Amorphous Calcium Phosphate Based Polymeric Composites: Effects of Polymer Composition and Filler's Particle Size on Composite Properties

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Abstract. This study explores how a) the resin grafting potential for amorphous calcium phosphate (ACP) and b) particle size of ACP affects physicochemical properties of composites. Copolymers and composites were evaluated for biaxial flexure strength (BFS), degree of vinyl conversion (DC), mineral ion release and water sorption (WS). Milled ACP composites were superior to unmilled ACP composites and exhibited 62 % and 77 % higher BFS values (dry and wet state, respectively). The average DC of copolymers 24 h after curing was 80 %. DC of composites decreased 10.3 % for unmilled Zr-ACP and 4.6 % for milled Zr-ACP when compared to the corresponding copolymers. The WS increased as follows: copolymers < milled Zr-ACP composites increased with the increasing EBPADMA/TEGDMA ratio in the matrix. They were significantly above the minimum necessary for the redeposition of HAP to occur. No significant consumption of released calcium by the carboxylic groups of methacryloxyethyl phtahalate (MEP) occurred at a mass fraction of 2.6 % of MEP in the resin and improved ACP's dispersion within the polymer matrix after ball-milling.

Introduction

Bioactive, amorphous calcium phosphate (ACP) polymeric composites have been the focus of our recent research [1, 2]. However, as filler in polymeric composites ACP has no reinforcing ability. Consequently, ACP-based composites are mechanically inferior to glass-reinforced dental materials. In this study we report on the utility of fine-tuning the resin as a tool to improve anti-demineralizing/remineralizing ability of ethoxylated bisphenol А dimethacrylate (EBPADMA)-based ACP composites while - if not improving - at least not impeding their mechanical coherence, water sorption and photopolymerization efficacy. The working hypothesis was that improved ion release could be achieved by elevating the EBPADMA/triethylene glycol dimethacrylate (TEGDMA) ratio while lowering the level of multifunctional, adhesive monomer methacryloxyethyl phthalate (MEP) in the resin without adversely affecting the biaxial flexure strength (BFS), degree of vinyl conversion (DC) and water sorption (WS) of composites. A reduced level of MEP was used to minimize calcium uptake by the carboxylic groups of MEP. To test the above hypothesis, unmilled and milled hybrid zirconia-ACP (Zr-ACP) filler was formulated with EBPADMA/TEGDMA/HEMA/MEP resins of three different EBPADMA/TEGDMA ratios and evaluated for DC, BFS, WS and mineral ion release. In addition, the DC, BFS and WS of unfilled resins (copolymers) were determined to clarify the possible effect(s) of the filler type on these parameters.



Materials and Methods

Precipitation and Characterization of Zirconia-hybridized ACP (Zr-ACP) Fillers. Zr-ACP (assigned unmilled) was synthesized as detailed earlier [1,2]. A portion of unmilled Zr-ACP was mixed with high density ZrO_2 balls (2 mm in diameter) in isopropanol and milled at 57 rad/s for 2.5 h (assigned milled Zr-ACP). Conventional analytical methods/techniques were used to characterize the ACP fillers.

Formulation of the resins. Compositions of the experimental resins are given in Table 1. **Table 1.** Composition (mass fraction; %) of experimental resins.

Resin/monomer	EBPADMA	TEGDMA	HEMA	MEP
ETHMI	43.17	43.24	10.08	2.51
ETHMII	54.45	31.94	10.00	2.61
ETHMIII	62.85	23.22	10.36	2.57

The indicated acronyms are used throughout this manuscript. Resins were photoactivated by the addition of a mass fraction of 0.20 % camphorquinone and

0.80 % ethyl-4-N, N-dimethylamino benzoate.

Preparation of composite and copolymer specimens. Composite pastes (a mass fraction 60 % ETHM resin and 40 % ACP filler) were molded into disks [diameter: (15.1 ± 0.2) mm; thickness: (1.42 ± 0.11) mm)] and photo-polymerized with visible light (120 s per each side). An identical procedure was used to prepare copolymer disk specimens.

