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Original Article

Bioactive Ceramic Composites: A Dual Approach to Controlled Fluoride Delivery and Mechanical Reinforcement

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Abstract
This study investigates the development of α-tricalcium phosphate (α-TCP) composite cements modified with 7.5 wt% fluorapatite (FAp) to enhance their functional performance for potential dental and orthopedic applications. The composites were designed to simultaneously achieve sustained fluoride ion release and improved structural properties. Fluoride release kinetics were evaluated using ion-selective electrodes in a standard fluoride solution over seven days, while mechanical performance was assessed through compressive strength testing after immersion in simulated body fluid (SBF) for 0, 3, and 10 days. Results reveal a sustained release, consistent with diffusion from a dual-phase reservoir. Compressive strength analysis showed progressive strengthening of the composite, but with a significantly slower increase in the FAp-containing composite compared to pure α-TCP. This behavior suggests that while FAp enhances long-term bioactivity through controlled ion delivery, it may also modulate the dissolution–reprecipitation pathway of α-TCP conversion into hydroxyapatite, thereby delaying early mechanical maturation. Overall, these findings demonstrate that fluorapatite incorporation into α-TCP matrices enables the design of multifunctional biomaterials with tunable ion release and mechanical evolution, offering a promising pathway for next-generation regenerative cement technologies.
Keywords. Ceramic Composites, Fluoride Delivery, Mechanical Reinforcement.

Introduction

Calcium phosphate cements (CPCs) have emerged as leading synthetic bone and dental fillers due to their excellent biocompatibility, in situ hardening capability, and capacity to transform into biologically active hydroxyapatite (HAp) under physiological conditions. Tricalcium phosphates (TCP- $Ca_3(PO_4)_2$) represent biodegradable ceramic material that occurs as four allotropes, among which *α*- and *β*- are the most common ones. Since TCP is soluble in an aqueous environment, there is great potential for its use in bone tissue regeneration. However, depending on the numerous factors, such as Ca/P ratio, porosity, and purity, the resorption rate of TCP could vary in a significant manner (1–4). If a rate is too high, tissue will not be able to regenerate, thus making this material unsuitable as a scaffold.

Compared to HA, TCP with a molar ratio Ca/P of 1.5 resorbs faster, making it more challenging to control, but a good candidate for mixing with HA (5). In this manner, by adjusting the amounts of the two compounds, the desired bioactivity could be achieved. Allotrope *β*-TCP (*β*-$Ca_3(PO_4)_2$) has been thoroughly studied and incorporated as a replacement for bones (6–10). Similar to HA, *β*-TCP does not occur in nature, but it can be successfully synthesized using high-temperature techniques (11). It shows higher thermal stability than HA and faster resorption due to its solubility. However, the bioresorbability of the *β*-TCP is strongly influenced by porosity and surface roughness; therefore, there are different reports about its low bioactivity due to a high density (12). With proper morphology control, bioactivity can be significantly increased, resulting in a good material for use as a bone replacement (13). In addition, *β*-TCP can be used in commercial toothpastes for better teeth polishing (14-16). The other important calcium phosphate polymorphs, *α*-tricalcium phosphate (*α*-TCP), have also been recognized as a material for bone cement and bioceramics (3,17). Allotrope *α*-TCP (*α*-$Ca_3(PO_4)_2$) has the same chemical formula as *β*-TCP, but their crystal structures are different. *β*-TCP has a more ordered structure (18), which causes lower solubility compared to *α*-TCP. Being thermally stable, *α*-TCP is also obtained by high-temperature synthesis, above 1200 ˚C, and cannot be found in biological systems. Porous morphology can be obtained with the sintering process.

