallise fluorapatite on their surface.

The bioactive glass compositions of the invention may be used for various dental applications including promoting remineralisation of teeth, preventing caries, blocking dentinal tubules, treating dentine hypersensitivity and treating periodontal disease. They may also be used for various medical applications including use as a bone substitute.

A number of specific embodiments of the invention will now be described by way of example only with reference to the accompanying drawings of which:

Figure 1 shows schematically the blocking of dentinal tubules using a seed apatite crystal to nucleate further crystallisation of apatite from solution;

Figure 2 shows XRD diffraction patterns of QMMM1 glass after immersion in Tris buffer in order bottom to top 3, 6, 9, 24, 72 and 168 Hrs. Ap = Fluorapatite;

Figure 3 shows XRD diffraction patterns of QMMM2 glass after immersion in Tris buffer in sequential order bottom to top 3, 6, 9, 24, 72 and 168 Hrs. Ap = Fluorapatite;

Figure 4 shows XRD of Glasses 3 to 8 after 9 Hrs in Tris buffer in order of increasing fluorine content. Ap = Fluorapatite, F=Fluorite;

Figure 5 shows XRD patterns of Glasses 11 to 16 after 168Hrs in Tris buffer. Note the absence of sharp diffraction lines corresponding to apatite in the fluorine free glass QMEL4 and the presence of fluorite in the high fluorine content glasses;

Figure 6 shows open dentinal tubules in human dentine after exposure to 10% citric;

Figure 7 shows a typical example of blocked dentinal tubules by fluorapatite crystals following etching with citric acid and after exposure to glass QMEL7 for 168 Hrs in Tris buffer;

Figure 8 shows ^{19}F MAS-NMR spectra of high phosphate fluorine containing glasses after immersion in Tris buffer after 3 days;

Figure 9a shows ^{31}P MAS-NMR spectra for QMMM1 as a function of immersion time in Tris buffer;

Figure 9b shows the quantitative determination of proportion of residual orthophosphate species in the glass and formation of FAp obtained by deconvolution of ^{31}P MAS-NMR spectra from Figure 9a;

Figure 10 shows a differential scanning calorimetry trace of Glass QMIF3 showing the glass transition temperature and crystallization exotherms; and

Figure 11 shows the QMMM7 glass-ceramic.

Examples

The glass compositions shown in Table 1a were synthesised by a melt quench route.

For each composition, appropriate amounts of the oxides and fluorides listed in Table 1a were weighed out to give approximately 200g of batch. In the case of the oxides of calcium, strontium, sodium and potassium, the respective carbonates were used instead of the oxides. The batch was thoroughly mixed then placed in a 300ml

platinum/rhodium crucible. The temperature was raised to between 150 and 1550°C and held at that temperature for 1.5Hrs. The resulting melt was then shock quenched into water to produce a granular glass which was washed with ethanol and dried immediately at 125°C for 1 hour. The glass was then ground in a vibratory puck mill and sieved to give a particle size less than 45 microns prior to characterisation.

Table 1a Illustrative examples of glass compositions in mole percent

Glass	Code	SiO_2	P_2O_5	Na2O	CaO	SrO	NaF	CaF_2	SrF_2	K_2O	ZnO
1	45S5	46.1	2.6	24.3	26.9	0.0	0.0	0.0	0.0	0.0	0.0
2	ICIE1	49.6	1.1	26.4	23.1	0.0	0.0	0.0	0.0	0.0	0.0
3	QMMM1	34.8	5.8	22.7	28.0	0.0	8.7	0.0	0.0	0.0	0.0
4	QMSMD	35.5	5.9	27.6	24.1	0.0	0.0	6.9	0.0	0.0	0.0
5	QMMM2	31.7	5.3	16.1	30.0	0.0	17.0	0.0	0.0	0.0	0.0
6	QMMM3	29.0	4.8	10.5	31.7	0.0	24.0	0.0	0.0	0.0	0.0
7	QMMM4	26.6	4.4	5.6	33.2	0.0	30.2	0.0	0.0	0.0	0.0
8	QMMM5	28.4	4.7	22.1	19.3	0.0	0.0	25.5	0.0	0.0	0.0
9	QMMM6	25.7	4.3	19.9	17.4	0.0	0.0	32.7	0.0	0.0	0.0
10	QMMM7	34.6	5.7	0.0	50.4	0.0	0.0	9.3	0.0	0.0	0.0
11	QMEL4	44.0	5.0	10.0	15.0	16.7	0.0	0.0	0.0	8.3	1.0
12	QMEL5Na	42.5	4.8	5.1	16.8	18.0	8.9	0.0	0.0	8.0	1.0
13	QMEL6	40.2	4.6	9.1	13.7	15.2	0.0	4.7	4.0	7.6	0.9
14	QMEL7	38.4	4.4	8.7	13.1	14.5	0.0	6.9	5.9	7.2	0.9
15	QMEL8	36.7	4.2	8.3	12.5	13.9	0.0	9.0	7.7	6.9	0.8
16	QMEL9	33.4	3.8	7.6	11.4	12.6	0.0	13.0	11.1	6.3	0.8
17	QMEL10	30.3	3.4	6.9	10.3	11.5	0.0	16.7	14.4	5.7	0.7
18	QMIF2	35.9	5.9	4.9	48.9	0.0	5.8	0.0	0.0	0.0	0.0
19	QMIF3	35.9	5.9	7.3	46.4	0.0	5.8	0.0	0.0	0.0	0.0
20	QMIF4	35.9	5.9	9.7	43.9	0.0	5.8	0.0	0.0	0.0	0.0
21	CaNaR1	34.5	6.3	14.5	38.9	0.0	5.8	0.0	0.0	0.0	0.0
22	CaNaR2	34.5	6.3	19.3	34.1	0.0	5.8	0.0	0.0	0.0	0.0
23	CaNaR3	34.5	6.3	24.2	29.2	0.0	5.8	0.0	0.0	0.0	0.0
24	CaNaR4	34.5	6.3	29.0	24.4	0.0	5.8	0.0	0.0	0.0	0.0
25	PhoIn4	35.6	5.8	25.2	27.6	0.0	5.8	0.0	0.0	0.0	0.0
26	PhoIn5	31.7	7.7	26.1	28.7	0.0	5.8	0.0	0.0	0.0	0.0

Note Glasses 1-2 and 11 are included for comparison purposes only and are not according to the invention.

