SYNTHESIS AND CHARACTERISATIONS OF IRON-DOPED AKERMANITE CERAMIC BY SOL-GEL METHOD

Yanny Marliana Baba Ismail*, Nur Azika Diana Mat Yaki and Fitria Pebriani Naibaho

Biomaterials Niche Group, School of Materials and Mineral Resources Engineering, Engineering Campus, Universiti Sains Malaysia, 14300 Nibong Tebal, Penang, Malaysia.

*yannymarliana@usm.my

Abstract. Calcium silicate-based (CaSi) ceramics have been reported to be an alternative material to the well-known calcium phosphate (CaP) groups for bone repair treatment. Among the CaSi-based ceramics, akermanite (Akr: $Ca_2MgSi_2O_7$) is distinctive with its controlled biodegradation rate, mechanical properties and outstanding osteoconductivity, reportedly due to the release of Si, Ca, and Mg when in contact with the biological environment. To produce a series of iron-doped akermanite microsphere bioceramics as a potential material for bone applications. According to Goldschmidt's Rules of Substitution, the smaller trivalent ions of Fe^{3+} were hypothesised to substitute into the larger Mg^{2+} sites in the host structure of akermanite. Subsequently, $Ca_2Mg_{1-x}Fe_xSi_2O_7$ (with x= 0.6, 0.9, and 1.2 mol%) powders were synthesised by sol-gel route and then calcined at 1300°C. X-ray diffraction patterns showed akermanite phase did not change despite the Fe^{3+} substitution into the host structure, i.e., akermanite was detected as the primary phase with diopside and merwinite as the minor phases. Fourier transform infrared spectra also demonstrated that the silicate remained unchanged, which could be attributed to the structural stability with dopant concentration. The elemental analysis proved that Fe^{3+} has been successfully substituted into the host structure with varying trivalent ion concentrations. However, none of the compositions exhibited microsphere formation; they created agglomerated particles with irregular shapes. All the as-synthesised Fe-doped Akr powders were determined to be bioactive, as shown by the apatite formation when immersed in the simulated body fluid (SBF). This occurred as early as seven days with 0.9 mol% Fe^{3+} revealing needle-like apatite covering most of the surface of the akermanite.

Keywords: Akermanite, iron-doped akermanite, trivalent ion, sol-gel, bioactivity

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1. INTRODUCTION

Acquiring a novel biomaterial to treat large bone defects has become a real challenge to researchers focused on tissue engineering field. Amongst these new biomaterials, a large growing focus has recently been on bioceramics derived from calcium magnesium silicates (Ca-Mg-Si). Akermanite (Akr) is one of the melilite Ca-Mg-Si groups of sorosilicates with a chemical formula of $Ca_2MgSi_2O_7$. Reports have shown that it is a potential future bone material owing to its exceptional properties, which include good biodegradability and degradability rate, good bioactivity, and superior mechanical properties [1-2]. This akermanite ceramic has been frequently compared with calcium phosphates (CaP)-based materials such as hydroxyapatite and ®-tricalcium phosphate ceramics [3-4].

The bioactivity of akermanite investigated by soaking in simulated body fluid (SBF) for 10 days solution was determined by Wu et al. (2004), and they found a hydroxyapatite interface layer developed on the surface [5]. Alkaline ions (Ca^{2+}, Mg^{2+} and Si^{4+}) from akermanite dissolution were able to stimulate bone growth [6-7]. These ions enhance osteoblast proliferation and collagen production, thus promoting bone growth. Hence, with the exceptional characteristics shown by akermanite, it shows a significant promise as a bone substitute material, which may come in the form of dense ceramics, bone filler microspheres and 3D porous scaffolds and thus noteworthy for addressing extensive bone defects [8].

