Evaluation of the Dynamic Behavior, Elastic Properties, and in Vitro Bioactivity of Some Borophosphosilicate Glasses for Orthopedic Applications

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Abstract

The present work employed the finite element model (FEM) to predict the influence of successive increases in borate (B_2O_3) contents, from 0 to 25 mol%, on both the mechanical properties and dynamic behavior. By feeding the isotropic elasticity characteristics of the phosphosilicate glass to the model, such as Young's modulus, density, and maximum compressive stress of the produced glass samples to fit the aim of their clinical use. The effect of successive addition of B_2O_3 on the in vitro bioactivity of the examined glasses in addition to examined after being dipped in simulated body fluid (SBF) at different times. Moreover, tracking the formation of hydroxyapatite (HA)-like layers on their surfaces using X-ray diffraction technique (XRD) technique and scanning electron microscopy (SEM). The results obtained indicated that increasing B_2O_3 content to 25% was responsible for improving the deflect resistance by 39%. On the other hand, neither shear stress nor principles stress was affected by this increase in B_2O_3 content. Moreover, the gradual increases in B_2O_3 contents were very helpful in improving the bioactivity of the samples. From these promising results, the prepared glasses can be successfully used in bone replacement applications.

1. Introduction

It is well-known that bone tissue can repair itself when damaged. Unfortunately, if this damage is significant, the bone tissue will not be able to heal itself without outside medical help [1]. Based on this fact, various biomaterials have been developed in the last fifty years, thanks to the extensive efforts of scientists to help bone repair and bone regeneration [2].

In tight correlation with medical needs, bioactive materials have received great attention for use in different biomedical applications due to their promising characteristics. Accordingly, it can be considered that bioceramics and their composites are favorable for these applications [3, 4]. In this context, bioactive glass (BG) is one of the most promising candidates for use as a bone replacement material due to its great ability to form a hydroxyapatite (HA) layer when infused into the human body, along with its excellent biocompatibility [5–7]. It is worth noting that these amazing biomaterials were discovered due to the tireless efforts of Professor L.L. Hench at the University of Florida in 1969 [8]. In addition, during the formation of the HA layer, the ions released from BG are very beneficial for inducing the proliferation and differentiation of osteoblasts [9]. Knowing that the properties of the prepared BGs are strongly related to their chemical composition, one can expect that researchers are still motivated to continue searching for glass compositions that have many unique and attractive properties for use in bone substitute applications [3, 10, 11].

Phosphate-based glasses (PBGs) have many attractive characteristics such as high solubility rate, good bioactivity, and excellent biocompatibility due to their similarity to the human bones [12]. Unfortunately, their poor chemical durability coupled with low mechanical properties are the most constraints to their use in biomedical applications [13]. Therefore, there is an urgent need to improve their properties above. To counteract these limitations, the addition of silicon dioxide (SiO_2) as a glass former is beneficial

because it has suitable mechanical properties and good biocompatibility and biological significance in bone formation and calcification [11, 14–16].

Boron is a natural element found in several organs within the human body, such as bone, hair, and nails, besides its important role in stimulating some essential metabolic enzymes [17, 18]. Boron also enhances RNA synthesis in fibroblast cells and stimulates bone formation. It is considered an effective agent for bone tissue engineering applications [19, 20]. Moreover, boron can be added to bioactive silicate glasses to enhance bioactivity [21–23]. In addition, boron-containing glasses are characterized by low chemical stability, and therefore, they can be converted to HA faster and more completely when dipped in simulated body fluid (SBF) [24–26].

Over the past few decades, many articles have studied the bioactivity of borophosphate [27–29], borosilicate [30–32], and phosphosilicate glasses and glass-ceramics [33–35]. However, the bioactivity of borophosphosilicate glasses with a detailed prediction of the behavior of these glasses when implanted in the human body under body weight, investigate and explore the effect of increased loads and their relationship to the deflection that occurs in the structure of the samples and whether the bioactive glass samples will undergo yield or fracture has not been previously studied.

