

Research Article

Preparation and characterization of ZnO modified solid state sintered 45S5 bioactive ceramics

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ABSTRACT

In this research, the traditional 45S5 bioactive glass powder was modified using ZnO (<20 μm) by powder metallurgy route. Five different bioactive ceramics compositions (45BC, 45BC₁, 45BC₃, 45BC₅ and 45BC₇) were formulated containing varied amounts of ZnO in the step of 1, 3, 5 and 7 wt % respectively. Each body was thoroughly mixed in a porcelain-lined ball mill to ensure proper homogenization followed by an addition of prepared 2 % PVA (Polyvinyl alcohol) and then again thoroughly mixed. The batch material was uniaxially pressed at 70 MPa using a cylindrical mould of 40 × 20 mm. A total of 20 samples from each body composition were produced and allowed to dry in an ambient temperature followed by sintering at 1000 °C for 2h at the rate of 5 °C/min. The samples were then allowed to anneal within the furnace to room temperature. Selected samples were later immersed inside simulated body fluid. Physical, mechanical, microstructure and phase evaluation were conducted to examine the developed bioactive ceramics. The results showed that the bulk density increased from 1.6 to 2.64 g/cm³ while porosity decrease from 95 % to 58 % across the series, with increasing ZnO addition. Sample 45BC₇ showed maximum hardness and compressive strength of 7.98 GPa and 83.54 MPa respectively. The carbonate-hydroxyapatite/hydroxyapatite (CHA/HA) deposits were found to also increased with ZnO addition showing good bioactivity, which affirms that the developed bioactive ceramics can bond well with living tissues, thus its suitability for bone regeneration.

1. Introduction

The two primary causes of injury and bone tissue damages in humans are aging and accidents. It has been discovered in recent times that with the rapid increase in the population of the elderly and the aged that the disturbance of motility in elderly and aged persons is also on the increase, thus giving rise to an increase in the number of aged people demanding failed tissue replacement [1,2]. The medical means of solving this problem has been by xenograft (bovine bone), allograft and autograft [3–5]. However, the major drawbacks identified with the application of xenograft are viral infections, increased immunogenicity and low osteogenicity while human allograft is associated with risk of infections and tumour cells transmission, delayed fusion time, immunological and blood group incompatibility and poor osteoinductive abilities among others [3–5]. One effective approach among other substitution methods or materials, which will result in a no immunological response, non-toxic and complete compatibility is autografting

[6].

However, a major setback associated with this approach is limited donor bone supply and the trauma involved during extraction of a donor tissue [3]. As a result of this, artificial bone tissues made of ceramic and metals have been developed to simplify the process of bone regeneration and healing.

With the rapid increase in population and as human life span continues to grow, the demand for biomaterials will continue to increase. This has however stimulated research into suitable artificial materials that could be used for bone regeneration and repair.

Presently, several artificial biomaterials ranging from calcium orthophosphate, bioactive glasses and glass-ceramics, human demineralized bone matrix, variety of polymers and composites, among others targeted at bone regeneration and repair have been developed [7,8]. Among these biomaterials, bioactive glasses and glass-ceramics are materials of choice given that they have been well investigated and their excellent biocompatibility and bone-bonding ability ascertained.

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Bioactive glasses are typically amorphous silicates-based materials that are biologically compatible, bond to bone and stimulate new bone growth whilst dissolving overtime. They possess the ability to restore a diseased or damaged bone to its original state and function (bone regeneration). Since its first discovery in late 1969 by Hench [9], several bioactive glasses have been developed among which is the 45S5 bioglass, which is very prominent given that it is the first to be developed with a composition of 45 wt%, SiO₂, 24.5 wt% Na₂O, 24.5 wt% CaO and 6 wt% P₂O₅ respectively. Despite their excellent bioactivity and biocompatibility, bioactive glasses are limited to very low load-bearing applications due to their poor mechanical properties resulting from their brittleness, and low fracture toughness [10,11]. Due to these drawbacks: high brittleness, poor mechanical strength and low fracture observed in bioactive glasses, bioactive glass-ceramics (BGCs) containing a precipitation of various crystalline phases was developed with a combination of improved mechanical strength and bioactivity [11].