Recent studies suggest that the field is progressing towards doping these Ca-Mg silicates with various oxides containing metal ions such as Fe^{3+}, Cu^{2+}, Ba^{2+}, Co^{2+}, Sr^{2+}, etc. This modification aims to confer superior or novel properties to the materials. Iron (Fe^{3+}) is one of the metallic ions typically involved in many metabolic processes. It is naturally present in the human body, particularly in the bones (ranging from 0.0003 to 0.012 wt%) as well as in teeth (at 0.0055 wt%) [9]. Researchers have reported that the presence of Fe^{3+} improves mechanical properties (strength, toughness and hardness) as well as enhances bone repair and formation (osteogenesis) [10-11].

Akermanite ceramics can be synthesised via dry or wet chemical syntheses. Akermanite powders have been prepared and reported by techniques such as sol-gel, co-precipitation, solid-state reaction and combustion methods. Among these, sol-gel has been reported as one technique to produce microspheres of calcium silicate-based materials [12]. Sol-gel involves the transformation of sol to gel during the reactions of the chemical precursors, then being heat treated to produce the ceramic powders with the intended properties. The sol-gel method offers morphological control and high-purity powders, a simple and cheaper process as compared to the high-end flame spheroidisation and tube furnace methods, which are commonly used in the production of microsphere ceramics. However, strict parameter control is required in sol gel method, and these include suitable precursors (either salts or alkoxides), the pH of solution, maturation of the transparent gelling stage and drying temperature, as they determine the formation of the ceramic powders, particularly the shape and size of the particles [4].

Many attempts have been made to develop microspheres for bone-filling applications [12]. Microspheres offer several advantages with respect to 3D dense or porous scaffolds, and this includes the flexibility to fit in any defect site, better reactivity resulting from the larger surface area, and the possibility to be designed in hollow structures that would allow the encapsulation of other polymers or biological elements (e.g., protein, peptide, growth factors and genes) to improve cell adhesion and activities further. Various inorganic and organic materials, including glass ceramics, biopolymers, calcium carbonate ceramics and apatite

based bioceramics, have been investigated to produce microspheres with consistent shapes and sizes but it still remains a critical challenge faced by researchers [13-15].

Although considerable progress has been made in developing akermanite-based ceramics for bone repair and regeneration, however the physicochemical and *in vitro* bioactivity of these microsphere ceramics are scarcely reported. Therefore, the main aim of this study is to investigate the feasibility of the sol-gel method in producing microspheres of Fe-doped akermanite ceramics with varying Fe^{3+} concentrations (0.6, 0.9, and 1.2 mol%), which would then be investigated for their physicochemical properties and *in vitro* bioactivity. The microsphere ceramics were prepared using the sol-gel method, and subsequently, the powders obtained were calcined at 1300 °C for 3 hours in an air atmosphere.

2. MATERIALS AND METHODS

2.1 Preparation of Powders

The akermanite powder was initially prepared using a sol-gel wet chemical method synthesised at ambient temperature. Tetraethyl orthosilicate ($Si(C_2H_5O)_4$, TEOS), magnesium nitrate hexahydrate ($Mg(NO_3)_2.6H_2O$) and calcium nitrate tetrahydrate ($Ca(NO_3)_2.4H_2O$), were the sources for the Si^{4+}, Mg^{2+} and Ca^{2+} ions, respectively. Initially, TEOS was mixed in water and 2M nitric acid (HNO_3) with a mol ratio of TEOS:H_2O: HNO_3 = 1:8:0.16 and hydrolysed for 30 min under constant stirring. Then, the mixture was wadded with $Mg(NO_3)_2.6H_2O$ and $Ca(NO_3)_2.4H_2O$ with a mol ratio of TEOS: $Mg(NO_3)_2.6H_2O$: $Ca(NO_3)_2.4H_2O$ = 2:1:2. Subsequently the mixtures were mixed with a magnetic stirrer for 5 h at room temperature. Undoped akermanite (Akr) was used as the experimental control. Then different amounts of Fe^{3+} (0.6, 0.9, and 1.2 mol%) were introduced as dopants into the host structure to synthesise iron-doped akermanite powders (Fe-Akr). The dopant employed was Iron (III) oxide (Fe_2O_3). All chemicals utilised in this work were purchased from Sigma-Aldrich (United Kingdom). After the chemical reaction, the mixture was maintained at 60 °C for 24 hours and dried at 120 °C for 48 hours to obtain the dry gel. The dry gel was ground, sieved to 250 mesh and calcined at 1300 °C for 3 hours in an air atmosphere.