Table 1a includes a number of glasses not covered by the present invention for comparison purposes, including the well known 45S5 glass composition (Glass 1) and the extensively studied and characterised ICIE1 glass composition (Glass 2). These compositions are typical of those used commercially. Also included for comparison is Glass 11, which includes no fluoride, and Glasses 12, 13, 16 and 17 which include various fluoride contents.

In the existing patents and the majority of the published scientific literature, bioactive glasses are generally expressed in weight percent. However since SiO_2, CaO and Na_2O have similar molecular weights (60, 56 and 62 respectively), an amount given in weight percent does not significantly alter when converted to mole percent.

Glasses 3 and 5-8 have SiO_2 contents below 35 mole % and would be regarded as highly invert glasses. An invert glass is a glass where there is less than 50 mole percent of the SiO_2 the network forming oxide. Highly invert glasses are highly disrupted and are prone to crystallisation and are generally difficult to form. However they are very surface reactive and dissolve readily which is a very desirable feature for a bioactive glass. Glasses 6 to 8 have SiO_2 contents below 30 mole %. It is generally considered impossible to produce highly invert glasses (ie with <40mole%SiO_2) without resorting to very specialised rapid quenching methods. It was therefore surprising to be able to synthesise glasses with silica contents well below 40 mole% with conventional quenching.

Glass composition 9 (QMMM6) has an exceptionally high fluoride content, and exploded on contact with water during fritting, that is, on pouring the molten liquid glass rapidly into water to produce a granular glass. It is thought that this glass reacted vigorously with water.

Table 1b Compositions of sodium free glasses

	SiO_2	CaO	P_2O_5	CaF_2	Ca:P	F:P	T_m (°C)	As Quenched Glass
QMXJC14	38.1	55.5	6.3	0	4.4	0.0	1550	Amorphous
QMXJC01	37.0	53.9	6.1	3.0	4.6	0.5	1550	Amorphous
QMXJC02	36.4	53.0	6.0	4.5	4.8	0.8	1500	Amorphous
QMXJC03	35.9	52.2	6.0	6.0	4.9	1.0	1500	Amorphous
QMMM7	34.6	50.4	5.7	9.3	5.2	1.6	1450	FAp
QMXJC04	32.9	48.0	5.5	13.6	5.6	2.5	1450	FAp+C
QMXJC05	31.4	45.7	5.2	17.8	6.1	3.4	1450	FAp+C+CaF_2
QMXJC06	28.4	41.4	4.7	25.5	7.1	5.4	1450	FAp+C+CaF_2

High fluorite content glasses from Table 1b crystallised to fluorine containing crystal phases such as FAP cuspidine ($Ca_4Si_2O_9F_2$) and fluorite upon quenching. The amorphous glasses in Table 1 all formed large amounts of apatite within 24 hours in both Tris buffer and SBF. The high melt temperatures of the low fluoride content glasses is undesirable for economic reasons

Each of the glasses of Table 1a was immersed in a Tris Buffer solution at a concentration of 75mg in 50ml. The Tris Buffer was prepared as follows:

7.545g of Tris (hydroxymethyl) amino methane (THAM) was transferred into a graduated flask filled with approximately 400ml of deionised water. Once the THAM had dissolved, 22.1ml of 2N HCl was added to the flask, which was then made up to 1000ml with deionised water and adjusted to pH 7.25 at 37°C.

All of the Glasses in accordance with the invention formed apatite when immersed in the Tris buffer. Comparative Glasses 1-2 and 11 did not form significant quantities of apatite when immersed in the Tris buffer. As discussed above, immersion in Tris buffer represents a far more severe test of bioactivity than the standard test for bioactivity which determines whether the glass forms an apatite in SBF.

Figures 2 to 11 illustrate the invention.

75mg of glasses 11 to 16 with a particle size <45 microns were added to 50ml of Tris buffer at pH 7.25 along with a 1 mm slice cut through the mid coronal section of a human tooth section treated with 10% citric acid to expose the dentinal tubules.

After periods of 3, 6, 9, 24, 72 and 168Hrs the tooth section was recovered and the solution filtered. The resulting solid was dried at 37°C and examined by Fourier Transform Infrared spectroscopy (FTIR), X-ray powder diffraction (XRD) and solid state Magic Angle Spinning – Nuclear Magnetic Resonance (MAS-NMR) spectroscopy looking at ^{19}F and ^{31}P. The pH of the solution was measured and the free fluoride ion concentration was also measured.

X-ray powder diffraction and FTIR spectroscopy showed the presence of a crystalline apatite formed in solution from 6 Hrs with a split phosphate band at approximately 560cm^{-1} and 600cm^{-1}. The amount of apatite formed increased in time up to 24 Hrs. ^{19}F and ^{31}P MAS-NMR showed the apatite to be a fluorapatite with a characteristic peak with a chemical shift at -103ppm in the ^{19}F MAS-NMR spectra and a peak at 2.9ppm in the ^{31}PMAS-NMR spectra corresponding to fluorapatite.

Examination of the dentine slices by scanning electron microscopy showed the dentinal tubules to be open prior to treatment with the bioactive glasses (Figure 6) and to be occluded after treatment with a calcium phosphate ratio close to that of apatite at 1.6 (Figure 7).

The same procedure was repeated for Glass 1 which is the well known 45S5 glass. XRD and FTIR showed that no significant apatite had been formed under these conditions and there was no occlusion of the dentinal tubules under these conditions.

Figures 2-5 show the formation of apatite after immersion of the glasses in Tris buffer for various times.

Figure 4 shows the formation of apatite and fluorite in Glasses 3 to 8 after 9 hours immersion in Tris buffer. The formation of fluorite at the expense of fluorapatite is seen at higher fluoride contents in the glass.

Figure 5 shows the XRD diffraction patterns obtained for multicomponent Glasses 11-16 containing Sr, Zn and K after immersion in Tris buffer for 168 hours. The fluoride free glass, Glass 11, forms no apatite whilst the glasses containing fluoride form apatite until the glass contains 18 mol % MF_2 where M is Ca and Sr, after which both fluorapatite and fluorite form. Above 18 mol % MF_2, the glass forms predominantly fluorite and relatively little fluorapatite. It can be seen clearly that incorporating fluoride in the glass composition aids fluorapatite formation providing excessive amounts of fluoride are not used. There therefore exists an optimum fluoride content for FAp formation.

