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Zinc-based glass polyalkenoate cements with improved setting times and mechanical properties

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Abstract

The suitability of glass polyalkenoate cements (GPCs) for skeletal applications is limited by the presence, in the glass phase, of the aluminium ion (Al^{3+}), a neurotoxin. The zinc ion (Zn^{2+}), a bacteriocide, has been incorporated into aluminium-free GPCs based on zinc silicate glasses. However, these GPCs have considerably shorter working times and poorer mechanical properties than their Al^{3+}-containing counterparts. Based on results for calcium phosphate cements, there is an indication that mixing a GPC with an organic compound, tricalcium citrate (TSC), may lead to cements with improved rheological and mechanical properties. We developed a range of Zn-based GPCs and determined their working times (T_w), setting times (T_s), compressive strength (CS) and biaxial flexural strengths (BFS). A GPC composed of 1 g of a calcium–zinc silicate glass (BT100) mixed with a 50 wt.% aqueous solution on polyacrylic acid (coded E9, M_w 80,800) at a powder liquid ratio of 2:1.5 exhibited the best combination of T_w, T_s, CS and BFS. We also found that the addition of TSC (over the range 5–15 wt.%) to a GPC led to significant increases in both T_w (from 40 ± 3 to 100 ± 4 s) and T_s (from 70 ± 2 to 3000 ± 4 s) accompanied by changes in both CS and BFS that were affected by the duration of the aging time of the specimens in distilled water (for example, after aging for 7 days CS dropped from 62 ± 2 to 17 ± 1 MPa, while after aging for 30 days, BFS increased 27 ± 6 to 31 ± 7 MPa and then dropped to 17 ± 1 MPa). Future modification and characterization of the examined GPCs are needed before they may be considered as candidates for orthopaedic applications.

Keywords: Glass polyalkenoate cements; Trisodium citrate; Mechanical properties

1. Introduction

Glass polyalkenoate cements (GPCs) are used in both restorative and luting applications in dentistry [1]. They have potential as bone cements because they adhere to both surgical metals and the mineral phase of bone [2,3], they set without shrinkage [4] or significant heat evolution [5], and they have mechanical properties (compressive strength up to 200 MPa [6], biaxial flexural strength up to 50 MPa [7], setting times up to 6 min [8]) similar to those necessary for use in orthopaedic procedures ISO5833 [9].

GPCs set by the reaction of an aluminosilicate glass with an aqueous solution of polyalkenoic acid, usually polyacrylic acid (PAA). The acid attacks and degrades the glass structure, releasing metal cations into the aqueous phase. These cations then become chelated by the carboxylate groups on the acid chains and serve to cross-link the matrix [10,11]. The set cement consists of reacted and unreacted glass particles embedded in a hydrated polysalt matrix. The setting process is regarded as a continuous process evinced by a change in mechanical properties with maturation [12].

The presence of aluminium (Al) in the glass phase of all commercial GPCs has restricted their use in orthopaedics, as Al^{3+} causes defective bone mineralization [13,14] and has been implicated in the pathogenesis of degenerative brain diseases [15–18]. In reconstructive otoneurosurgery, release of Al^{3+} from a GPC was considered the principle cause of a case of sub-acute fatal encephalopathy [17].

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Thus, for GPCs to be considered for similar applications in the future it is necessary to completely remove Al^{3+} from these cements. Fortunately, Zn^{2+} can act as both a network modifying oxide and an intermediate oxide in a similar fashion to Al^{3+} [18], and this has resulted in the development of GPCs based on calcium–zinc silicate glasses, rather than on calcium aluminosilicate glasses [19,20]. Zn^{2+} also has the ability to increase the DNA of osteoblasts [21], resulting in increased bone mass [22]. Therefore, Zn-based GPCs (Zn-GPCs) have potential for orthopaedic applications.

Research on Zn-GPCs has been expanded by the addition of strontium oxide (SrO) to the CaO–ZnO–SiO_2 glass phase of cements [23]. Strontium (Sr^{2+}) was added at the expense of Ca (possible due to the similar ionic radii of Ca^{2+} and Sr^{2+}) for three reasons: it is a radiopacifier, it has antibacterial properties [24] and it assists in the formation of healthy bone [25,26].