2.2 Characterization Techniques

X-ray diffraction (XRD, Bruker D8) was employed to analyse the crystallinity and phase analysis of the as-calcined Fe-Akr powders. The XRD patterns were recorded in a range of $2\theta = 20°$ to 60° with a step size of 0.02 using Cu Kα radiation (λ = 1.541 Å). The XRD patterns obtained were compared with the International Centre for Diffraction Data (ICDD) files. Further, the functional groups of as-calcined Fe-Akr powders were determined using the Fourier Transform Infrared (FTIR) spectroscopy, which employed a transmittance mode (T%) at wavelength intervals ranging from 400 to 4000 cm^{-1} four times. The ability for apatite-formation to indicate a good bioactivity of the material was conducted in accordance with the procedure described by Kokubo and Takadama (2006) in which akermanite samples were soaked in a newly prepared simulated body fluid (SBF) solution at pH 7.40, over a period of for 1, 3, and 7 days [16]. After each designated soaking period, the samples were carefully removed from the SBF, cleaned, and dried. The collected samples were then analysed by XRD for new apatite phase formation. The samples soaked in SBF were also subjected to microstructural imaging using the Field Emission Scanning Electron Microscope (FESEM;

Zeiss SupraTM Gemini 35 VP) along with an Energy Dispersive X-ray (EDAX) spectroscope that featured an AMETEK® microanalysis system.

3. RESULTS AND DISCUSSION

3.1 Physicochemical Analysis

Figure 1(a) depicts the resultant diffraction peaks of the pure Akr and Fe-Akr ceramics, which were synthesised by the sol-gel technique with varying concentrations of Fe^{3+}. It can be analysed that three main phases of CaSi were detected, i.e., akermanite, $Ca_2MgSi_2O_7$ (ICDD #96-900-6540) at $2\theta \approx 28.93°$ and 31.15°, diopside, $CaMgSi_2O_6$ (ICDD #96-900-4554) at $2\theta \approx 29.86°$ and merwinite, $Ca_3MgSi_2O_8$ (ICDD #96-900-0256) at $2\theta \approx 32.14°$, 32.62° and 33.46.

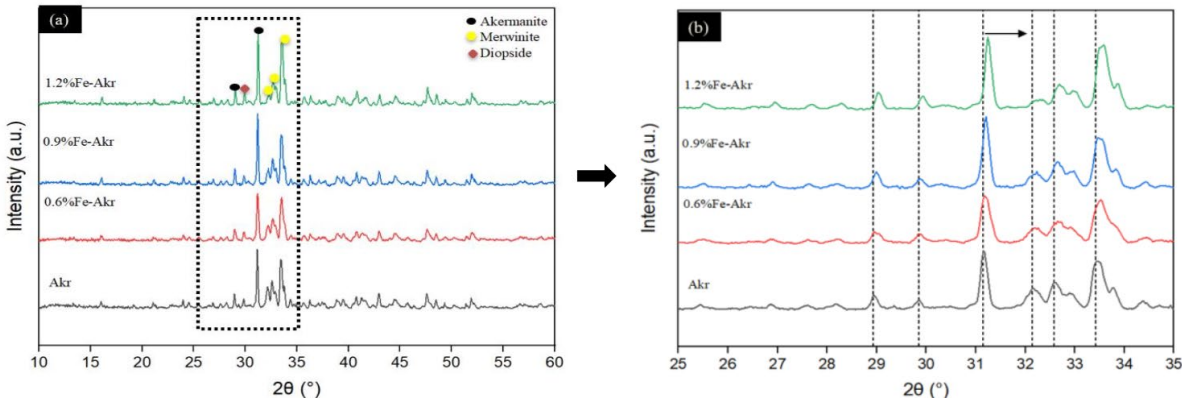

Figure 1: (a) XRD patterns of Akr and Fe-doped Akr ceramics, and (b) enlarged XRD patterns