As mentioned, it is more soluble than *β*-TCP, which makes it a more suitable candidate for scaffolds (18–21). Possibility of *α*-TCP to transform spontaneously into hydroxyapatite (HAp) after the application in the mouth surrounding put it in the focus of researchers as the material that would fill the cavity after removal of damaged dental tissue and also remineralize the surrounding tissue. Major drawback in TCPs use lies in their brittleness, which could be overcome by combination with more ductile materials (7). To overcome these limitations, the incorporation of secondary phases such as fluorapatite (FAp, $Ca_{10}(PO_4)_6F_2$) has been proposed. FAp differs from HAp by the substitution of hydroxide ions with fluoride, which lowers solubility, enhances chemical stability, and provides a reservoir for sustained fluoride release—a well-known promoter of remineralization and inhibitor of bacterial demineralization in dental and orthopedic contexts (22,23). Fluoride ions play a multifaceted role in bone and tooth health: they stabilize the apatite lattice, increase crystal size and hardness, and modulate osteoblastic activity. In vivo studies have demonstrated that controlled fluoride delivery can accelerate bone formation and improve implant integration (24). However,

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high fluoride concentrations may be cytotoxic, so tuning both the amount and release kinetics is critical (25–27). Embedding FAp particles within an α-TCP matrix offers a means to modulate the initial burst and sustained fluoride release phases by acting as an ion-exchange reservoir while simultaneously reinforcing the cement microstructure.

Over the last two decades, great effort has been employed to produce more efficient, aesthetically acceptable and endurable dental materials, of which some will be presented in this chapter. To produce bone-like material for orthopedic use, HAp was successfully modified with fluorine and chlorine (28). Borkowski et al. used sol-gel method and calcination for the synthesis of FAp to achieve higher bioactivity compared to HAp (29). They varied calcination temperature to find FAp sample with optimal porosity and highest F^- ions release ability. In vitro tests proved the absence of toxic effect on the cells, while the best FAp sample showed high cell-proliferation potential, which makes this material safe for the use in orthopedic applications. For the increase of corrosion resistance, Mansoorianfar and associates introduced fluorine into the HAp (30). Along with the corrosion protective coating, obtained fluorhydroxyapatite showed good biocompatibility, tested on MG-63 osteoblast cells. Khan et al. synthesized FAp nanoparticles, using them as fillers for polyurethane (PU) matrix, to build nanocomposite for root canal filling (31). Investigations showed efficient F-ion release from the composite, as well as a homogenous structure and good adhesion to the surrounding tissue. In some researches, FAp and HAp nanoparticles were investigated as scaffolds for orthopedic and dental application (32–34). Altaie et al. prepared an acrylate-based composite scaffold containing silanised barium aluminium silicate glass particles and FAp as reinforcement (35). The results showed that the addition of FAp increased fracture toughness and enabled F^- ion release in the acid environment, suggesting that this composite could find application as a smart dental material. Montazeri et al. used sol-gel method to synthesize nano-FAp to investigate biocompatibility (36). In vitro tests on animal fibroblast cells showed the absence of cytotoxicity, making this material suitable for the potential application as a bone scaffold. As a mechanical reinforcement to the restorative material, FAp and HAp nanoparticles were embedded in a glass-ionomer cement (37,38). Barandehfard et al. synthesized nano-FAp and HAp using the wet-chemical precipitation method, to reinforce glass-ionomer cement (39). Performed compressive, tensile, and microhardness tests on the obtained composites showed an improvement of all the investigated mechanical properties before and after the immersion in distilled water.