Physicochemical appraisal of copolymers and composites. *Biaxial flexure strength (BFS*; [3]) of dry and wet disk specimens ($n \ge 5$; 40 d of immersion in HEPES-buffered saline, 23 °C) was determined by using a computer-controlled Universal Testing Machine (crosshead speed: 0.5 mm/min). The vinyl conversion (DC) of copolymers and composites ($n \ge 8$ /group) was measured by monitoring changes in the 1637 cm⁻¹ IR absorption band for the vinyl group against that of phenyl ring at 1582 cm⁻¹ (internal standard) 24 h after photocuring [4]. *Mineral ion release* was examined at 23 °C from individual composite disk specimens ($n \ge 3$) in a continuously stirred, buffered (pH = 7.40) saline solution. Ca and PO₄ levels were determined spectrophotometrically [5, 6]. The thermodynamic stability of immersion solutions containing the maximum levels of Ca and PO₄ released from composites was calculated using the Gibbs free-energy expression:

$$\Delta G^{\circ} = -2.303 \,(\text{RT/n}) \ln \left(\text{IAP/K}_{\text{sp}}\right) \tag{1}$$

where IAP is the ionic activity product for the hydroxyapatite $(Ca_{10}(OH)_2(PO_4)_6; HAP)$, K_{sp} is the HAP's thermodynamic solubility product, R is the ideal gas constant, T is the absolute temperature and n is the number of ions in the IAP (n = 18). Chemist software provided by MicroMath Research, St. Louis, MO, USA, was used for the IAP calculations. *Water sorption (WS)* of copolymer and dry composite disk specimens (n \geq 5) was determined gravimetrically [7] in an air atmosphere of 75 % relative humidity (close systems; 23 °C).

Statistical analysis of the experimental data. Experimental data were analyzed by ANOVA ($\alpha = 0.05$). Significant differences between specific groups were determined by all pair-wise multiple comparisons (two-tail t-test; unequal variances). One standard deviation (SD) is given in this paper for comparative purposes as the estimated standard uncertainty of the measurements.

Results

BFS, DC, ΔG° and WS results are summarized in **Table 2.** Resin composition had no significant effect on the BFS of either dry or wet copolymer specimens. The average dry BFS (*group mean values*) of copolymers was (81 ± 24) MPa, milled composites (75 ± 11) MPa and unmilled composites (46 ± 15) MPa. The BFS of wet specimens decreased in the following order: copolymers (71 ± 25) MPa > milled composites (54 ± 12) MPa > unmilled composites (30 ± 5) MPa. Milled composites maintained higher BFS than the unmilled composites in both dry and wet state (62 % and 77 %, respectively). Analysis of the 24 h DC data (*group mean values*) revealed an average (80.2 ± 2.1) % of



vinyl conversion in copolymer series. In both unmilled and milled composite series DC decreased in the following order: ETHMI > (ETHMII, ETHMIII). Generally, irrespective of the resin composition, DC of composites was reduced up to 10.3 % (unmilled ACP specimens) and up to 4.6 % (milled ACP specimens) compared to the corresponding copolymers. The maximum concentrations of *Ca and PO₄ released from composites* increased significantly with the increasing EBPADMA/TEGDMA ratio in the resin for both types of composites. *Attained supersaturations* (taken as a measure of the anti-demineralizing/remineralizing capacity) were significantly above a minimum necessary for mineral redeposition ($\Delta G^{\circ} < 0$) to occur. Copolymers adsorbed a maximum of a mass fraction between 1.28 % and 1.77 % water, the unmilled ACP composites adsorbed a mass fraction between 2.24 % and 2.52 % and the milled ACP composites adsorbed a mass fraction between 1.65 % and 2.12 % water. The WS of copolymers and milled ACP composites decreased with the increasing EBPADMA/TEGDMA ratio in the resin: WS_{ETHMI} > WS_{ETHMII}.

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Resin/cop	oolymer/composite	Bl (M dry	FS Pa) wet	DC (%)	ΔG° $(kJ/mol)^{\#}$	WS (mass %)
ETHMI	copolymer	76(25)	68(30)	80.4(2.0)	n/a	1.77(0.11)
	unmilled ACP	57(13)	31 (4)	76.6(3.3)	-[4.35(0.21)]	2.52(0.19)
	milled ACP	70(10)	60 (9)	80.3(1.4)	-[3.42(0.39)]	2.12(0.16)
ETHMII	copolymer	82(23)	67(27)	80.3(1.0)	n/a	1.64(0.15)
	unmilled ACP	46(13)	27 (3)	70.4(4.3)	-[4.65(0.22]	2.48(0.19)
	milled ACP	78(11)	51 (9)	74.4(4.2)	-[4.32(0.36)]	1.97(0.04)
ETHMIII	copolymer	83(26)	78(20)	79.6(3.2)	n/a	1.28(0.08)
	unmilled ACP	41(16)	31 (6)	68.8(4.2)	-[4.67(0.23)]	2.24(0.20)
	milled ACP	78(12)	50(16)	74.8(0.9)	-[4.79(0.20)]	1.65(0.13)
group	copolymer	81(24)	71(25)	80.2(2.1)		
mean	unmilled ACP	46(15)	30 (5)	71.9(5.1)	nd	nd
value	milled ACP	75(11)	54(12)	76.5(3.7)		

	Table 2. Physicochemical pro	perties [®] of ETHM copolyme	ers and their ACP composites.
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^{*} All results expressed as mean(SD); number of samples as indicated in the Materials and Methods section. [#]Negative ΔG° value indicates solution supersaturated with respect to stoichiometric hydroxyapatite, Ca₁₀(OH)₂(PO₄)₆.