2. Methodology

2.1. Glass preparation

Melt quenched $25\text{Na}_2\text{O}-20\text{CaO}-10\text{SiO}_2-(45-x)\text{P}_2\text{O}_5-x\text{B}_2\text{O}_3$ glasses with $x=0, 10, 20$, and 25 mol% have been prepared from starting materials of analytical reagent grade. Silicon oxide (SiO_2), sodium carbonate (Na_2CO_3), calcium carbonate (CaCO_3), orthoboric acid (H_3BO_3), and ammonium dihydrogen phosphate ($\text{NH}_4\text{H}_2\text{PO}_4$) powders were thoroughly mixed in the appropriate quantities and then ground in an agate mortar. The weighed well-mixed batches were melted in a porcelain crucible in an electric furnace at 1100°C for 3 h. The molten liquid was occasionally stirred to ensure homogeneous mixing of all constituents and to obtain bubble-free samples. The glass, formed by quenching the melt on a stainless-steel mold, was immediately transferred to another muffle furnace for annealing at about 350°C for 1 h. Then, the muffle was switched off, and the temperature decreased to room temperature with a rate of 20°C/h . The nominal compositions of the prepared glasses, together with their abbreviations, are given in Table 1.

2.1. Structural characterization of glasses

In this study, Fourier transform infrared (FTIR; Vertex 80, Bruker, Germany) spectroscopy was carried out to examine the molecular structure of as-prepared glasses. The FTIR absorption spectra of the tested samples were immediately collected by an attenuated total reflection (ATR) unit, at room temperature, in the wavenumber range $4000-400\text{ cm}^{-1}$, 60 scans with a 4 cm^{-1} . Moreover, X-ray diffraction technique (XRD; Philips PW 1373; X-ray powder diffractometer with CuK-Ni filtered radiation) was employed in this work to ensure the amorphous structure of the glass samples and follow up the formation of HA-like layer

on their surfaces after their soaking in simulated body fluid (SBF) solution for different time periods; namely 3, 7 and 10 days.

2.2. In vitro bioactivity (bone-bonding) assessment of glass samples

In vitro bioactivity was assessed by soaking the glass samples in simulated body fluid (SBF) prepared according to the recipe described by Kokubo *et al.* [36,37]. The glasses were ground to grains and sieved, keeping the ratio of specimen mass to the volume of SBF solution= 0.01 g/mL to achieve an excess SBF volume surrounding the samples [38]. Then, they were subjected to XRD technique to follow the formation of the HA layer. Moreover, cubic slabs of glass samples with dimensions of 5×5×5 mm³ were prepared for examination by scanning electron microscopy (SEM; Quanta FEG250; with an accelerating voltage of 30 kV and magnification of × 10 up to × 300,000) after soaking in SBF solution for 3, 7 and 10 days.

2.3. Density measurement

The density (ρ) of each glass sample was measured at room temperature using the Archimedes method with water as the immersion liquid.

2.4. Mechanical properties

As mentioned before in our recent articles [39,40], all glass samples' microhardness and compressive strength were measured according to ASTM: B933-09 and ASTM E9, respectively. On the other hand, the ultrasonic wave velocities (longitudinal and shear) propagated in the samples were obtained at room temperature, using pulse-echo technique MATEC Model MBS8000 DSP (ultrasonic digital signal processing) system with 5 MHz resonating as described in Refs. [41-43].

Longitudinal (V_L^2) and shear (V_S^2) ultrasonic velocities can be used to determine the values of Lamé's constants, i.e., λ and μ as the followings:

$$\begin{aligned}\lambda &= \rho(V_L^2 - 2V_S^2) & \dots\dots\dots (1) \\ \mu &= \rho V_S^2 & \dots\dots\dots (2) \\ L &= \lambda + 2\mu & \dots\dots\dots (3) \\ G &= \mu & \dots\dots\dots (4) \\ E &= \mu \frac{3\lambda + 2\mu}{\lambda + \mu} & \dots\dots\dots (5) \\ B &= \lambda + \frac{2}{3}\mu & \dots\dots\dots (6) \\ v &= \frac{\lambda}{2(\lambda + \mu)} & \dots\dots\dots (7)\end{aligned}$$