Figure 8 shows ^{19}F MAS-NMR spectra for glasses after immersion in Tris buffer showing the characteristic peak for Fap at -103ppm. Figure 9a shows ^{31}P MAS-NMR spectra for Glass 4 (QMMM1) following immersion in Tris buffer at pH=7.25 for time periods from 0 to 168Hrs. The phosphorus is present in the initial glass as a mixed Ca/Na orthophosphate species with a chemical shift of approximately 9ppm. Following the immersion the original peak disappears and is progressively replaced by a new peak at about 3ppm corresponding to a calcium orthophosphate of which FAP is an example. Deconvolution of the spectra enables quantification of the proportions of glass and FAP as a function of time which are shown in Figure 9b. It can be seen that this glass forms FAP very rapidly and FAP forms in under 6 Hrs.

Figure 10 shows the DSC trace for glass 18 QMIF3 Table 1a This glass has a low sodium content and a Tg of about 670°C. The first crystallisation exotherm, Tc1 corresponds to the crystallisation of FAP. Heat treating this glass to 800°C results in the formation of FAP, which acts as seed crystals for further FAP formation and accelerates the formation of further FAP when immersed in Simulated Body Fluid or Tris buffer. This FAP glass-ceramic may be used either as an additive for toothpastes or as a bone substitute. This glass with its sodium content reduces the melt temperature to below 1500°C which facilitates economical melting compared to glasses containing no alkali metal, as well as casting to form complex shapes required for custom made bone protheses. The higher calcium content compared to

glasses of the QMMM1 to QMMM5 series facilitates the formation of FAP in Tris buffer and SBF.

FAP was synthesised by mixing tricalcium phosphate ($Ca_3(PO_4)_2$) and CaF_2 in powder form with a particle size <50 microns in the stoichiometric ratio for FAP. This mixture was then solid state reacted for 16Hrs at 1050°C in an alumina crucible. The resulting solid was ground and sieved to give a powder <5microns. An XRD pattern of the powder showed it to be FAP

The FAP was then added at a concentration of 2.5% to bioactive glass 4 QMSMD Following immersion of the glass/FAP mixture in Tris buffer it was found to accelerate apatite formation and resulting in larger FAP crystals as evidenced by reduced line broadening by XRD.

Table 2 Glass transition temperatures and calculated hardness values for example glasses.

Glass	Code	Tg (°C)	Hardness GPa)	NC
1	45S5	530	4.98	2.11
2	ICIE1	513	4.84	2.09
3	QMMM1	484	4.60	2.08
4	QMSMD	450	4.32	2.08
5	QMMM2	440	4.23	2.08
6	QMMM3	416	4.03	2.08
7	QMMM4	408	3.97	2.08
8	QMMM5	383	3.76	2.08
9	QMMM6	-	-	2.08
10	QMMM7	663	6.08	2.08
11	QMEL4	500	4.73	2.44
12	QMEL5	480	4.57	2.43
13	QMEL6	469	4.47	2.44
14	QMEL7	454	4.35	2.44
15	QMEL8	441	4.24	2.44

16	QMEL9	425	4.11	2.44
17	QMEL10	400	3.90	2.44
18	QMIF2	700	6.39	2.08
19	QMIF3	674	6.18	2.08
20	QMIF4	630	5.81	2.08
21	CaNaR1	575	5.35	2
22	CaNaR2	523	4.92	2
23	CaNaR3	487	4.62	2
24	CaNaR4	462	4.42	2
25	PhoIn1	485	4.61	2
26	PhoIn4	487	4.62	2
27	PhoIn5	483	4.59	2
Enamel			3.5	

Hardness calculated using an experimentally determined model where Hardness =0.0083*Tg+0.5812. Experimentally the hardness of the 45S5 glass was determined to be 4.68GPa. close to the calculated value at 4.98GPa.Note the hardness decreases with increasing fluorine content in the glass for glasses ICSW9 to QMMM5 and from QMEL4 to QMEL10.

Reduced hardness of the glass is an important factor with regard to abrasive wear of toothpastes and the bioactive glass should be no harder than that of enamel in order to avoid enamel wear during tooth brushing.

Figure 11 shows the QMMM7 glass-ceramic. The initial glass was found to contain FAp on slow quenching (Bottom Pattern) and is in fact a FAp glass-ceramic. On immersion of this glass in Tris buffer the amorphous glass phase dissolves forming more FAp. The FAp is thought to form on the existing FAp crystallites. The diffraction lines are much sharper indicating the FAp crystals are >50nm in contrast to totally amorphous glasses in the absence of FAp Crystallites that give rise to broad diffraction lines corresponding to Nano sized FAp crystals (ie <50nm). Similar results were obtained in SBF. Rapid quenching resulted in this glass being amorphous but crystallization of FAp could be achieved by heat treating at 783°C.

The above embodiments have been described to illustrate the invention, and are not intended to be limiting. The skilled person will be readily able to devise alternative embodiments without departing from the scope of the claims.

CLAIMS

1. A bioactive glass composition comprising one or more glasses comprising SiO_2, P_2O_5 and a fluoride, the SiO_2 content being less than 40 mole %, the P_2O_5 content being at least 4 mole %, and the fluoride content being greater than 1 mole %.

2. The bioactive glass composition of claim 1, wherein the SiO_2 content is less than 39 mole %, more preferably less than 38 mole %, most preferably less than 35 mole %.

3. The bioactive glass composition of claim 1 or claim 2, wherein the SiO_2 content is more than 25 mole %.

4. The bioactive glass composition of any preceding claim, wherein the P_2O_5 content is greater than 4.5 mole %, more preferably greater than 5 mole %.

5. The bioactive glass composition of any preceding claim, wherein the P_2O_5 content is less than 10 mole %, more preferably less than 7 mole %.

6. The bioactive glass composition of any preceding claim, wherein the fluoride content is greater than 3 mole %, more preferably greater than 4 mole %, most preferably greater than 5 mole %.