The synthesised $Ca_2(Mg_{1-x}Fe_x)Si_2O_7$ ceramics showed a tetragonal crystal system with a space group of P-4 21m and Z= 2. It is well-documented that Akr ceramics produced at high temperatures typically exhibit sharp, well-defined peak patterns that suggest a regular and ordered arrangement of atoms in their crystal lattice. However, introducing dopants into the host structure might affect the crystallinity. The results of Fe-doped Akr showed that alterations in the crystallinity had occurred, in which the intensity of main peaks slightly decreased, indicating a reduction in crystallinity. The partially enlarged XRD patterns from $2\theta = 25°–35$, Figure 1(b), clearly depicted that the substitution of Fe^{3+} into akermanite had also shifted the diffraction peak towards the larger 2θ angles with increasing Fe^{3+} concentration. This shift is attributed to the contraction in both axes, where the larger Mg^{2+} (0.57 Å for four coordination numbers) sites were partially substituted with the smaller Fe^{3+} (0.49 Å for four coordination numbers) [17].

Figure 2 shows the functional groups of Akr and Fe-Akr series (different concentrations) analysed using transmittance mode FTIR. The transmittance spectra of the calcined samples confirmed the formation of akermanite structure. The akermanite was affirmed by the dual ν2 (O–Si–O) absorption bands at 637 and 688 cm^{-1}, the ν2 (Si–O) stretching modes at 846, 855 and 922 cm^{-1}, the symmetric stretching ν1 (Si–O–Si) band at 995 cm^{-1}, the Ca=O band at 591 cm^{-1} and the ν (O-Ca–O) bending modes at 404 cm^{-1} and the ν (O–Mg–O) bending modes at 495 and 515 cm^{-1}.

The substitution of Fe^{3+} into the akermanite host structure does not affect the functional groups. This is simply due to the small amounts of Fe^{3+} used. Therefore, the FTIR spectra of the Fe-doped Akr ceramics series remained similar to the controlled Akr samples.

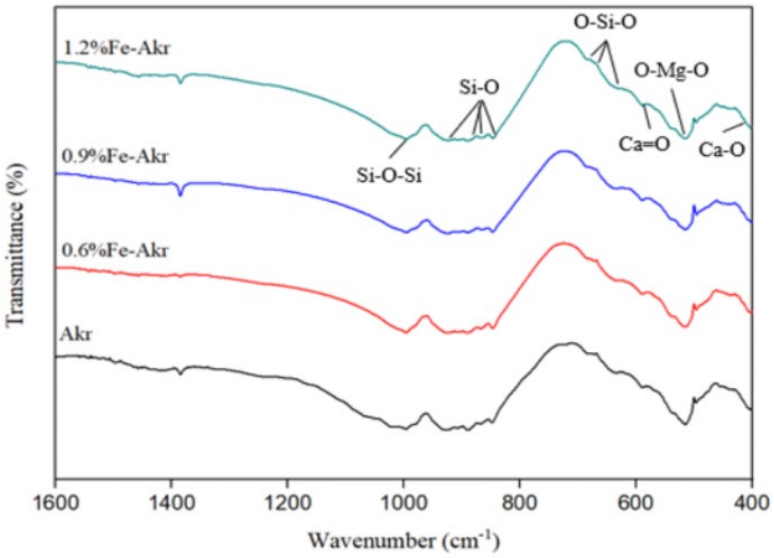

Figure 2: FTIR spectra of calcined Akr and Fe-doped Akr ceramics series at different concentrations produced at 1300 °C.