Recently, in order to further improve the mechanical strength, bioactivity, biocompatibility and degradability (dissolution rate) of BGCs, research efforts are now channelled towards modifying their composition through the addition or doping with other oxides, which are hard and good bioactive agents. Previously, oxides such as ZrO₂, TiO₂, CoO, Ta₂O₅, SrO, CuO among others had been fully explored to modify traditional 45S5 bioactive glass base composition using melt-quenching approach with promising results observed in terms of improved mechanical properties, degradability and bioactivity [12–17] while scarce literature has been reported on the use of ZnO as a modifying agent in 45S5 bioglass composition using solid state sintering to obtain 45S5 bioceramics (45BCs). Zinc is an essential element in the human body, as well as a good antimicrobial agent. Therefore, the addition of ZnO to modify 45S5 composition in this work is deemed to be of great benefit in terms of improving both the mechanical and bioactivity properties of the bioactive ceramics.

In this regard, this work aims at the preparation of 45S5 bioactive ceramics (45BCs) by modifying traditional 45S5 composition with varying amounts of ZnO by solid-state sintering process. Detailed physical, mechanical, phase, microstructure and in vitro bioactivity properties shall be investigated to affirm the effects of ZnO and its variation on the developed modified 45BCs.

2. Materials and methods

2.1. Sample preparation

Traditional 45S5 bioglass with nominal composition of 45SiO₂ – 24.5Na₂O – 24.5CaO – 6P₂O₅ (wt. %) was used as the base composition in this work. Five different compositions of 45BCs comprising varying amount of ZnO in (45 – x) SiO₂ – 24.5Na₂O – 24.5CaO – 6P₂O₅ – xZnO (where x = 0, 1, 3, 5 and 7 wt % respectively) system were prepared as indicated in Table 1. High purity analytical grade materials such as fine-grained quartz, anhydrous sodium carbonate, calcium oxide and ammonium di-hydrogen orthophosphate were procured as the source of SiO₂, Na₂O, CaO and P₂O₅ respectively while ZnO was added to the batch for partial replacement of SiO₂. A total of 20 samples were prepared from each body composition listed in Table 1. Each batch material was accurately measured using digital weighing balance and poured into porcelain mortar and a pestle was thoroughly mixed for several minutes

to ensure homogeneity of the material. After mixing, it was poured into a porcelain lined laboratory jar mill to mix the materials properly with addition of prepared 2 % PVA solution and blended thoroughly to ensure a uniform batch. The batch material was poured into a cylindrical steel mould of 40 mm by 20 mm and uniaxially pressed at a pressure of 70 MPa using hydraulic powder pressing machine. The samples were then allowed to dry in an ambient temperature followed by sintering at 1000 °C for a holding period of 2 h at the rate of 5 °C/min. The samples were then allowed to cool within the furnace to room temperature.

2.2. Preparation of simulated body fluid (SBF)/in vitro bioactivity test

SBF solution was prepared by dissolving chemical-grade reagent in accordance to Kokubo and Takadama [18]. Each selected sample from the 45BCs series was then immersed in the SBF solution placed inside a plastic beaker. The plastic beaker was then placed inside the water bath whilst the temperature is maintained at 37 °C for varying soaking time of 4 and 7 h respectively. After each period, the respective sample was evacuated and dropped inside acetone for 5 s to stop the surface mineralization followed by drying in a desiccator. The samples were afterward analysed by scanning electron microscopy and X-ray diffraction to assess its bioactivity by assessment of carbonate-hydroxyapatite/hydroxyapatite (CHA/HA) phase deposited.

2.3. Characterization

The microstructure of the sintered base (unmodified) and modified samples were characterized using scanning electron microscope (JSM-6100 JEOL, Japan) while X-ray diffractometer (Rigaku miniflex 600, Japan) was used to investigate the crystalline phases after sintering and evolution of the hydroxyapatite layer respectively after in-vitro test. Other tests carried out include bulk density, porosity, micro-hardness and compressive strength respectively. Detailed information on how the samples were characterized was reported recently by the author [19, 20].