7. The bioactive glass composition of any preceding claim, wherein the fluoride content is less than 25mole %, more preferably less than 18 mole %.

8. The bioactive glass composition of any preceding claim, wherein the composition comprises up to 57 mole %, more preferably up to 50 mole %, of CaO and SrO combined.

9. The bioactive glass composition of any preceding claim, wherein the composition comprises up to 40 mole % K_2O.

10. The bioactive glass composition of any preceding claim, wherein the composition comprises up to 5 mole % ZnO and ZnF_2 combined.

11. The bioactive glass composition of any preceding claim, wherein the composition comprises up to 12 mole % of MgO and MgF_2 combined.

12. The bioactive glass composition of any preceding claim, wherein the composition comprises an apatite.

13. The bioactive glass composition of Claim 12, wherein the composition comprises at least 0.1 weight percent of an apatite.

14. The bioactive glass composition of Claim 12 or Claim 13, wherein the apatite is fluorapatite.

15. The bioactive glass composition of any of Claims 12 to 14, wherein the apatite is crystallised from the glass, and the size of the crystals is in the range 30nm to 5μ, preferably 30nm to 3μ.

16 The bioactive glass composition of Claims 1 to 11, wherein the glass(es) have been pre-treated so that they have crystallised fluorapatite on their surface.

17. The bioactive glass composition of Claim 16, wherein the surface fluorapatite has a crystal size less than 5μm, preferably less than 1μ.