Discussion

The BFS of dry and wet copolymer and composite specimens was unaffected by the resin composition. The type of the filler utilized, however, had a major effect on the BFS of the composites. The reduction in BFS of composites compared to copolymers, typically seen with the unmilled ACP composites [1], was not observed with dry milled ACP/ETHM specimens. Only after exposure to water, these composites were, on average, 24 % weaker than the corresponding copolymers, compared to a 58 % reduction in unmilled ACP composite specimens. This lesser reduction in the BFS of milled composite specimens is attributed to their ability to maintain the filler/matrix interface less vulnerable to spatial changes that may occur during Ca and PO₄ release from composites. EBPADMA, relatively hydrophobic analog a of 2,2-bis[p-(2'-hydroxy-3'-methacryloxypropoxy)phenyl]propane (Bis-GMA; a base monomer utilized in a majority of commercial dental materials) has been recently identified [1] as an essential component of the resins that reach high DC upon photocuring and, therefore, have a minimal potential for leaching-out the unreacted monomeric species. A sought-after effect of EBPADMA on the DC is attributed primarily to the higher flexibility and the lower viscosity of this monomer compared to



Bis-GMA. A maximum reduction in DC of 10.3 % established for unmilled ACP composites compares well with the reduction of DC observed in Bis-GMA- and EBPADMA-based binary and ternary resin composites utilizing the same type of ACP filler (up to 14.4 % and 14.2 %, respectively; [1]). Utilizing milled ACP diminishes the reduction in the DC of ETHM composites (up to 4.6 %) compared to their copolymers. A functional dependence between the attained supersaturation and the EBPADMA/TEGDMA molar ratio in the resin was more apparent in milled- than the unmilled ACP/ETHM composites, For milled ACP composites this relationship could be described by the following expression: $\Delta G^{\circ} = -1.56$ (EBPADMA/TEGDMA molar ratio) – 2.77; (R² = 0.935). At given concentration of MEP in the resin, no adverse consumption of released Ca by the MEP's carboxylic groups occurred. Ca-MEP binding could not be detected in ETHMI, ETHMII or ETHMIII copolymer disks exposed to saline solutions that initially contained 1.5 mmol/L Ca. The observed decrease in WS with the increasing EBPADMA/TEGDMA ratio is most probably related to the increasing overall hydrophobicity of the resin matrix as the level of relatively hydrophobic EBPADMA monomer increases. The WS of ACP/ETHM composites is additionally affected by the water-ACP interactions resulting in an increase of WS for 42 % to 75% and 20 % to 29 % for unmilled ACP composites and milled ACP composites, respectively, compared to unfilled copolymers. The superior behavior of milled ACP composites in comparison with the unmilled ones can possibly be related to the more intimate contact between this filler and the ETHM resins.

Conclusion

The chemical composition of the monomer system used to form the matrix phase of ACP-filled EBPADMA/TEGDMA/HEMA/MEP composites can affect their anti-demineralizing/remineralizing ability. Higher calcium and phosphate release is achievable by elevating the EBPADMA/TEGDMA ratio and by keeping the MEP level sufficiently low to avoid excessive Ca-binding with the reactive carboxylic groups of MEP. Fine-tuning of the ETHM resin may help in reducing the level of water sorption by these composites. In addition, utilizing milled ACP may lower water sorption and enhance the mechanical stability of ACP composites.

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Disclaimer

Certain commercial materials and equipment are identified in this work for adequate definition of the experimental procedures. In no instance does such identification imply recommendation or endorsement by ADAF or NIST, or that the material and the equipment identified is necessarily the best available for the purpose.

References

- [1] D. Skrtic, J.M. Antonucci and E.D. Eanes: J. Res. Natl. Inst. Stands. Technol. 108 (2003) 167-182.
- [2] D. Skrtic D, J.M. Antonucci, E.D. Eanes and N. Eidelman: Biomaterials 25 (2004)1141-1150.
- [3] American Society for Testing and Materials ASTM F417-78. 1984, Philadelphia, PA.
- [4] J.M. Antonucci, W.G. McDonough, D.W. Liu and D. Skrtic: Polym. Mater: Science & Engineering 88 (2003) 50-51.
- [5] G.L. Vogel, L.C. Chow and W.E. Brown: Caries Res. 7 (1983) 23-31.
- [6] J. Murphy and J.P. Riley: Anal. Chim. Acta 27 (1962) 31-36.
- [7] D.Skrtic and J.M. Antonucci: Biomaterials 24 (2003) 2881-2888.



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