3.2 Morphological and Elemental Analyses

Figure 3 reveals that the investigated compositions were not able to produce the intended microsphere structure. Instead, the morphologies of the as-calcined Fe-doped Akermanite (Fe-doped Akr) exhibited agglomerated particles with irregular shapes. This phenomenon may be attributed to both rapid particle nucleation and growth, as well as inadequate dispersion of precursor materials during synthesis. The parameters and precursors utilised in this sol-gel method were probably not feasible to produce akermanite ceramics in the form of microspheres. Hence, further optimisation of the synthesis, including encapsulating the powders with biopolymer and using a stabilising agent, could help produce microsphere akermanite-based ceramics.

Energy dispersive X-ray analysis (EDX) was used to determine the element composition in the akermanite and Fe-doped akermanite ceramics produced. Despite the agglomerated state of powders obtained, the elemental analysis shown in Figure 3(a2) to (d2) confirmed the presence of Ca, Mg, Si, and O as the main constituents of akermanite ceramics and Fe as the minor element. This indicates that Fe^{3+} has been successfully substituted into the host structure, although XRD analyses showed no phase change.

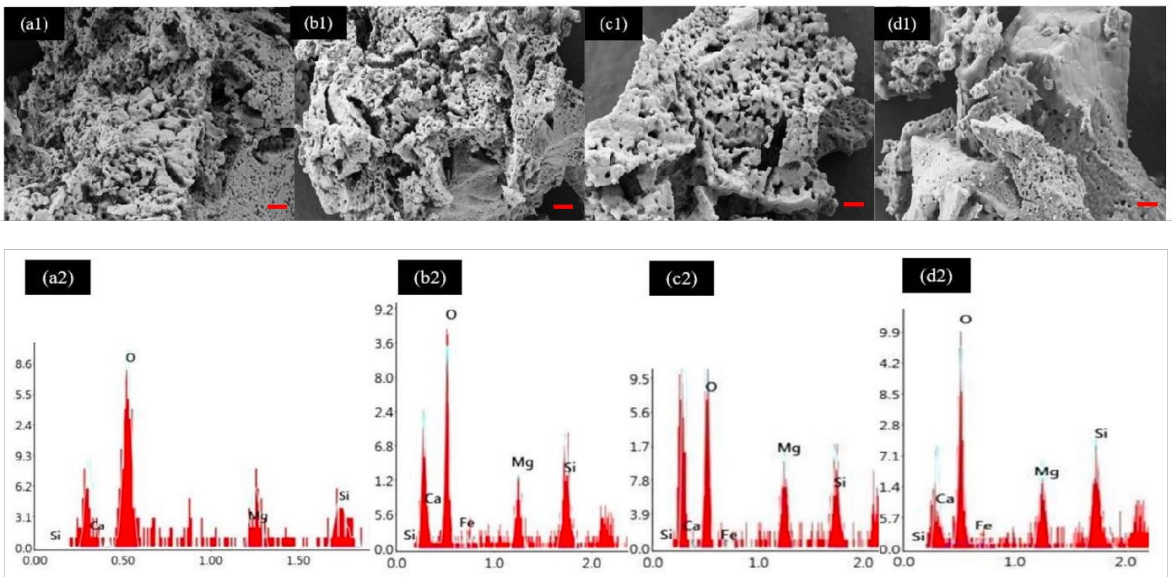

Figure 3: FESEM and EDX analyses (represented in at%) of Akr and Fe-doped AKr produced at a temperature of 1300 °C: (a1) – (a2) Akr, (b1) – (b2)0.6%Fe-Akr, (c1) – (c2)0.9%Fe-Akr, and (d1) – (d2)1.2%Fe-Akr (Magnification = 5000 X, scale bar = 2µm)

3.3 In vitro Bioactivity Test

This test often includes evaluating the ability of materials to induce mineralisation, which involves the deposition of CaP (also known as apatite layer) on the surface of samples. In the present work, the *in vitro* bioactivity test was conducted by incubating the as-calcined powders in simulated body fluid (SBF) for 7 days, followed by phase and morphological analyses using XRD and FESEM, respectively.