3. Results And Discussion

3.1 Structural characterization of glasses using FTIR spectroscopy

In contrast to the XRD technique, FTIR spectroscopy is able to record the functional groups of glasses in the mid-IR region in a precise manner [44]. Based on this concept, FTIR spectroscopy was carried out to examine the molecular structure of the prepared glasses, as shown in Fig. 1. Before assigning the spectra obtained from the glass samples, it is preferable to briefly mention some facts about the chemistry of phosphate bioactive glass (PBG) as follows:

As discussed in Refs. [29,45], in the absence of modifier oxides, PBG is mainly composed of PO_4^{3-} tetrahedral units in chain/ring structures, having much non-bridging oxygen (NBO) atoms. Therefore, these glasses are characterized by low chemical durability along with low melting temperatures. However, in the presence of modifier oxides (MO), the phosphate network is depolymerized as a result of the replacement of some of the P–O–P links with –P–O–M– ones leading to a considerable change in the glass structure from Q^3 units to tetrahedral chains in the metaphosphate (Q^2 units), pyrophosphate (Q^1 units) and orthophosphate (Q^0 anions) bearing in mind that this conversion depends on the type and contents of modifying oxides. On the other hand, borate consists of three boron-oxygen triangles forming boroxol rings/groups (B_3O_6). However, this coordination is changed from triangular to tetrahedral after adding alkali oxide (CaO) or alkaline earth oxide (Na_2O). The FTIR absorption bands of phosphate groups can be classified into three fundamental regions; namely region of $1400\text{--}1150\text{ cm}^{-1}$ that represents the vibrations of non-bridging PO_2 groups, region of $1150\text{--}900\text{ cm}^{-1}$ that symbolizes the vibrations of P–O and PO_3 groups and region of $900\text{--}700\text{ cm}^{-1}$ that expresses the vibrations of bridging P–O–P groups. However, borate groups exhibit three spectral regions at $800\text{--}600$, $1500\text{--}1200$, and $1200\text{--}850\text{ cm}^{-1}$, which emerge from the B–O stretching mode of the borate part, B–O stretching mode of BO_3 and BO_4 units, respectively [23]. Importantly, the most characteristic region for bioactive silicate glasses falls in the spectral region $1050\text{--}850\text{ cm}^{-1}$. Based upon the abovementioned regions, the present spectra can be assigned according to the literature [21,23,46–49] as follows:

- B–O stretching vibrations of the triangular (BO_3 , BO_2O^-) units can be confirmed by the weak band located at 1250 cm^{-1} , considering that the increase in B_2O_3 contents leads to a considerable increase in its intensity until it reaches medium one.
- A single sharp, strong band can indicate the symmetric stretching mode of the P=O bond at 1200 cm^{-1} . As expected, an increase in B_2O_3 contents causes its intensity to decrease until it reaches a medium intensity.
- Intense broadband located near 1045 cm^{-1} can be attributed to the superposition of symmetric stretching mode of Q^2 units, symmetric stretching mode of O–P–O bonds, asymmetric stretching mode of Si–O–Si vibrations, and asymmetric stretching vibration of tetrahedral borate units.
- A weak band at 970 cm^{-1} can be ascribed to symmetric stretching vibrations of Si–O–Si and B–O bond of tetrahedral BO_4 groups. Of note, by increasing B_2O_3 content in the glass composition, the

intensity of this band increases.

- The asymmetric stretching mode of the P–O–P bonds accompanying the formation of Q² chains can be represented by having two shoulders at 925 and 820 cm⁻¹. On the other hand, a medium band at 765 cm⁻¹ can be assigned to the symmetric stretching vibration of P–O–P and the bending/deformation modes of different borate units. Moreover, the shoulder at 925 cm⁻¹ represents an asymmetric stretching mode of the Si–O bond.
- Broadband at 470 cm⁻¹ can be ascribed to the overlapping of bending vibrations of the B–O–B bonds, Q¹ units of phosphate groups, and Si–O bonds. It is reasonable to expect that the intensity of this band considerably increases due to the increased contents of B₂O₃, which also results in the conversion of some Q² phosphate units to Q¹ ones.
- Bending vibrations of P–O–P and Si–O bonds can be indicated by the presence of a medium band found at 465 cm⁻¹.