Elghazel and asscociates presented a study of FAp addition to *β*-TCP on the mechanical performace of the obtained composite (6). The results showed that FAp concentration increases wear resistance, which is important for the use in dental applications. Wei et al. prepared FAp-based cement for the restoration of enamel [235]. The cement showed good mechanical and adhesive properties, as well as high biocompatibility tested on L929 fibroblast cells, which opened a pathway for the investigations of this FAp-based material as a direct enamel repair. Azami et al. investigated composite containing calcium fluoride and co-substituted HAp with FAp for the treatment of osteoporosis (40). The composite showed high bioactivity, which was tested in simulated body fluid (SBF). In the recent research published by Anastasiou and associates, doping of FAp with Sr^+ and Ce^{3+} ions was reported, to modify chitosan-based scaffolds efficient against bacteria appearing at the implantation site (41). The results suggested that Ce^{3+} doped FAp could be applied in reconstructive surgery, due to a high osteoconductivity and antimicrobial activity. With the emerging development of nanotechnology, the biocompatibility and bioactivity of calcium phosphate-based dental materials can be enhanced and controlled using various synthesis routes (7,42). Stojanovic et al. presented the synthesis of *α*-TCP implants in order to evaluate biocompatibility and potential for use in dentistry (43). The histological analysis of animal tissue after different numbers of days with the implanted *α*-TCP revealed high biocompatibility, similar to commonly used ceramics. Along with non-toxicity, this material provided efficient production of collagen fibers. Continued research is necessary to optimize these composites for specific clinical applications, ensuring their efficacy and safety in bone and dental tissue engineering.

This study was conducted to investigates the development of α-tricalcium phosphate (α-TCP) composite cements modified with 7.5 wt% fluorapatite (FAp) to enhance their functional performance for potential dental and orthopedic applications.

Methods

Composite preparation

In order to obtain ceramic composites, synthesized FAp powder was added in 7.5 wt% to the *α*-TCP powder. Further, in a prepared mixture of powders, the phosphate solution (2.5 wt% Na_2HPO_4) was added at a liquid to powder ratio of 0.32 ml/g, and the tablets were formed. Composite tablets were made in accordance with ISO 6876 standard for root canal sealing materials.

Characterization of composites

For F^- ion release test, *α*-TCP, FAp and composite pills were placed in glasses that were filled with standard fluoride solution with added Fluoride Ionic Strength Adjustor (ISA). Measurements using Ion Selective Electrode (ISE) method were performed after 5 minutes, 1 hour, 1, 3 and 7 days, in order to measure the release of F^- ions from pills with 7.5wt% % of FAp in alpha-TCP. Mechanical tests of composite tablets were

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performed on a Shimadzu universal testing machine. Each tablet was tested after immersing in SBF for 0, 3, and 10 days. A compressive test was performed using a steel plate with a mass of 0.1535 kg (applied force was 1.51 N), with a speed of 5mm/min. Surface of the specimens was $2.5 \cdot 10^{-5}$ m^2. Measurement of compressive strength and stroke strain for each composite was performed on five samples.

Results and discussion

Fluoride-ion release kinetics

The time-resolved fluoride ion release profile for the 7.5 wt% FAp-containing α-TCP composite is shown in Figure 1. An initial burst is detected within the first hour, which then drops and gradually increases again over the subsequent time points. This biphasic pattern suggests a multi-step release mechanism. The early release phase likely results from loosely bound or surface-associated fluoride ions being rapidly leached into the solution. This is followed by a transient decline, potentially due to the precipitation of secondary calcium phosphate phases or the formation of a temporary passivation layer, which may temporarily hinder further ion diffusion. After this initial drop, the sustained increase in fluoride concentration implies that the FAp phase undergoes slow dissolution or ion exchange in the acidic or near-neutral environment of the test solution. This is consistent with reports indicating that FAp, due to its lower solubility compared to HAp, can act as a reservoir for controlled fluoride release over extended periods (24,44). Such a controlled release profile is especially desirable in clinical settings, where fluoride plays dual roles—stimulating osteoblastic activity and inhibiting bacterial proliferation. However, excessive initial release might pose a cytotoxic risk, emphasizing the importance of tuning FAp content and dispersion (26,27). The observed release behavior also supports the hypothesis that fluorapatite addition alters the cement's microstructure, possibly by influencing crystallization kinetics or inducing microheterogeneity that affects diffusion pathways. Overall, the release profile observed in this study aligns with the design goals of developing α-TCP-based formulations that combine structural reinforcement with sustained therapeutic ion delivery.