18. The bioactive glass composition of any preceding claim for use in dental applications or as a bone substitute.

19. A bioactive glass composition substantially as described herein with reference to the examples.

20. A toothpaste comprising a bioactive glass composition according to any preceding claim.

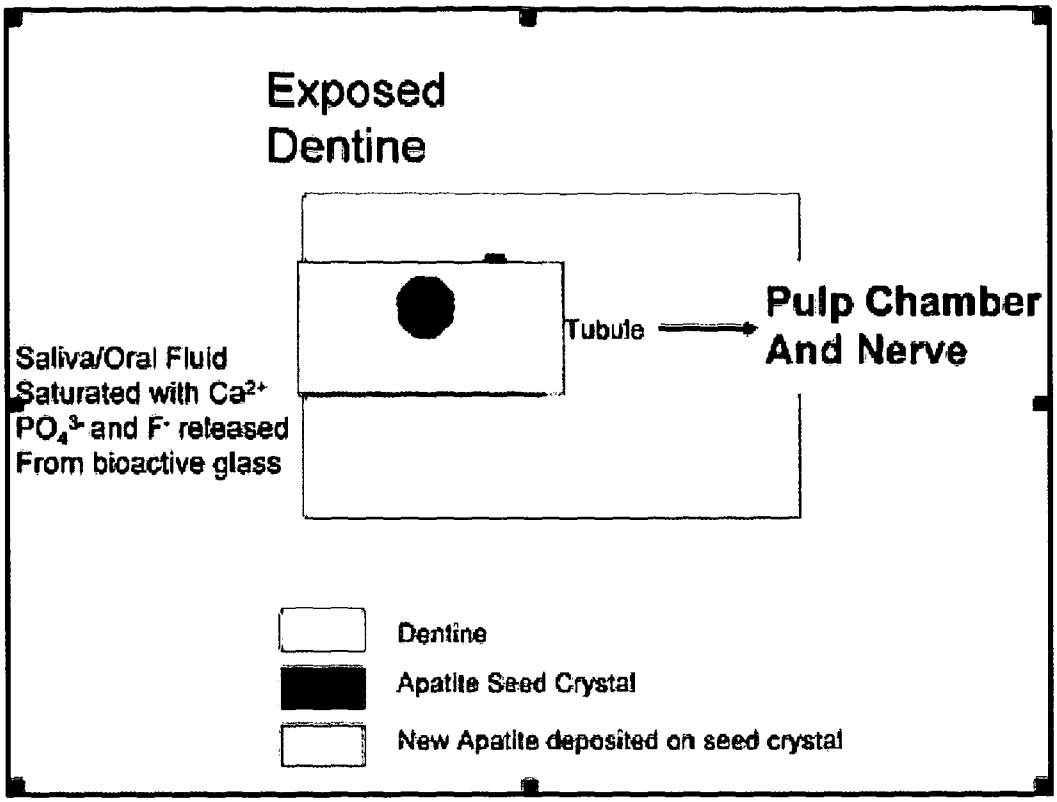

Figure 1

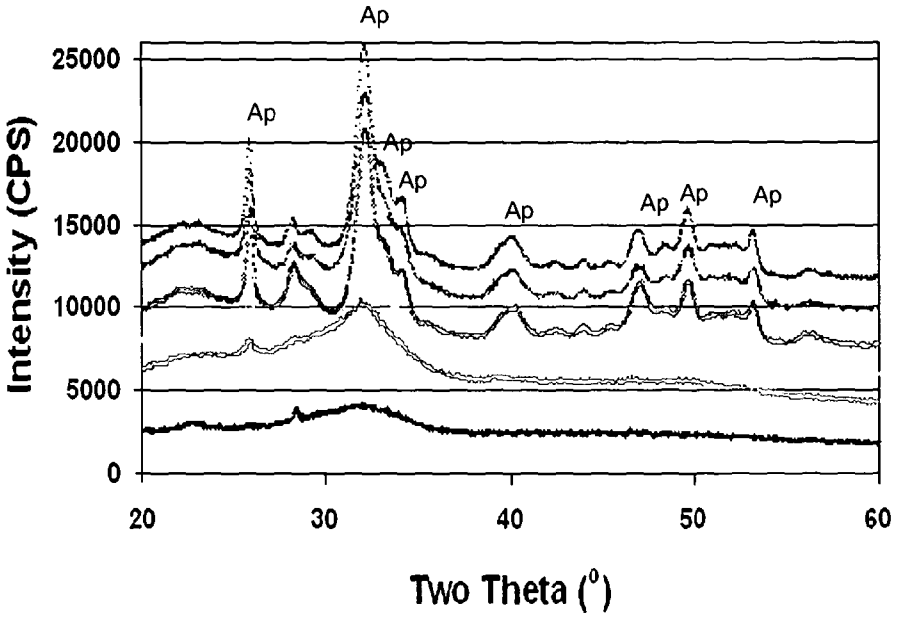

Figure 2

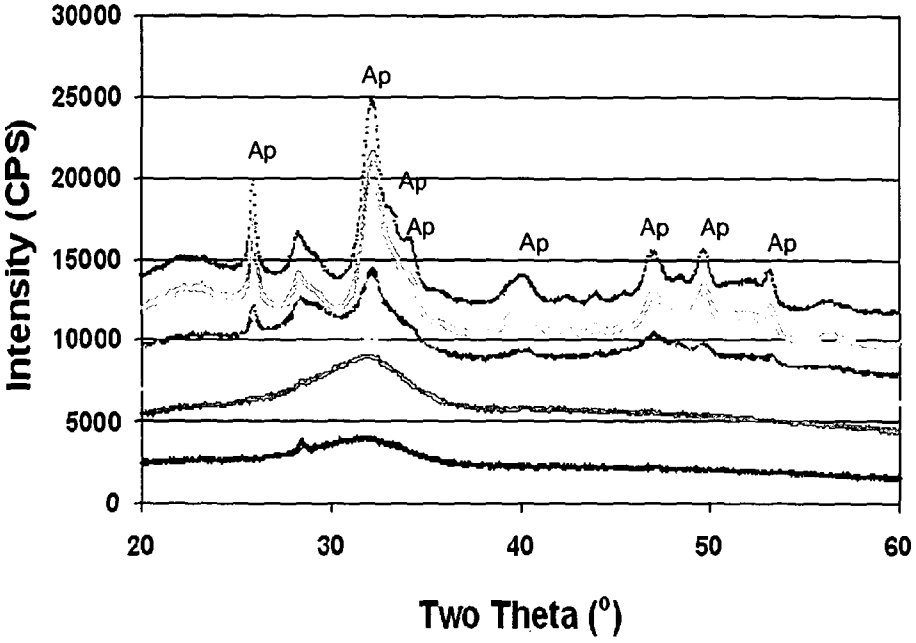
30000
25000
20000
15000
10000
5000
0
Intensity (CPS)
20
30
40
50
60
Two Theta (°)
Ap
Ap
Ap
Ap
Ap
Ap
Ap
Ap