3.2 Evaluation of bioactivity behavior (bone-bonding) of prepared glass samples

3.2.1 XRD analysis

In this work, glass samples were subjected to XRD technique before and after dipping in SBF solution for different time periods, i.e., 3, 7, and 10 days to ensure their amorphous structure as well as the formation of an apatite-like layer on their surfaces as shown in Fig. 2 (a-d). It is suggested from Fig. 2a that all samples have an amorphous structure as indicated by the presence of broadband at $2\theta=20\text{--}30^\circ$. This observation is extremely important as it refers to the correct preparation procedures for glass samples [50]. On the other hand, the soaked samples in SBF solution exhibit crystalline HA layer, which is easily identified according to (JCPDS No. 19-0272), bearing in mind that the bioactivity of samples are positively affected by increasing soaking time as well as B₂O₃ contents where the best bioactivity is observed for S4 sample after its soaking in SBF solution for 10 days. The most likely explanation for the enhancement of the bioactivity of the examined samples with increasing incubation time is that increasing the soaking time leads to an increase of Ca²⁺ and PO₄³⁻ ions on their surfaces [46]. It is generally considered that the existence of Na⁺ and Ca²⁺ in the prepared glasses act as modifiers for the network where they trigger the formation of non-bridging oxygen (NBO) atoms which in turn increase the degradation of glasses. In this regard, it is very meaningful to discuss the famous mechanism proposed by Hench *et al.* [8], which described the formation of an HA-layer on silicate-based glass surfaces, which usually occurs through specific steps. These steps begin by exchanging Na⁺ ions, from the soaked glass sample, with H⁺ ones, from SBF solution, causing breakage in the glass network and forming Si–OH groups at the glass/SBF interface. Then, these groups are polycondensed, leading to the formation of a silica gel layer on the glass sample surface. On the opposite side, OH⁻ groups work as effective nucleation sites for the precipitation as well as crystallization of HA layer. These stages are finalized by the formation of sufficient HA nuclei and immigration of Ca²⁺ and PO₄³⁻ groups from SBF solution and glass matrix producing amorphous calcium phosphate (Ca–P) film. Consequently, significant growth for

HA layer is achieved. Since the current glass system has a low SiO₂ content while being rich in P₂O₅ and B₂O₃, we should expect other mechanisms for the bioactivity of the prepared glass samples.

As discussed in Ref. [51], the affinity of Na⁺ and Ca²⁺ ions to the phosphate network is much higher than the silicate network. Therefore, the latter network suffers from polymerization, causing the formation of Si-O-Si and Si-O-P linkages. The latter linkages are responsible for reducing the bioactivity of glass. Fortunately, the present glass system possesses a lower contribution of SiO₂ than that of P₂O₅; the bioactivity of the examined S1 sample is not greatly affected by Si-O-P groups. Increasing the content of B₂O₃ contributes to the improvement of bioactivity considerably. One possible reason for this positive result is that when B₂O₃ increases, at the expense of P₂O₅, it helps to reach a non-stoichiometric ratio of Ca:P. Another reason is the high solubility of B₂O₃, which contributes to breaking the glass network and the formation of B-OH bonds that act as a catalyst for bioactivity [52]. Noteworthy, the aforementioned stages greatly contribute to precipitation of calcium phosphate (Ca-P) layer on the glasses surfaces and subsequently turn into a crystalline layer, i.e., HA. Importantly, the formation of HA layer can be clearly understood with the help of the following Eqn. [47,48]:

It cannot be denied that HA nuclei's heterogeneous nucleation can be achieved by the super-saturation limit elevation above the critical level. Notably, the increase of released Na⁺ ions is responsible for such an increase in the super-saturation level of the soaking solution in connection to HA. Then, enlargement of HA nuclei occurs due to the consumption of Ca²⁺, PO₄³⁻ and OH⁻ ions from the SBF [53].