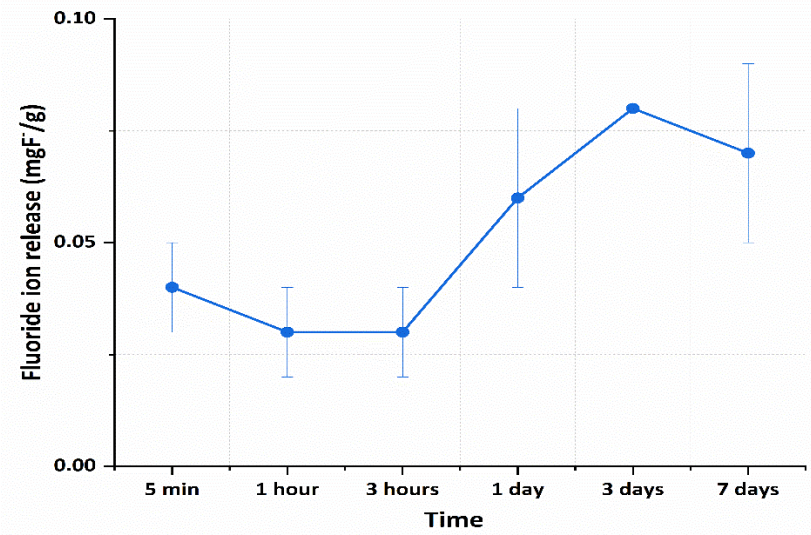

Figure 1. Fluoride ion release (mg F^-/g composite) versus immersion time in hours for 7.5 wt % FAp formulation. Error bars denote ± standard deviation.

Compressive test

Compressive strength testing was performed on α-TCP and α-TCP/7.5 wt% FAp composites after immersion in SBF for 0, 3, and 10 days to monitor the effect of FAp addition on mechanical maturation. The results indicate that while both compositions exhibit strength gain over time, the sample without FAp shows a sharper increase, particularly between day 3 and day 10. This difference is likely attributable to the transformation of α-TCP into hydroxyapatite, a process enhanced in the absence of FAp. The fluoride substitution in the FAp lattice reduces solubility and thus may slow down dissolution-reprecipitation dynamics, delaying full HAp conversion. Furthermore, FAp particles could act as inert fillers within the α-TCP matrix, inhibiting microstructural densification and reducing the rate at which interlocking HAp crystals form. Despite this reduced strength gain, the 7.5 wt% FAp composite may offer advantages in terms of long-term stability, as FAp is less soluble and thus contributes to structural integrity under physiological conditions. However, for load-bearing applications that require rapid mechanical development, a high FAp loading may be suboptimal. Previous literature has highlighted that moderate FAp incorporation (2.5–5 wt%) provides a better balance between bioactivity and mechanical evolution (44,45). In this context, the slower strength development observed for the 7.5 wt% composite underscores the need to tailor FAp content to the intended clinical scenario favoring lower concentrations for early load-bearing and higher ones for long-term ion release.

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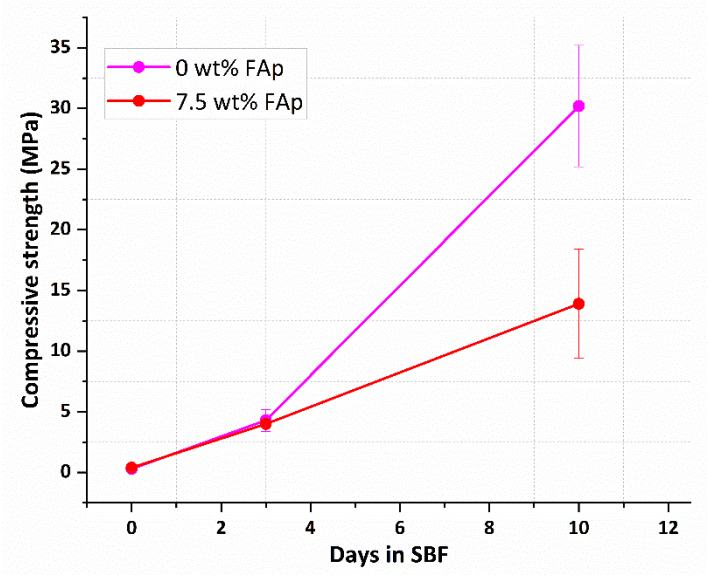