It is observed that the XRD peak intensities of Akr, 0.6%Fe-Akr, 0.9%Fe-Akr, and 1.2%Fe-Akr ceramics after immersion in SBF for 1 day had shown a reduction (Figure 4). This behaviour suggests the dissolution of akermanite ceramics during the early stage of immersion under hydrolysis. As the samples were immersed in SBF, the ions in the fluid (consisting of Ca^{2+}, Mg^{2+} and Si^{4+}) would interact with the surface of the akermanite-based samples. Over time, this interaction leads to the formation of apatite crystals on the akermanite surfaces. A substantial increase in apatite peak intensity continued, and other peaks (i.e., akermanite, diopside and merwinite) appeared at 28.96°, 29.38°, 31.18°, 32.53° and 33.43° after 7 days of immersion.

Newly grown apatite crystals formed on all akermanite substrates as early as 7 days of soaking (Figure 5). Interestingly, the morphologies of the apatite crystals formed are different. Akr demonstrated a platy-like crystal of apatite covering the surface. However, at 0.6%Fe-Akr and 0.9%Fe-Akr, the presence of iron ions started to influence the crystal structure and growth kinetics of the apatite, potentially changing from platy-like apatite to needle-shaped apatite crystals. At higher iron doping of 1.2%Fe-Akr, the morphology of the apatite layer exhibits more noticeable needle-shaped compared to 0.6%Fe-Akr and 0.9%Fe-Akr.