3.2.2. SEM analysis

In order to follow the formation of HA layer on the surface of S4 sample after soaking in SBF solution for 3, 7, and 10 days, SEM was used in this work, as shown in Fig. 3 (a-c), respectively. It should be noted that the selection of this sample for SEM examination is based on the XRD results obtained, which show that the best bioactivity characterized S4 sample among all tested samples as a result of containing the highest percentage of B₂O₃. It is possible to see from Fig. 3a the formation of a large number of HA crystals seen individually without the formation of the characteristic shape of the layer reflecting that the poor crystallization of these crystals. However, as can be seen from Fig. 3b, the prolonged soaking time of up to 7 days causes the number of HA crystals to increase with somewhat formation of the characteristic shape of the HA layer. Lastly, it is clearly evident from Fig. 3c that soaking the same sample in SBF solution for 10 days leads to the formation of a dense layer with few HA crystals. This indicates that the sample needs additional time to crystallize all the crystals formed or that another layer is starting to form. As discussed above, the soaking time improves the formation of the apatite layer on the surface of the same sample.

Undoubtedly, the perfect match between the bioactive ceramics and the mineral part of human bone is an important factor in forming a strong bond between these interfaces. Given that the formation of the HA

layer is highly dependent on the surface texture of the examined specimen, glass grains are preferred for many biomedical applications, including antibiotics, gene delivery, and growth factors [54,55].

3.3 The properties of the prepared glass samples

3.3.1 Density

It cannot be denied that density is considered a fundamental property and can be calculated based on glass composition [56]. The density values for the as-prepared glass specimens were measured and illustrated in Fig. 4. It is interesting to see from this figure that the density decreases with increasing boron contents in the as-prepared samples despite the slight increase in the density value of B_2O_3 (2.46 g/cm³) compared to that of P_2O_5 (2.39 g/cm³). The reason for this result is that the successive increase in the content of B_2O_3 , at the expense of P_2O_5 , increases the number of NBOs as a result of the conversion of some Q^2 units to Q^1 ones, which was confirmed by the obtained FTIR spectra, that leads to a slight decrease in the density. This explanation is supported by the results discussed by Yamusa *et al.* [57], who reported that the increase in the number of NBOs in the glass structure is responsible for decreasing the density of the glass samples. It should be noted that because B_2O_3 is a network former, the density values are not always a good indicator of the packing density within the glass structure [58].

3.3.2 Mechanical properties

Generally, the clinical applications of bone substitute materials are greatly affected by their mechanical properties [44]. In this sense, microhardness, fracture toughness, compressive strength, longitudinal and shear velocities, Young's modulus, longitudinal modulus, bulk modulus, shear modulus, and Poisson's ratio of all glasses were measured and illustrated in Figs. 5-8. The figures show the role of increasing B_2O_3 contents in improving the mechanical properties of all samples. On the contrary, fracture toughness exhibits an opposite trend to other mechanical properties as it decreases by successive increases in B_2O_3 contents. These results can be explained on the basis that the current glass system is composed of three formers, i.e., SiO_2 , P_2O_5 , and B_2O_3 , along with glass modifiers. When B_2O_3 is added to P_2O_5 , the phosphate glass structure is changed from a link structure to a framework structure due to the formation of B–O–P bonds, which in turn improves the mechanical properties of the investigated samples [59]. Notably, the obtained values of compressive strength and fracture toughness closely match those of cortical bone, i.e., 100-180 MPa and 2-12 MPa.m^{0.5}, respectively [60]. Noteworthy, these results are in good agreement with those reported in Ref. [61], which mentioned that the increase of boron content, at the expense of phosphate ones, is responsible for giving the studied glass samples this recorded increase in their mechanical properties. Importantly, the good mechanical properties of these glasses give them a substantial advantage to be used in load-bearing sites [36,37].

3.4 Finite element model analysis

Model and boundary condition

A finite element model (FEM) was created using the ANSYS software to predict the compositions' mechanical characteristics and dynamic behavior. Four different concentrations of boric acid have varied the designs of the investigated work; hence this variation reflected on the experimental mechanical properties discussed before. The studied compositions samples were modeled according to the real data acquired from the experimental tests. The isotropic elasticity parameters such as Young's modulus, density, and the maximum compressive stress were fed to the model for each composition. The samples were designed to match the purpose of its application; for example, the biomedical plate used to fix the bone was modeled, as shown in Fig. 9. With a Young's modulus of 20 GPa and a Poisson ratio of 0.3, the bone material is considered to be isotropic and homogeneous throughout the bone. Hence the calculations will be based on the load response on the investigated plates; we have used isotropy herein for convenience sake because our goal is to demonstrate the effect of different loads on the plates that are fixed to the bone.