Figure 2. Compression test

Conclusion

This study confirms that incorporating fluorapatite (FAp) into α-tricalcium phosphate (α-TCP) cements significantly affects both fluoride release kinetics and mechanical performance. The release profile from the 7.5 wt% FAp formulation demonstrates a dual-phase mechanism: an initial burst followed by sustained release, aligning well with therapeutic objectives for bone and dental regeneration. This behavior is indicative of FAp's function as a long-term ion reservoir, gradually supplying fluoride through controlled dissolution, a feature essential for promoting remineralization and enhancing antibacterial properties in clinical contexts. Mechanically, both pure α-TCP and the FAp-modified composite displayed time-dependent strength improvements due to the progressive transformation of α-TCP into hydroxyapatite in SBF. However, the 7.5 wt% FAp sample exhibited a slower strength gain over the 10-day immersion period. This reduced mechanical maturation can be attributed to fluoride-induced modulation of dissolution and reprecipitation kinetics, as well as potential microstructural inhomogeneities introduced by the FAp phase. Taken together, the findings highlight a trade-off between structural reinforcement and bioactivity modulation. While high FAp content supports sustained ion delivery and long-term biostability, it may impede rapid strength development. Therefore, for applications requiring early mechanical reliability, lower FAp loadings may be preferable, whereas for prolonged bioactive effects, particularly in low-load environments, higher FAp concentrations could offer superior performance. Future work should explore intermediate FAp concentrations (e.g., 3-5 wt%) to identify optimal formulations that balance these dual requirements. Furthermore, in vivo assessments are essential to validate the cytocompatibility, osteointegration potential, and long-term performance of these bioceramic systems under physiological loading conditions.

Conflicts of Interest

The authors declare no conflicts of interest.

References

1. Koutsopoulos S. Synthesis and characterization of hydroxyapatite crystals: A review study on the analytical methods. J Biomed Mater Res. 2002;62(4):600–12. DOI: 10.1002/jbm.10280
2. Dos Santos V, Brandalise RN, Savaris M. Engineering of Biomaterials. Cham: Springer International Publishing; 2017. (Topics in Mining, Metallurgy and Materials Engineering). DOI: 10.1007/978-3-319-58607-6
3. Caldas IP, Alves GG, Barbosa IB, Scelza P, De Noronha F, Scelza MZ. In vitro cytotoxicity of dental adhesives: A systematic review. Dental Materials. 2019;35(2):195–205. DOI: 10.1016/j.dental.2018.11.028
4. Kwon S, Jun Y, Hong S, Lee I, Kim H, Won YY. Calcium Phosphate Bioceramics with Various Porosities and Dissolution Rates. Journal of the American Ceramic Society. 2002;85(12):3129–31. DOI: 10.1111/j.1151-2916.2002.tb00599.x
5. Eliaz N, Metoki N. Calcium Phosphate Bioceramics: A Review of Their History, Structure, Properties, Coating Technologies and Biomedical Applications. Materials. 2017;10(4):334. DOI: 10.3390/ma10040334
6. Elghazel A, Taktak R, Elleuch K, Bouaziz J. Mechanical and tribological properties of tricalcium phosphate reinforced with fluorapatite as coating for orthopedic implant. Materials Letters. 2018;215:53–7. DOI: 10.1016/j.matlet.2017.12.044
7. Taktak R, Elghazel A, Bouaziz J, Charfi S, Keskes H. Tricalcium phosphate-Fluorapatite as bone tissue engineering: Evaluation of bioactivity and biocompatibility. Materials Science and Engineering: C. 2018;86:121–8. DOI: 10.1016/j.msec.2017.11.011