Figure 3

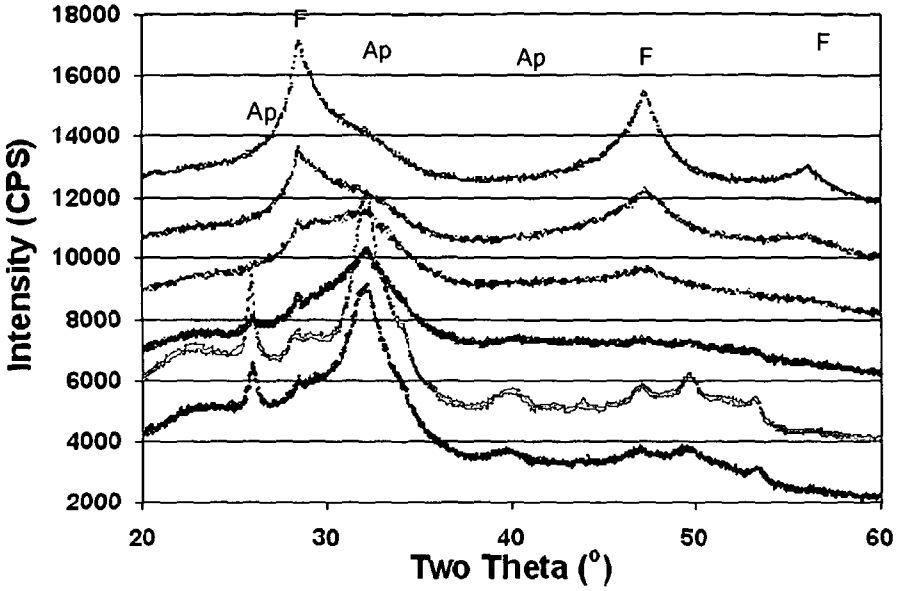

Figure 4

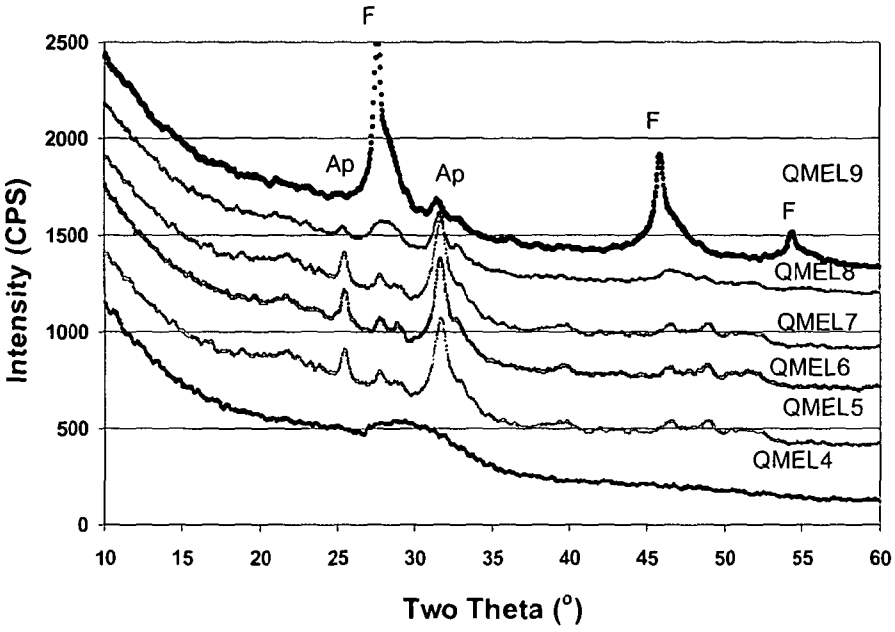

Figure 5

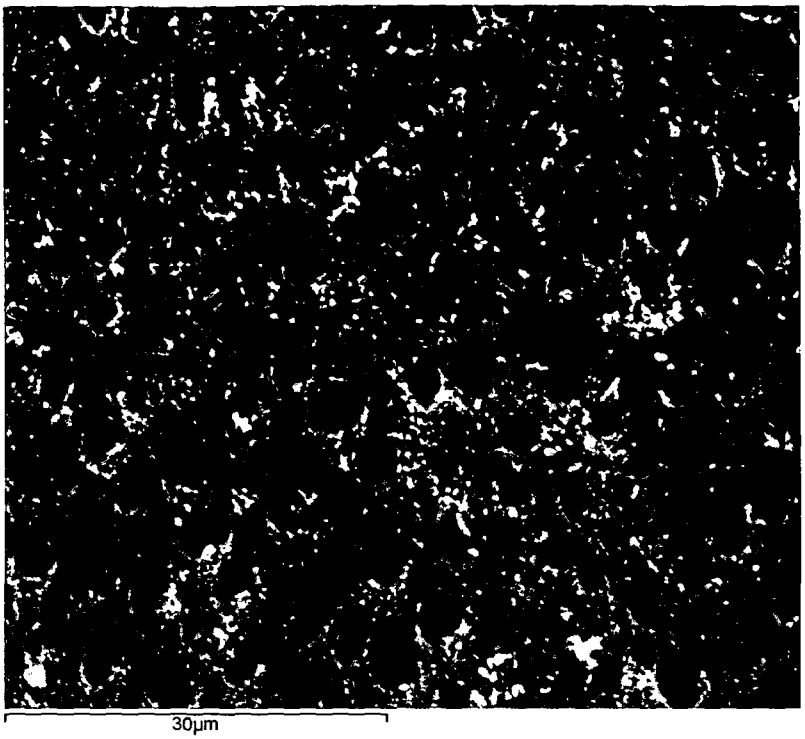

Figure 6

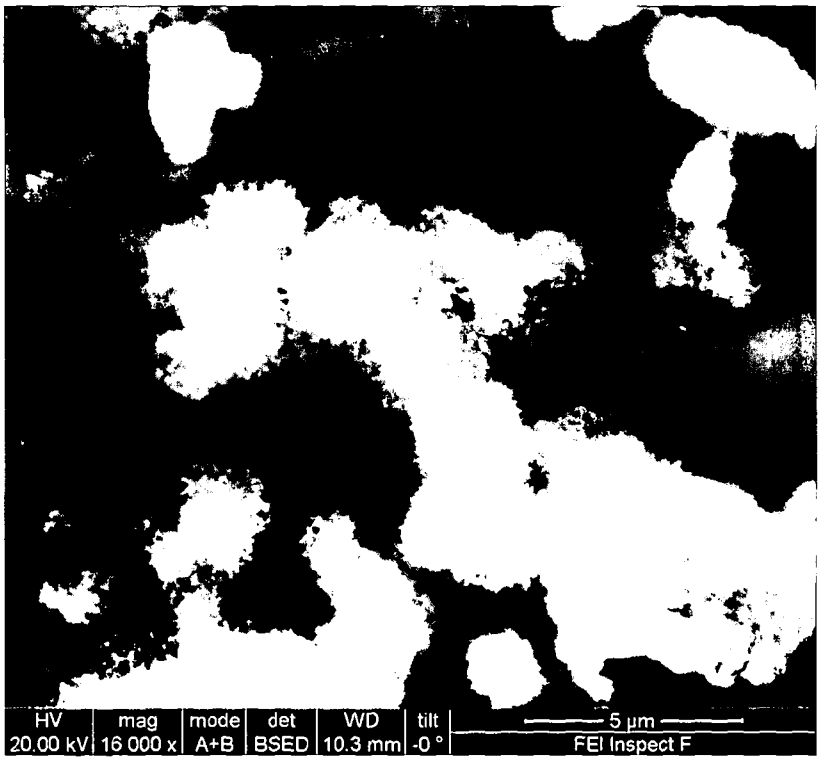

Figure 7

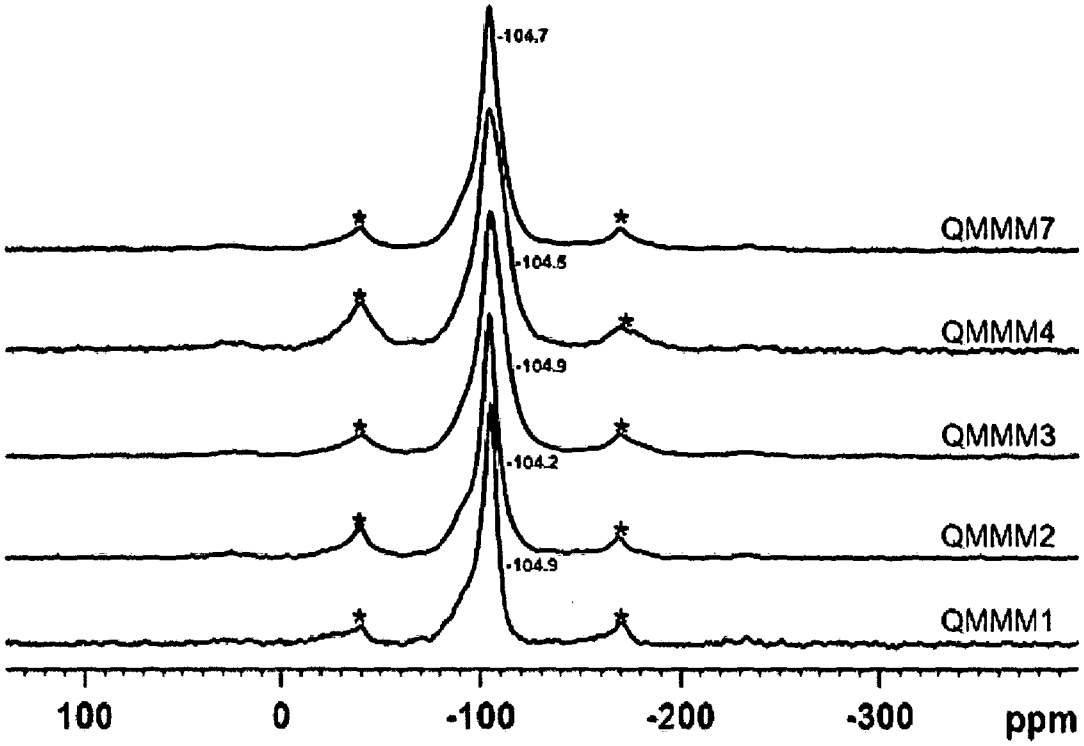
-104.7
QMMM7
-104.5
QMMM4
-104.9
QMMM3
-104.2
QMMM2
-104.9
QMMM1
100
0
-100
-200
-300
ppm