Meshing techniques and size greatly influence the accuracy of the solution result for both mechanical and dynamic behavior. Many attempts were made to select the greatest possible resolution that could be attained and matched with the experimental test. According to the FEA solutions and meshing types, three meshing approaches were examined to choose the closest value to the experimental test: multi-zone, triangles, and quadrilateral dominant. The investigated model uses the Quad/Tri meshing method with 8108 nodes and 4166 elements. Boundary conditions were assigned using fixed support from one side of the investigated model. Static structural module and eigenvalue buckling were utilized to predict and model the mechanical properties of the studied compositions. At the same time, Modal analysis was conducted for the modeled sample; the first six mode shapes and their natural frequencies were computed. 10N force was applied at the end of the plate to calculate and plot the frequency response function. Furthermore, the harmonic response module was used in its superposition mode as part of the solution method, and the solution interval was set to 100 increment points to increase the resolution of the results in the frequency response function (FRF) plot.

3.4.2. Deflection effect

Fig. 10 shows the effect of the applied load on the deflection of the investigated compositions. It is evident from the figure that there is a linear relationship between increased loads and their effect on the deflection of the structure. As the B_2O_3 contents increased, the structure deflection decreased. This can be attributed to the increase in the composition strength. The improvement in the resistance to deflect (from 0 to 25 mol% B_2O_3) is achieved by 39%. While from (0 to 10 mol% B_2O_3) was enhanced by noticed 8.11 %. A significant improvement is achieved when increasing the B_2O_3 contents are more than 20 (mol.%).

3.4.3 Buckling analysis

Recent research shows that these structural glasses can sustain substantial dead loads caused by body weight. Because of their great slenderness, these glass samples are prone to buckling failure and must thus be examined under this probable limit condition. Analytical buckling analysis of glass columns may

typically be conducted using a conventional formula for columns subjected to axial stresses. Fig. 11-a shows the effect of applied load on load multiplier; hence, buckling occurs when a component loses stability, regardless of material strength. This loss of stability happens within the material's elastic range. The load multiplier for all investigated samples was greater than 1; hence the loads applied are fewer than the critical load that can cause buckling. The exponential relationship between the applied load and the load multiplier reflects that increasing loads are getting too close to the critical load, causing the plates to collapse. Using a 1kN load, the S4 compositions enhance the buckling behavior by 73% more than the S1. The buckling deflection takes various behavior during failure mode; Fig. 11-b shows that increasing the boric acid contents in the investigated composition enhances and alerts the failure results from the extra loads. Fig. 12 illustrates the simulation of the primary first sixth buckling failure modes.

3.4.4 Stress analysis

The Von-Mises stress determines whether a material will yield or fracture. A material will yield if its value located under load is equal to or greater than its simple tension yield limit. Fig. 13 shows the effect of the different percentages of boric acid on the maximum equivalent stresses. There is no significant impact on the stress value throughout all the investigated compositions, as illustrated in Table 2. By increasing the load, the equivalent Von-Mises stress is increased, and this result logically due to the loads are approaching the yield point.

3.4.5 Dynamic behavior

The structures and materials have inherent vibration frequencies at which they will deform, a phenomenon known as resonance. Each natural frequency is connected with a mode, which is a shape that describes the deformation of the structure. The first mode is the lowest frequency at which deformation occurs. When a structure vibrates, the initial mode generally specifies the highest loads in the structure or how that structure will interact with the rest of the system surrounding it. The FEA showed the effect of different compositions properties on the dynamics behavior; hence, the resonant frequency on the most important parameters used to identify the dynamic behavior of materials subjected to dynamic or excitation sources near the structure's natural frequency. The modal analysis was used to predict the resonant frequency throughout the various mode shapes. In the current investigation, the primary sixth modes are simulated as shown in Fig. 14, and the corresponding resonant frequencies are represented in Fig. 15. As the excitation source is increased, the resonant frequency moves from resonant mode to another at a specific value. The higher resonant frequencies were achieved by (25 mol.% B_2O_3) content. The FRF was plotted in Fig. 16; at the first mode shape, the maximum resonant frequency was 360.67 Hz for the composition (25 mol.% B_2O_3), while the minimum was recorded 232.66 Hz for the (0 mol.% B_2O_3). According to these results, increasing the mechanical properties of isotropic parameters leads to an increase in the natural frequency value.