3. Results and discussion

3.1. Density and porosity

Fig. 1 shows the density and porosity of base and ZnO modified 45BCs respectively. It is observed that the density increases as the weight percent of the ZnO added increases, from 1.62 to 2.64 g/cm³ for

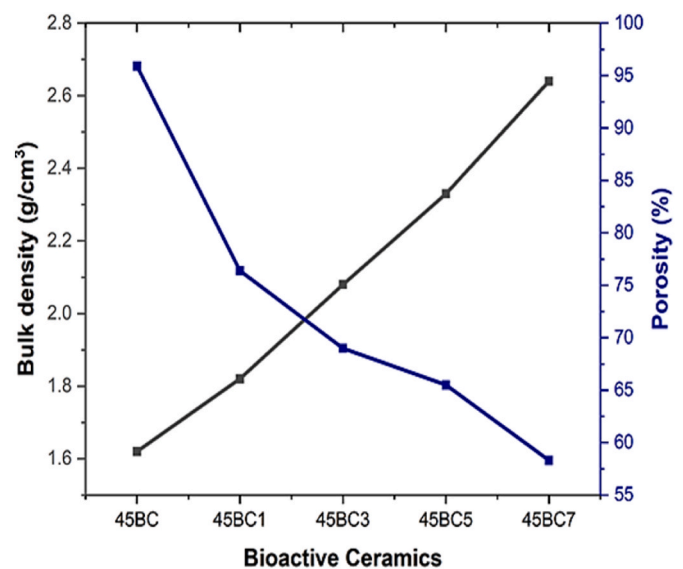


Fig. 1. Density and porosity.

Table 1

Batch formulation of the BCs in % weight.

Samples	SiO ₂	Na ₂ O	CaO	P ₂ O ₅	ZnO
45BC	45	24.5	24.5	6	–
45BC ₁	44	24.5	24.5	6	1
45BC ₃	42	24.5	24.5	6	3
45BC ₅	40	24.5	24.5	6	5
45BC ₇	38	24.5	24.5	6	7

samples 45BC to 45BC₇ while the highest density to 2.64 g/cm³ was observed for sample 45BC₇. The increase in density can be attributed to the replacement of a light element Si ($\rho = 2.33$ g/cm³) with heavier elements, Zn ($\rho = 7.14$ g/cm³). However, it can be observed in the context of this research that the addition of ZnO though heavier as replacement of SiO₂ did not increase the density of the ZnO modified 45S5 BCs substantially, which might be due to the intense emission process of the gas evolved by the decomposition of PVA at heating rate (5 °C/min) used. This intense emission of gas created several pores in the inner structure of the samples, thus lowering density and increased porosity. In terms of porosity, all the samples were all of appreciable high percentage porosity. However, the base (unmodified) bioceramic samples possess the highest porosity of approx. 96 % while the least porosity of approx. 58 % is observed for modified sample 45BC₇. However, porosity is of high relevance for any bioactive material to be considered for application as a biomedical implant. The percent porosity observed for all the samples are all within the range observed from previous studies [21,22].

3.2. Micro-hardness and compressive strength

Fig. 2 represents the micro-hardness and the compressive strength values obtained for both base and modified 45BCs. It is observed that both the microhardness and the compressive strength show a similar trend as their values increase as the percent weight of ZnO added increases. This result indicates the beneficial effect of ZnO added to the modified samples over the unmodified samples in terms of micro-hardness and compressive strength. Sample 45BC₇ possess the maximum micro-hardness and compressive strength of 7.98 GPa and 83.54 MPa, respectively. The improvement in hardness and compressive strength has been attributed to the fact that as the densification of the bioactive ceramic increases, the compactness of the glass structure also increases and consequently the better the microhardness and the compressive strength. Similar results have been obtained in previous literature where 45S5 bioglass-ceramics have been modified or doped with oxides such as CuO, CoO and SrO among others [14–16].

3.3. Microstructure evaluation (as-sintered BGCs samples)

Fig. 3(aandb) show the representative morphologies of the as-sintered 45BC, 45BC₅ and 45BC₇ samples containing 0, 5 and 7 wt % ZnO respectively. It can be observed that all the as-sintered 45BCs samples showed a somewhat dense microstructure with whitish and