Received*: 28-04-2025 -* ***Accepted****: 22-06-2025 -* ***Published****: 02-07-2025*

8. Champion E. Sintering of calcium phosphate bioceramics. Acta Biomaterialia. 2013;9(4):5855–75. DOI: 10.1016/j.actbio.2012.11.029
9. Gomes S, Vichery C, Descamps S, Martinez H, Kaur A, Jacobs A, et al. Cu-doping of calcium phosphate bioceramics: From mechanism to the control of cytotoxicity. Acta Biomaterialia. 2018;65:462–74. DOI: 10.1016/j.actbio.2017.10.028
10. Chen Y, Wang J, Zhu XD, Tang ZR, Yang X, Tan YF, et al. Enhanced effect of β-tricalcium phosphate phase on neovascularization of porous calcium phosphate ceramics: In vitro and in vivo evidence. Acta Biomaterialia. 2015;11:435–48. DOI: 10.1016/j.actbio.2014.09.028
11. Dorozhkin SV. Biphasic, triphasic and multiphasic calcium orthophosphates. Acta Biomaterialia. 2012;8(3):963–77. DOI: 10.1016/j.actbio.2011.09.003
12. Kamitakahara M, Ohtsuki C, Miyazaki T. Review Paper: Behavior of Ceramic Biomaterials Derived from Tricalcium Phosphate in Physiological Condition. J Biomater Appl. 2008;23(3):197–212. DOI: 10.1177/0885328208096798
13. Tebyanian H, Norahan MH, Eyni H, Movahedin M, Mortazavi SJ, Karami A, et al. Effects of collagen/β-tricalcium phosphate bone graft to regenerate bone in critically sized rabbit calvarial defects. Journal of Applied Biomaterials & Functional Materials. 2019;17(1):2280800018820490. DOI: 10.1177/2280800018820490
14. Petronis S, Locs J, Zalite V, Pilmane M, Skagers A, Salma I, et al. Impact of Biphasic Calcium Phosphate Bioceramics on Osteoporotic Hip Bone Mineralization *In Vivo* Six Months after Implantation. KEM. 2016;721:229–33. DOI: 10.4028/www.scientific.net/KEM.721.229
15. Suzuki O, Shiwaku Y, Hamai R. Octacalcium phosphate bone substitute materials: Comparison between properties of biomaterials and other calcium phosphate materials. Dent Mater J. 2020;39(2):187–99. DOI: 10.4012/dmj.2020-001
16. Dorozhkin SV. Calcium orthophosphates (CaPO 4): Occurrence and properties. Morphologie. 2017;101(334):125–42. DOI: 10.1016/j.morpho.2017.03.007
17. Ayoub G, Veljovic D, Zebic ML, Miletic V, Palcevskis E, Petrovic R, et al. Composite nanostructured hydroxyapatite/yttrium stabilized zirconia dental inserts – The processing and application as dentin substitutes. Ceramics International. 2018;44(15):18200–8. DOI: 10.1016/j.ceramint.2018.07.028
18. Carrodeguas RG, De Aza S. α-Tricalcium phosphate: Synthesis, properties and biomedical applications. Acta Biomaterialia. 2011;7(10):3536–46. DOI: 10.1016/j.actbio.2011.06.019
19. Cicek G, Aksoy EA, Durucan C, Hasirci N. Alpha-tricalcium phosphate (α-TCP): solid state synthesis from different calcium precursors and the hydraulic reactivity. J Mater Sci: Mater Med. 2011;22(4):809–17. DOI: 10.1007/s10856-011-4283-x
20. Perez RA, Kim H. Core–shell designed scaffolds of alginate/alpha-tricalcium phosphate for the loading and delivery of biological proteins. J Biomedical Materials Res. 2013;101A(4):1103–12. DOI: 10.1002/jbm.a.34406