Low doses of Sr (300 mg kg^{-1} day^{-1} of Sr^{2+} for 9 weeks) can inhibit bone resorption [27] and stimulate bone formation in both animal [26] and clinical trials [28]. Strontium ranelate (SR; manufactured as Protelos®, Servier Laboratories, Ireland) can halve the risk of spinal fracture in patients after 1 year of treatment [29]. In vitro studies have shown that SR inhibits osteoclast activity [30] and stimulates osteoblast proliferation [25]. Strontium has an affinity for bone [31] and is incorporated into it by surface exchange and ionic substitution. The authors have reported on the incremental replacement of Ca with Sr [32]. Zn/Sr-GPCs have potential as Zn^{2+} release will enhance osteoconductivity and Sr^{2+} release will stimulate osteoblast proliferation.

Previous work by the authors [33,34] has shown that it is possible to produce a structurally integral bioactive GPC from a calcium–zinc silicate glass. However, the authors have also reported that the working times of these cements were too short and their strengths too weak for load-bearing applications [35]. Thus it is necessary to develop stronger cements with increased working times by the addition of other reagents. However, it is essential that these reagents do not adversely affect the bioactivity of the cement. Organic additives have been employed in the development of calcium phosphate cements (CPCs) for skeletal applications [35,36]. One of those additives, trisodium citrate, TSC ($Na_3C_6H_5O_7$), is of interest because citrate ions are present in bone mineral. TSC has also been shown to reduce the viscosity of CPC pastes at lower concentrations [37]. Having postulated that this was a consequence of mutual electrostatic repulsion of the reactant particles after adsorption of citrate ions following neutralization of the carboxylic acid groups, a novel CPC consisting of tetracalcium phosphate (TTCP) and monetite (DCPA) was mixed with TSC. The CPC was both injectable and 400% stronger than the same cement made with water. It has also been reported that TSC incorporation into CPCs increases both setting time [38,39] and compressive strength [39].

The objective of this work is to investigate the effect of Sr incorporation into the glass phase on the working times, setting times and mechanical properties of resultant Zn-GPCs. Furthermore, this paper will investigate if the addition of TSC into the cement formulation affects these modalities, thus improving clinical applicability.

2. Materials and methods

2.1. Glass synthesis

A series of glasses were produced (Table 1). Appropriate amounts of analytical grade silica, zinc oxide, calcium carbonate and strontium carbonate (Sigma Aldrich, Dublin, Ireland) were weighed out in a plastic tub and mixed in a ball mill for 1 h, then dried in a vacuum oven (100 °C, 1 h). The glass batches were then transferred to mullite crucibles for firing (1480 °C, 1 h). The glass melts were shock quenched into water and the resulting grits were dried, ground and sieved to retrieve a <45 μm glass powder, which was used to form the cements.

2.2. Poly(acrylic) acid

Ciba speciality polymers (Bradford, UK) supplied PAA (M_w, 80,800 g mol^{-1}) in aqueous solution (25 mol.%). The PAA was freeze-dried, ground and sieved to retrieve a <90 μm powder.

2.3. Cement preparation

The initial cement series was prepared by thoroughly mixing the amounts of respective glass powders (<45 μm) with the appropriate amounts of PAA and distilled water on a glass plate (Table 2). Complete mixing was undertaken within 20 s. The concentrations of the PAA solutions are expressed in mass% (g of solute/total g of solution).

A second series of modified GPCs (mGPCs) was produced (Table 3) to examine the effect of TSC (Reagecon, Shannon, Ireland) on the working and setting times, as well as the mechanical properties of the BT100/50 wt.% cement

Table 1
Glass compositions (mol.%)

	SrO	CaO	ZnO	SiO_2
BT100	0	0.16	0.36	0.48
BT101	0.04	0.12	0.36	0.48
BT102	0.08	0.08	0.36	0.48

Table 2
Cement formulations examined in this study

Cement (wt.%)	Glass (g)	PAA (g)	Water (ml)
40	1	0.3	0.45
45	1	0.33	0.41
50	1	0.37	0.37

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