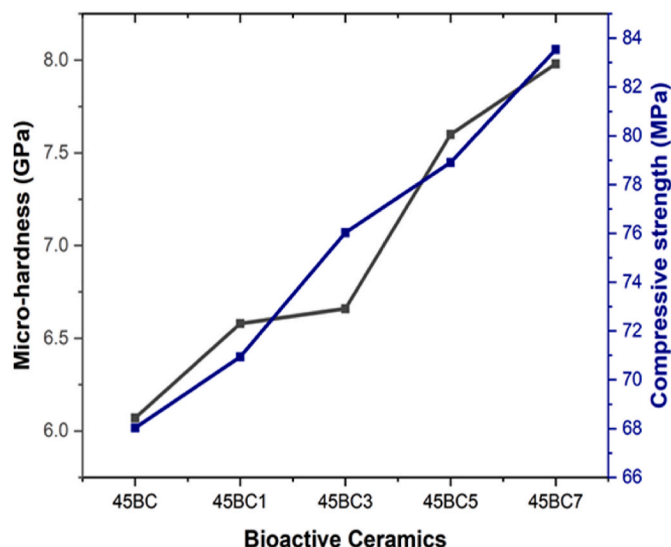
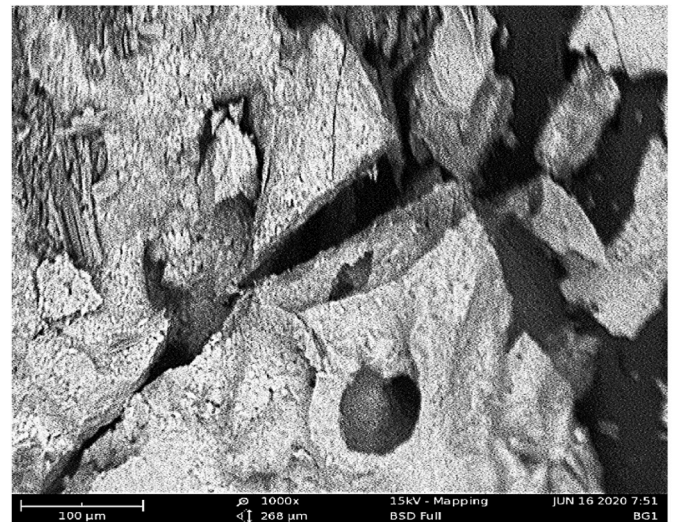
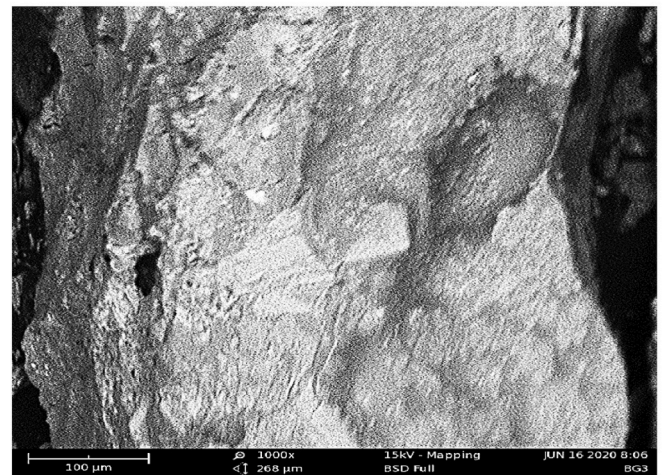


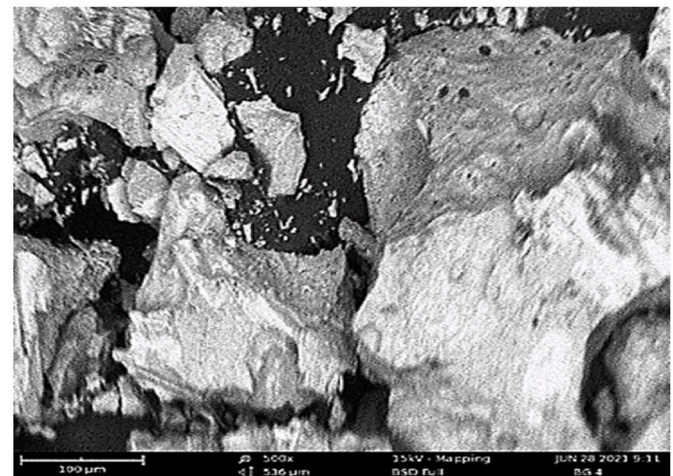
Fig. 2. Micro-hardness and compressive strength.