21. Casas-Luna M, Tan H, Tkachenko S, Salamon D, Montufar EB. Enhancement of mechanical properties of 3D-plotted tricalcium phosphate scaffolds by rapid sintering. Journal of the European Ceramic Society. 2019;39(14):4366–74. DOI: 10.1016/j.jeurceramsoc.2019.05.055
22. Li G, Chen K, Lei M, Wang T, Hu M, Li C. Construction of Fluoride-Rich Interphase for Sustained Magnesiophilic Site Release Toward High-Stability Chloride-Free Magnesium Metal Batteries. Advanced Energy Materials. 2024;14(38):2401507. DOI: 10.1002/aenm.202401507
23. Pal A, Oyane A, Nakamura M, Koga K, Nishida E, Miyaji H. Fluoride-Incorporated Apatite Coating on Collagen Sponge as a Carrier for Basic Fibroblast Growth Factor. IJMS. 2024;25(3):1495. DOI: 10.3390/ijms25031495
24. Borkowski L, Jojczuk M, Belcarz A, Pawlowska-Olszewska M, Kruk-Bachonko J, Radzki R, et al. Comparing the Healing Abilities of Fluorapatite and Hydroxyapatite Ceramics in Regenerating Bone Tissue: An In Vivo Study. Materials. 2023;16(17):5992. DOI: 10.3390/ma16175992
25. Agalakova NI, Gusev GP. Molecular Mechanisms of Cytotoxicity and Apoptosis Induced by Inorganic Fluoride. ISRN Cell Biology. 2012;2012:1–16. DOI: 10.5402/2012/403835
26. Wei Q, Deng H, Cui H, Fang J, Zuo Z, Deng J, et al. A mini review of fluoride-induced apoptotic pathways. Environ Sci Pollut Res. 2018;25(34):33926–35. DOI: 10.1007/s11356-018-3406-z
27. Wang Y, Xu J, Chen H, Shu Y, Peng W, Lai C, et al. Effects of prolonged fluoride exposure on innate immunity, intestinal mechanical, and immune barriers in mice. Research in Veterinary Science. 2023;164:105019. DOI: 10.1016/j.rvsc.2023.105019
28. Kannan S, Rebelo A, Ferreira JMF. Novel synthesis and structural characterization of fluorine and chlorine co-substituted hydroxyapatites. Journal of Inorganic Biochemistry. 2006;100(10):1692–7. DOI: 10.1016/j.jinorgbio.2006.06.005
29. Borkowski L, Przekora A, Belcarz A, Palka K, Jozefaciuk G, Lübek T, et al. Fluorapatite ceramics for bone tissue regeneration: Synthesis, characterization and assessment of biomedical potential. Materials Science and Engineering: C. 2020;116:111211. DOI: 10.1016/j.msec.2020.111211
30. Mansoorianfar M, Mansourianfar M, Fathi M, Bonakdar S, Ebrahimi M, Zahrani EM, et al. Surface modification of orthopedic implants by optimized fluorine-substituted hydroxyapatite coating: Enhancing corrosion behavior and cell function. Ceramics International. 2020;46(2):2139–46. DOI: 10.1016/j.ceramint.2019.09.197
31. Khan AS, Aamer S, Chaudhry AA, Wong FSL, Rehman IU. Synthesis and characterizations of a fluoride-releasing dental restorative material. Materials Science and Engineering: C. 2013;33(6):3458–64. DOI: 10.1016/j.msec.2013.04.029
32. Pajor K, Pajchel L, Kolmas J. Hydroxyapatite and Fluorapatite in Conservative Dentistry and Oral Implantology—A Review. Materials. 2019;12(17):2683. DOI: 10.3390/ma12172683
33. Xie C, Lu H, Li W, Chen F-M, Zhao Y-M. The use of calcium phosphate-based biomaterials in implant dentistry. J Mater Sci: Mater Med. 2012;23(3):853–62. DOI: 10.1007/s10856-011-4535-9