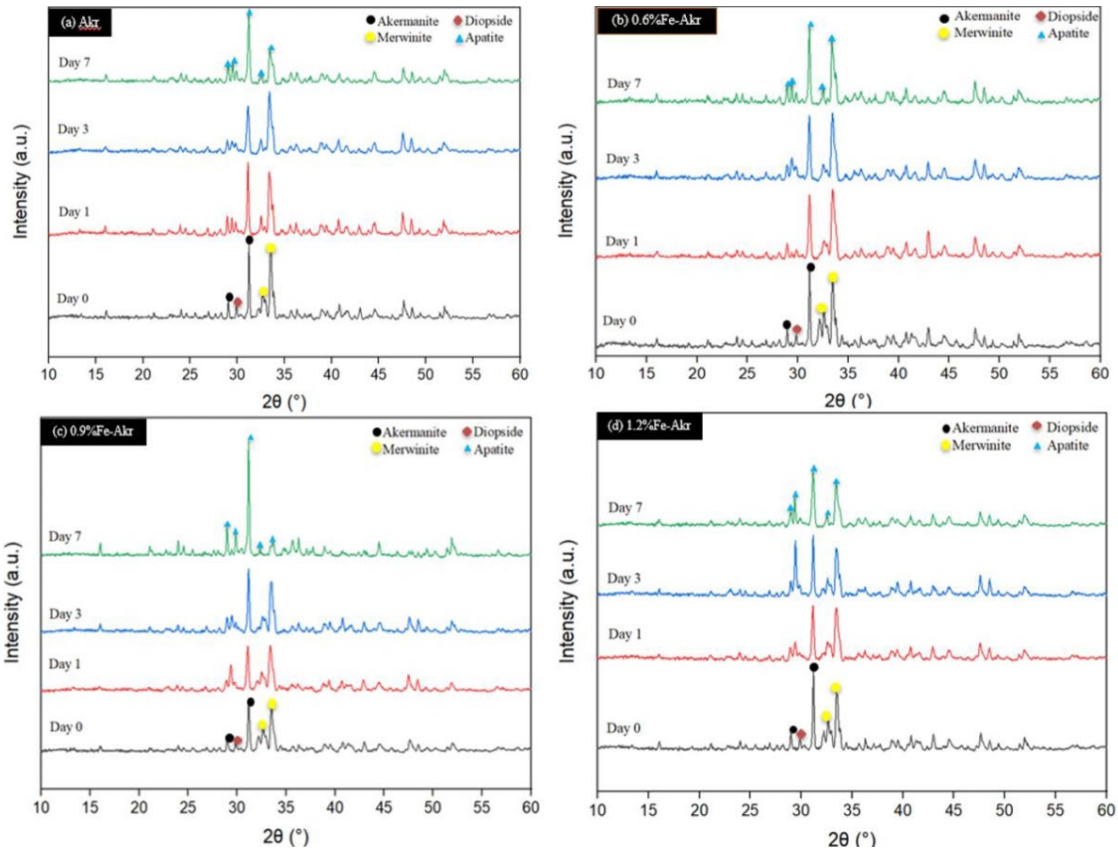

Figure 4: XRD spectra: (a) Akr, (b) 0.6%Fe-Akr, (c) 0.9%Fe-Akr, and (d) 1.2%Fe-Akr samples before and after soaking in SBF for 1, 3 and 7 days.

Besides, an increased tendency of the apatite nucleation was observed in the Fe-Akr samples relative to Akr alone. Herein, it is shown that Fe^{3+} substitution affects the *in vitro* bioactivity of akermanite, influencing its ability to induce apatite formation. This can be ascribed to the additional negative charges introduced by Fe^{3+} on the substrates, signifying that Fe^{3+} expedites the apatite accumulation process and augments crystallinity. Our earlier study documented a comparable observation, where Fe-doped Akr ceramics prepared by wet planetary ball milling showed better bioactivity than Akr ceramics; more area was covered by needle-like apatite [3].

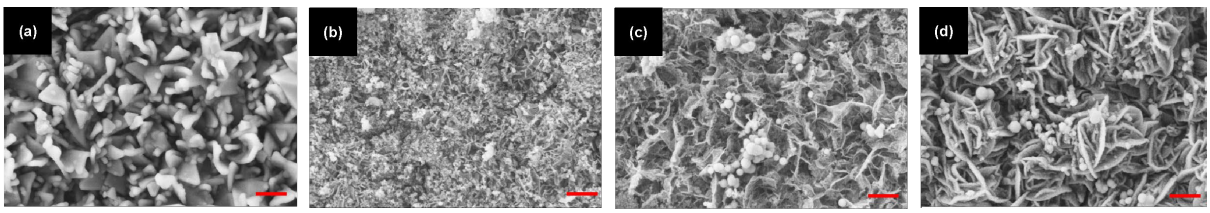

Figure 5: Morphological observation of (a) Akr, (b) 0.6%Fe-Akr, (c) 0.9%Fe-Akr, and (d) 1.2%Fe-Akr after 7 days soaking in SBF. (Magnification = 10,000X, scale bar = 3 μm)

4. CONCLUSIONS

Currently, parameters and precursors that are utilised in the sol-gel technique have led to the inadequate formation of Fe-doped akermanite microspheres. However, the method has proven effective in producing Fe-doped akermanite powders. Following consideration of both physicochemical and biological factors, a formulation of 0.9% Fe-Akr ceramic was determined to be the optimal choice, making it suitable for future bone material applications. Modifying the process to incorporate encapsulation of the powders with biopolymers and stabilising agents could facilitate the creation of Fe-doped akermanite microspheres.

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Author Contributions

All authors contributed toward data analysis, drafting, and critically revising the paper and agree to be accountable for all aspects of the work.

Disclosure of Conflict of Interest

The authors have no disclosures to declare.

Compliance with Ethical Standards

The work is compliant with ethical standards.

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