(a)



(b)



(c)

Fig. 3. Representative SEM image (a) 45BC (b) 45BC₅ (c) 45BC₇.

opaque-like bone structure containing varying macro and several micropores on the surface. The dark portions of the morphology indicate the 45BCs matrix as also reported by Aswad et al. [13]. The whitish and opaque-like colour is more pronounced in samples containing 5 and 7 wt % respectively as observed and this might be attributed to ZnO functioning as opacifier. This bone-like structure might suggest suitability for bone regeneration.

3.4. Phase evaluation (as-sintered BCs samples)

Fig. 4(a–c) show the representative phase evaluation carried out by X-ray diffraction analysis, while Table 2 indicates the quantitative phase analysis using the Rietveld refinement method with the software MAUD (Materials analysis using diffraction). It can be observed that the XRD spectra of all the bioactive ceramics indicate the presence of crystalline phases. These crystalline phases have been attributed to the presence of silicate and phosphate network in tandem to the possible phase separation of the two phases during sintering [23]. For all cases in both base 45BC and ZnO modified 45BCs, it is observed that the main and prevalent crystalline phase present is combeite (sodium-calcium-silicates, $\text{Na}_4\text{Ca}_3\text{Si}_6\text{O}_{16}$ and $\text{Na}_2\text{CaSi}_2\text{O}_6$) while other phases such as wollastonite, tri-calcium phosphate, and sodium phosphate were also observed. The presence of ZnO in form of changoite was also observed for 45BCs samples containing ZnO which indicates the reflection of ZnO added to those batches. These crystalline phases have been observed by previous studies [18,22,24–26] and have been affirmed to be the major determinant of any bioactive glass and glass-ceramic materials to be used as bioactive material either as dental or bone regeneration.

3.5. Microstructure evaluation (in-vitro)

Figs. 5–7 represent the morphologies of the as-sintered 45BC, 45BC₅ and 45BC₇ samples after immersion in SBF solution for a period of 4 and 7 h, respectively. It is observed clearly from the micrographs that the microstructure consists of different rod types and irregular grains in contrast with what was observed in the dense structured samples before

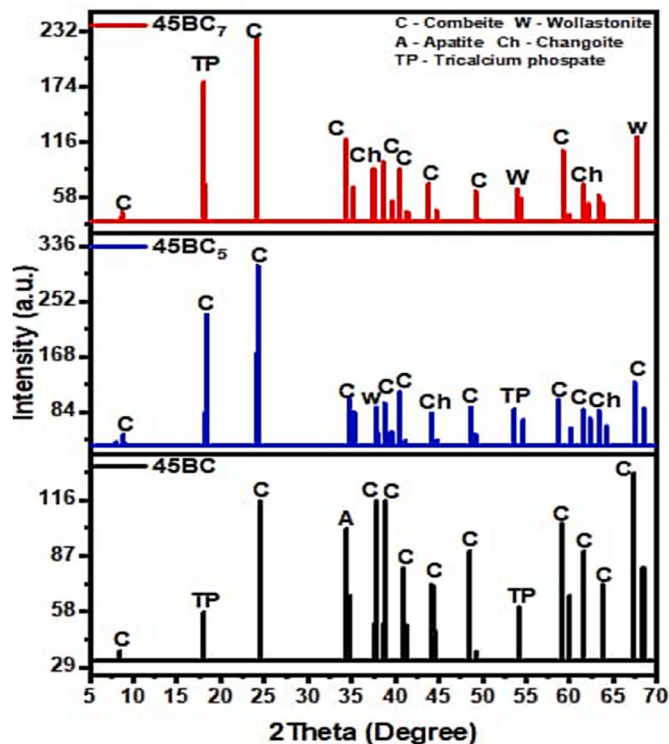
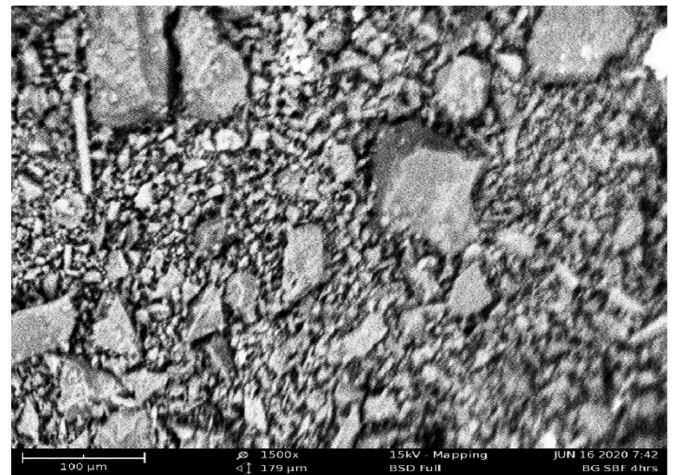


Fig. 4. Representative XRD spectra of (a) 45BC (b) 45BC₅ (c) 45BC₇.