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34. Anita Lett J, Sundareswari M, Ravichandran K. Porous hydroxyapatite scaffolds for orthopedic and dental applications - the role of binders. Materials Today: Proceedings. 2016;3(6):1672–7. DOI: 10.1016/j.matpr.2016.04.058
35. Altaie A, Bubb N, Franklin P, German MJ, Marie A, Wood DJ. Development and characterisation of dental composites containing anisotropic fluorapatite bundles and rods. Dental Materials. 2020;36(8):1071–85. DOI: 10.1016/j.dental.2020.05.003
36. Biazar E, Jahandideh R, Majdi A. Synthesis of fluorapatite–hydroxyapatite nanoparticles and toxicity investigations. IJN. 2011;197. DOI: 10.2147/IJN.S15461
37. Al-Noaman A, Karpukhina N, Rawlinson SCF, Hill RG. Effect of FA on bioactivity of bioactive glass coating for titanium dental implant. Part I: Composite powder. Journal of Non-Crystalline Solids. 2013;364:92–8. DOI: 10.1016/j.jnoncrysol.2012.11.051
38. Hsu SM, Ren F, Batich C, Clark AE, Craciun V, Esquivel-Upshaw JF. Dissolution activation energy of a fluorapatite glass-ceramic veneer for dental applications. Materials Science and Engineering: C. 2020;111:110802. DOI: 10.1016/j.msec.2020.110802
39. Barandehfard F, Kianpour Rad M, Hosseinnia A, Khoshroo K, Tahriri M, Jazayeri HE, et al. The addition of synthesized hydroxyapatite and fluorapatite nanoparticles to a glass-ionomer cement for dental restoration and its effects on mechanical properties. Ceramics International. 2016;42(15):17866–75. DOI: 10.1016/j.ceramint.2016.08.122
40. Azami M, Jalilifiroozinezhad S, Mozafari M, Rabiee M. Synthesis and solubility of calcium fluoride/hydroxy-fluorapatite nanocrystals for dental applications. Ceramics International. 2011;37(6):2007–14. DOI: 10.1016/j.ceramint.2011.02.025
41. Anastasiou AD, Nerantzaki M, Gounari E, Duggal MS, Giannoudis PV, Jha A, et al. Antibacterial properties and regenerative potential of Sr2+ and Ce3+ doped fluorapatites; a potential solution for peri-implantitis. Sci Rep. 2019;9(1):14469. DOI: 10.1038/s41598-019-50916-4
42. Balhaddad AA, Kansara AA, Hidan D, Weir MD, Xu HHK, Melo MAS. Toward dental caries: Exploring nanoparticle-based platforms and calcium phosphate compounds for dental restorative materials. Bioactive Materials. 2019;4:43–55. DOI: 10.1016/j.bioactmat.2018.12.002
43. D. S, Dj. J, Danica M, G. T, B. A, Zvezdana K. A tissue-implant reaction associated with subcutan implantation of alpha-tricalcium phosphate, dental ceramic and hydroxyapatite bioceramics in rats. Acta vet (Beogr). 2008;58(4):381–93. DOI: 10.2298/AVB0804381S
44. Trinca RB, Vela BF, Dos Santos Vilela H, Braga RR. Ion release mechanisms in composites containing CaP particles and hydrophilic monomers. Dental Materials. 2024;40(7):1047–55. DOI: 10.1016/j.dental.2024.05.008
45. Kazuz A, Radovanović Ž, Veljović Dj, Kojić V, Miletić V, Petrović R, et al. α-Tricalcium phosphate/fluorapatite based composite cements: Synthesis, mechanical properties, and biocompatibility. Ceramics International. 2020;46(16):25149–54. DOI: 10.1016/j.ceramint.2020.06.301

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