Figure 8

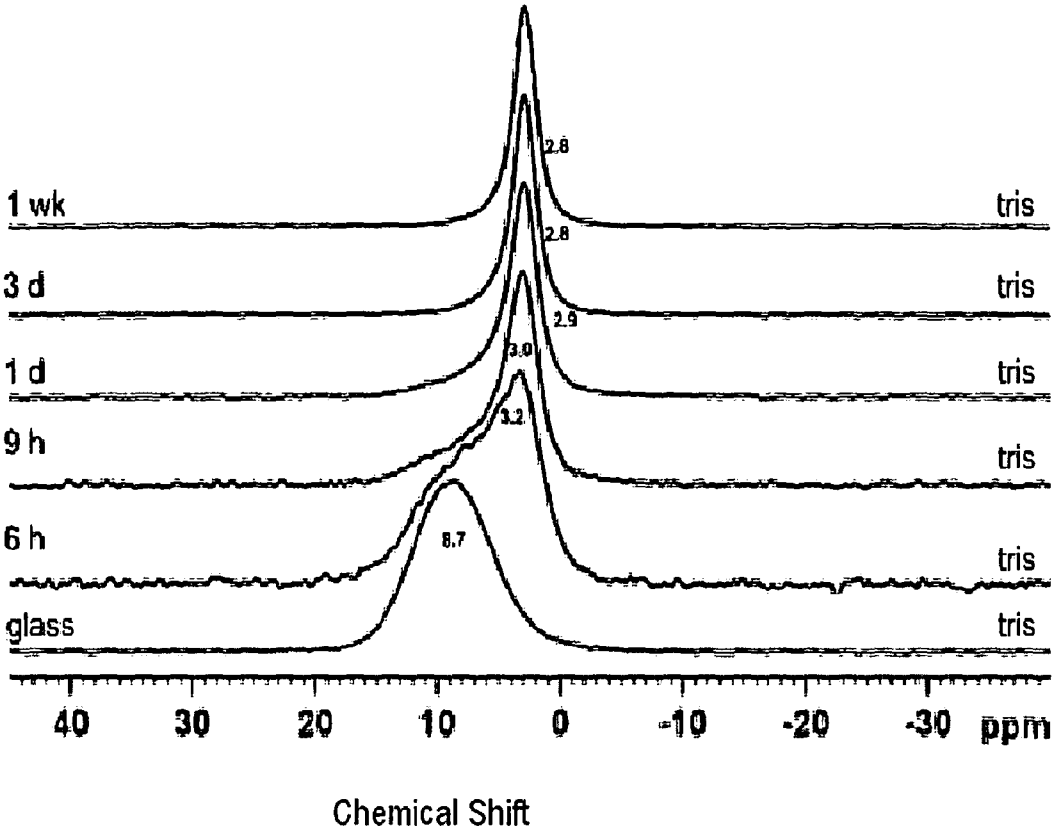

Figure 9a.

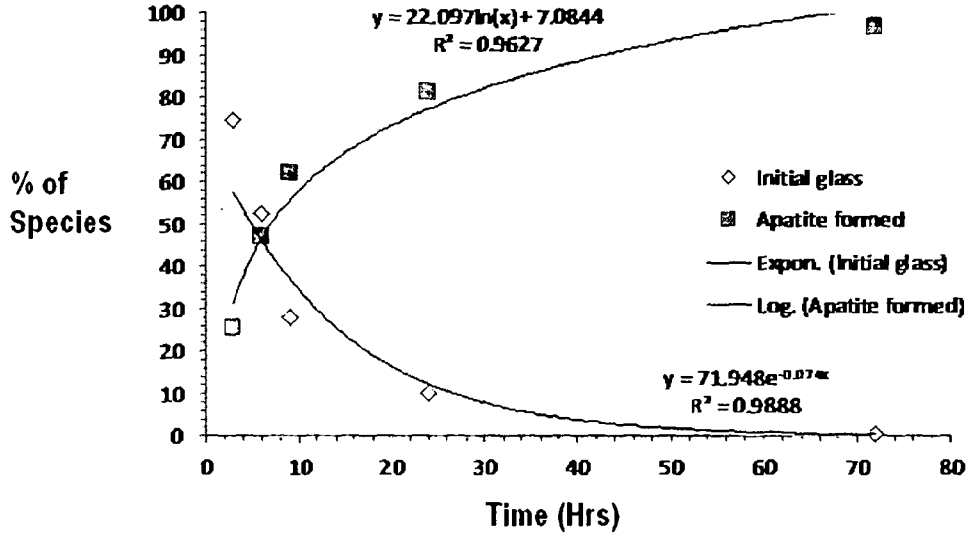

Figure 9b

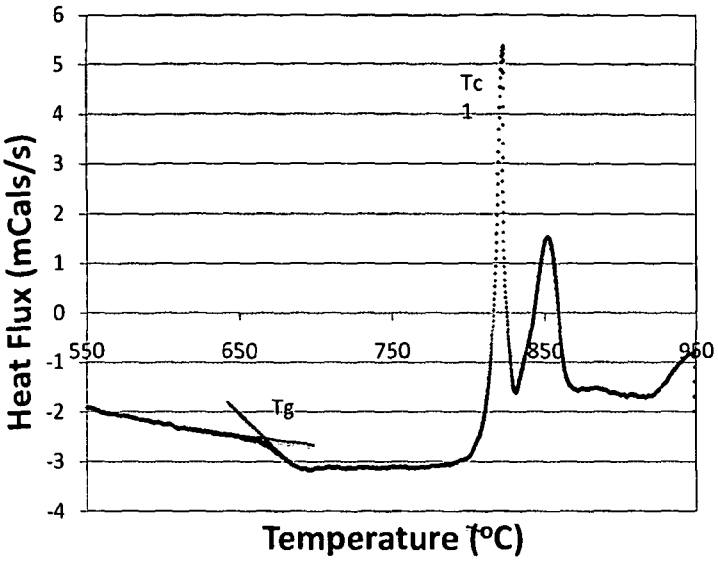
Heat Flux (mCals/s)
6
5
4
3
2
1
0
-1
-2
-3
-4
550
650
750
850
950
Tc
1
Tg
Temperature (°C)