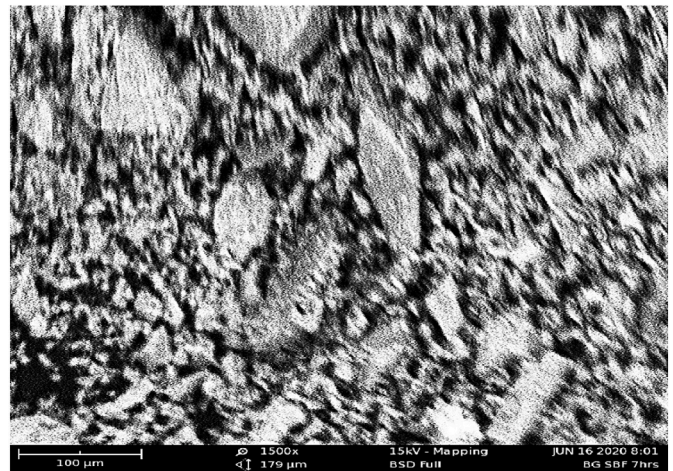
Table 2

Quantitative phase analysis by Rietveld method using MAUD Software.

Samples	Plane	Phase present	wt.%
45BC	001, 101, 002, 111, 200, 112, 121, 211, 113, 023, 311, 213, 114, 204, 100, 022, 302	Combeite	77.46
		Tricalcium phosphate	15.36
		Apatite	4.61
45BC ₅	110, 001, 100, 101, 110, 002, 111, 200, 112, 121, 211, 023, 104, 302, 204, 311, 002	Combeite	78.06
		Tricalcium phosphate	8.63
		Wollastonite	3.38
		Changoite	9.74
45BC ₇	213, 114, 113, 201, 001, 100, 110, 111, 200, 201, 112, 121, 204, 311, 302, 002, 100	Combeite	64.61
		Tricalcium phosphate	14.70
		Wollastonite	6.62
		Changoite	8.14



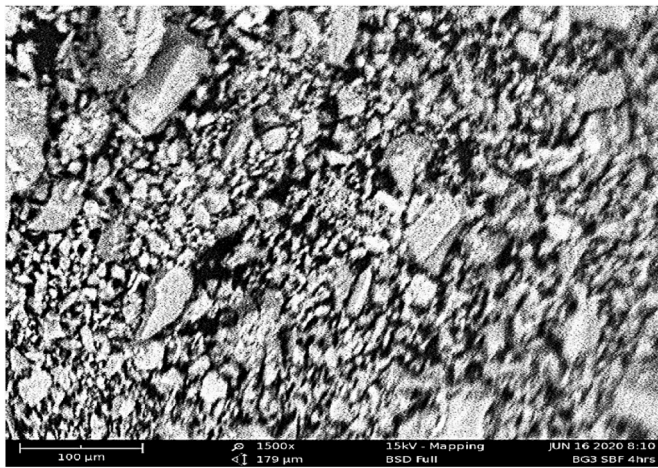
(a)



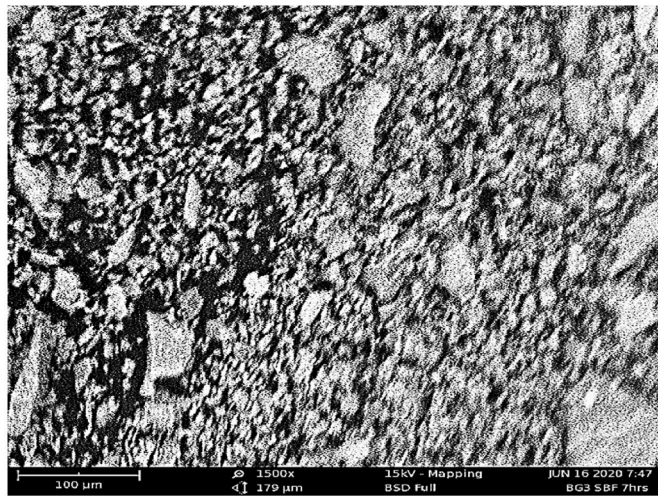
(b)

Fig. 5. SEM image of 45BC samples immersed in SBF for (a) 4 h (b) 7 h.

immersion in SBF, and this might be attributed to better reaction with the SBF solution in vitro suggesting good bonding ability if use in contact with living tissue in vivo. It is also clearly seen that the morphology of precipitation is quite somewhat similar among the 45BCs during the in



(a)



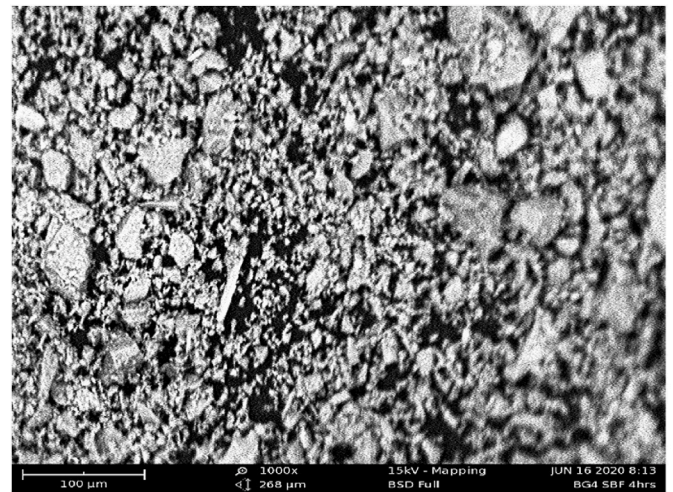
(b)

Fig. 6. SEM image of 45BC₅ samples immersed in SBF for (a) 4 h (b) 7 h.

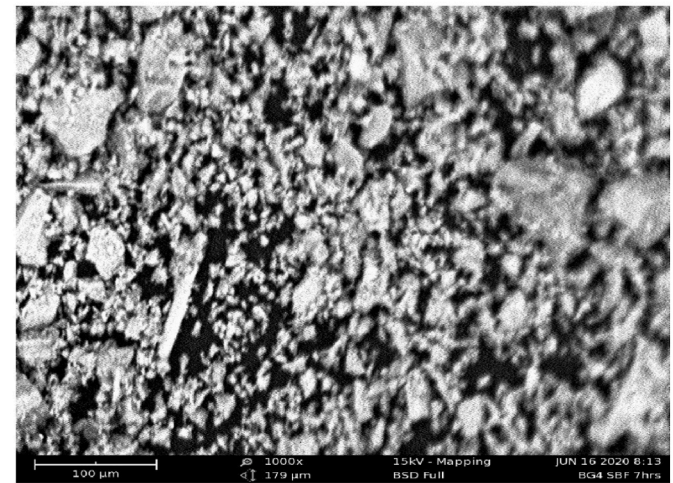
vitro assay. All the 45BCs surfaces were covered with somewhat irregular shapes and grounded whitish particles, which are finely dispersed on their entire surface within the 45BCs matrix. These finely dispersed whitish particles on the BCs surface is attributed to CHA/HA layers deposited due to good bioactivity reaction after immersion in SBF solution [17,27]. It is also observed that the CHA/HA layer became more compact and higher with an increase in immersion period while 45BCs containing ZnO showed more CHA/HA on their surfaces justifying ZnO as a good agent in enhancing bioactivity of bioactive glass-ceramics. This results also indicate that the developed 45BCs will be well bonded with living tissue when used in vivo.

3.6. Phase evaluation (in-vitro)

Fig. 8 shows the representative XRD pattern for the 45BCs samples while Table 3 indicates the phase data obtained. The representative phase diagram indicates the CHA/HA forming ability on both the base and modified 45BCs samples analysed using X-ray diffraction analysis after immersion in SBF solution for 4 and 7 h respectively. It can be observed that all the BCs samples showed similar phase evolution in SBF solution. However, in contrast to the phases observed before immersion in SBF solution, there is formation of two major apatite compounds in form of hydroxyapatite (HA) and carbonate-hydroxyapatite (CHA). It is



(a)



(b)

Fig. 7. SEM image of 45BC₇ samples immersed in SBF for (a) 4 h (b) 7 h.