Figure 10

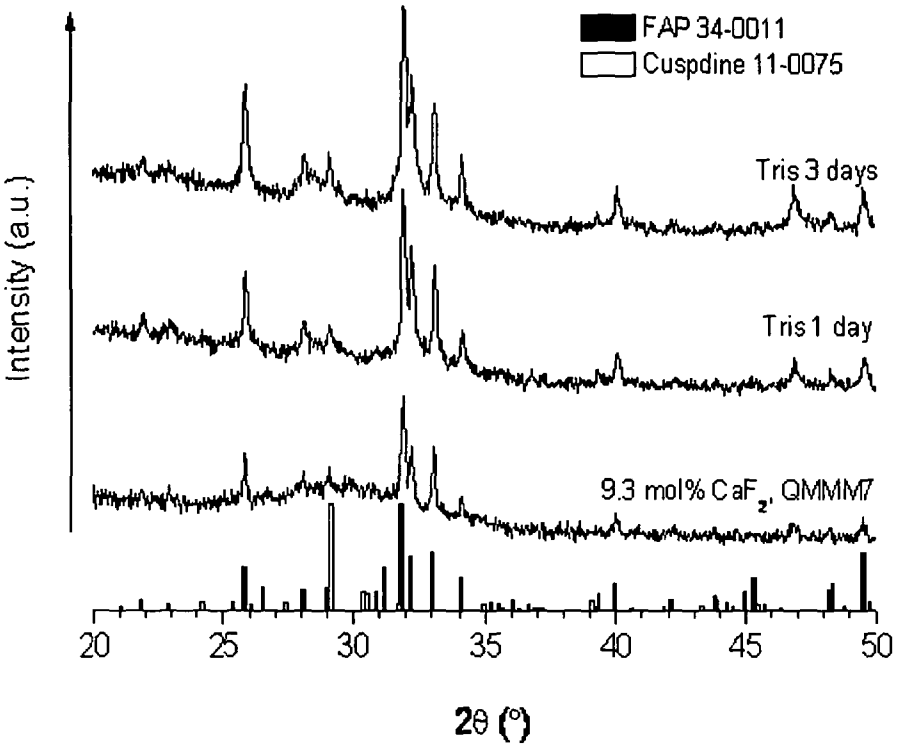
FAP 34-0011
Cuspdine 11-0075
Tris 3 days
Tris 1 day
9.3 mol% CaF2, QMMM7
Intensity (a.u.)
20
25
30
35
40
45
50
2θ (°)

Figure 11

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2011/000958

A. CLASSIFICATION OF SUBJECT MATTER
INV. C03C3/062 C03C4/00 C03C10/16 A61K8/25 A61K8/27
A61Q11/00 G01N33/15
ADD.
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
C03C A61K A61Q G01N

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)
EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 91/12212 A1 (THERA PATENT VERWALTUNGS GMBH [DE]; THERA GES FUER PATENTE [DE]) 22 August 1991 (1991-08-22) abstract page 4, line 14 - line 18 page 4, line 21 - page 5, line 15 examples 1, 2, 4-17; table 1 -----	1-18
X	DE 33 06 648 A1 (UNIV SCHILLER JENA [DD]) 22 September 1983 (1983-09-22) abstract page 7, paragraph 2 examples 3-8, 10, 12-15; table 1 -----	1-18

-/--

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
18 October 2011	24/10/2011

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Picard, Sybille

INTERNATIONAL SEARCH REPORT

International application No.
PCT/GB2011/000958

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☒ Claims Nos.: 19
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

see FURTHER INFORMATION sheet PCT/ISA/210

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

Continuation of Box II.2

Claims Nos.: 19

Art 6 PCT requires that claims must be clear and define the matter for which protection is sought. Independent claim 19 does not fulfill these requirements of Art. 6 PCT as the terms in that claim, namely a "glass composition substantially as described herein with reference to the examples" used are vague and do not enable to define which protection is requested.

The applicant's attention is drawn to the fact that claims relating to inventions in respect of which no international search report has been established need not be the subject of an international preliminary examination (Rule 66.1(e) PCT). The applicant is advised that the EPO policy when acting as an International Preliminary Examining Authority is normally not to carry out a preliminary examination on matter which has not been searched. This is the case irrespective of whether or not the claims are amended following receipt of the search report or during any Chapter II procedure. If the application proceeds into the regional phase before the EPO, the applicant is reminded that a search may be carried out during examination before the EPO (see EPO Guideline C-VI, 8.2), should the problems which led to the Article 17(2) declaration be overcome.

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2011/000958

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	DE 198 12 278 A1 (HERMSDORFER INST TECH KERAMIK [DE]) 23 September 1999 (1999-09-23) abstract column 1, line 51 - line 56 column 2, line 8 - line 13 column 2, line 24 - line 30	1-18
X	JP 60 239341 A (MINOLTA CAMERA KK) 28 November 1985 (1985-11-28) abstract page 248; examples 1-7; table page 249, left-hand column, paragraph 2	1-4, 7-13,18
X	US 4 643 982 A (KASUGA TOSHIHIRO [JP] ET AL) 17 February 1987 (1987-02-17) abstract examples 1, 2, 4-7, 9-17; table 1	1-13, 15-18
X	WO 2006/050829 A1 (DENTSPLY DE TREY GMBH [DE]; BLACKWELL GORDON [DE]) 18 May 2006 (2006-05-18) abstract examples; table 1, examples 1-7; table 2	1-11,18
X	US 2007/122356 A1 (KESSLER SUSANNE [DE] ET AL) 31 May 2007 (2007-05-31) abstract example A60; table 18	1,2, 4-11,18
A	US 6 244 871 B1 (LITKOWSKI LEONARD J [US] ET AL) 12 June 2001 (2001-06-12) abstract column 3, line 48 - line 60 column 4, line 66 - column 5, line 7	1-18,20

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/GB2011/000958

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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