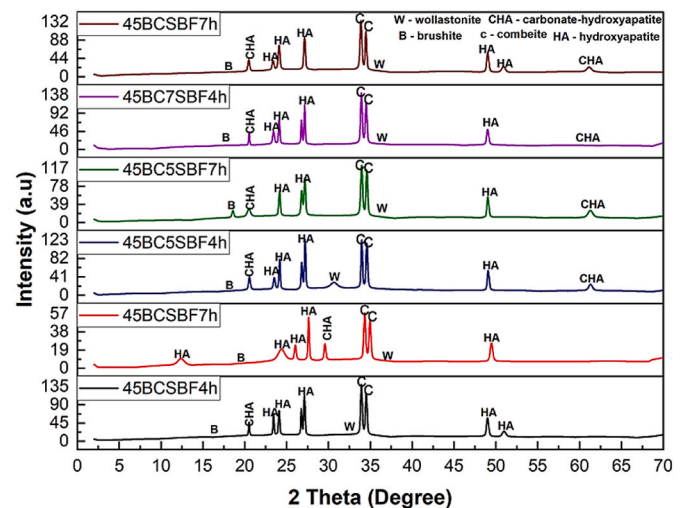


Fig. 8. Representative XRD pattern (in vitro) for the BCs samples.

Table 3

Phase data obtained by Rietveld method using MAUD Software.

Phase (%)→	Combeite	Hydroxyapatite	Wollastonite	Brushite	Carbonate-hydroxyapatite
45BCSBF (4 h)	49.90	35.57	2.90	0.50	11.1
45BCSBF (7 h)	31.0	47.0	2.0	0.90	18.7
45BC ₅ SBF (4 h)	36.60	47.50	6.40	–	9.46
45BC ₅ SBF (7 h)	33.0	47.20	2.18	8.0	8.75
45BC ₇ SBF (4 h)	46.0	40.80	3.70	3.75	5.60
45BC ₇ SBF (7 h)	45.0	41.30	1.70	0.50	11.20

also observed that the formation of HA gets stronger with immersion time in SBF solution. Hence, the XRD result has demonstrated that the BCs samples showed good bioactivity in-vitro and their mineralization product was CHA and HA. However, for the ZnO modified BCs samples, the addition of ZnO has been justified by higher formation of CHA and HA respectively while sample 45BC₅ displayed greater HA forming ability considering their higher percentage obtained in 45BC₅ samples. Similar results have been reported by previous studies [22].

4. Conclusions

This work successfully dealt with the development and characterization of ZnO modified 45S5 bioactive ceramics by solid state sintering for intended application as biomedical material either for dental or bone regeneration. This study has demonstrated the possibility of developing 45S5 bioceramics without melt-quenching, which reduced cost of energy required and time. The following conclusions can be drawn within the limit of this work:

- The developed 45BCs possessed considerable density, which increases as the % of ZnO added to the respective batch increases while they also possessed high porosity values to be recommended for use as scaffolds.
- The addition of ZnO to the modified 45BCs samples increases both the micro-hardness and compressive strength as compared with the base 45BCs; their micro-hardness and compressive strength increase with increase in ZnO addition.
- The results of the phase evolution showed combeite as the major and prevalent phase while other phases such as tri-calcium phosphate, wollastonite, sodium phosphate, and brushite were also present. These phases have been reported to be the main determinant for any material to be classified as bioactive material.
- The addition of ZnO really enhanced the bioactivity of the modified 45BCs samples in SBF solution as the formation of carbonate-hydroxyapatite (CHA) and hydroxyapatite (HA) are more and get stronger within the immersion period as indicated by the XRD analysis.
- The morphology also showed distinct differences before and after immersion in SBF as the immersed samples showed the presence of well-dispersed CHA/HAP but somewhat agglomerated on their surfaces.

CRedit authorship contribution statement

Seun S. Owoeye: Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Segun M. Abegunde:** Resources, Investigation. **Bolaji F. Oyeyemi:** Supervision, Resources. **Esther O. Isinkaye:** Validation, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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