4. Conclusions

The in vitro bioactivity of $\text{CaO-Na}_2\text{O-SiO}_2\text{-B}_2\text{O}_3\text{-P}_2\text{O}_5$ glasses towards simulated body fluid (SBF) was evaluated for prolonged soaking times of up to 10 days. The XRD patterns pointed out that the increased boron content in the glass compositions promoted the formation of a HA-like layer on the surfaces of the glass samples, which was in line with that obtained by SEM to give additional evidence to the formation of this layer. Furthermore, the increase in boron content significantly increased the microhardness and chemical durability of these glasses. However, boron caused a slight decrease in fracture toughness. It should be noted that increasing the B_2O_3 contents from 0 to 25 mol% was responsible for the 39% increase in the deflecting resistance, considering that this improvement started to be observed when the B_2O_3 content was increased by 20 mol%. Also, a glass sample containing 25 mol% B_2O_3 outperforms that containing 0 mol% B_2O_3 by 73%. By increasing the content of B_2O_3 in the investigated composition, the failure rate from the extra loads increased. On the other hand, the shear and principles stresses were not affected by the different compositions used in the present investigation. From the results obtained, it can be concluded that B_2O_3 has a significant role in enhancing the mechanical and dynamic properties; hence the dynamic properties were improved by increasing the resonance frequency.

Declarations

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Tables

Table 1. Nominal composition (mol.%) of borophosphosilicate glasses

Sample code	B ₂ O ₃	SiO ₂	Na ₂ O	CaO	P ₂ O ₅
S1	0	10	25	20	45
S2	10	10	25	20	35
S3	20	10	25	20	25
S4	25	10	25	20	20

Table 2. The average value of the equivalent stresses

Maximum Shear Stress MPa				
Load	0 mol.% B ₂ O ₃	10 mol.% B ₂ O ₃	20 mol.% B ₂ O ₃	25 mol.% B ₂ O ₃
100	2.58746	2.58743	2.58739	2.58731
200	5.17492	5.17485	5.17477	5.17462
300	7.76239	7.76228	7.76216	7.76193
400	10.34985	10.3497	10.34954	10.34925
500	12.93731	12.93713	12.93693	12.93656
600	15.52477	15.52456	15.52431	15.52387
700	18.11223	18.11198	18.1117	18.11118
800	20.6997	20.69941	20.69909	20.69849
900	23.28716	23.28683	23.28647	23.2858
1000	25.87462	25.87426	25.87386	25.87312
Load	Maximum Principle Stress MPa			
100	0.47932	0.47921	0.4791	0.47888
200	0.95863	0.95843	0.95819	0.95775
300	1.43795	1.43764	1.43729	1.43663
400	1.91727	1.91685	1.91639	1.9155
500	2.39658	2.39607	2.39548	2.39438
600	2.8759	2.87528	2.87458	2.87326
700	3.35522	3.3545	3.35368	3.35213
800	3.83454	3.83371	3.83278	3.83101
900	4.31385	4.31292	4.31187	4.30988
1000	4.79317	4.79214	4.79097	4.78876

Figures

Figure 1

FTIR absorption spectra of phosphosilicate glasses with successive increase in B₂O₃ content from 0 to 25 wt.%.

Figure 2

XRD patterns of a) as-prepared glasses and reacted glasses in SBF solution for b) 3 days, c) 7 days and d) 10 days.

Figure 3

SEM images of S4 sample after soaking in SBF solution for a) 3 days, b) 7 days and c) 10 days at two different magnification powers.

Figure 4

Bulk density of all prepared glass samples with different contents of B₂O₃ (mol.%)

Figure 5

Microhardness and fracture toughness of all glass samples versus B₂O₃ contents (mol.%)

Figure 6

Compressive strength of S1, S2, S3 and S4 glass samples

Figure 7

Longitudinal and shear ultrasonic velocities versus different boron oxide contents (mol.%).

Figure 8

a) Young's and elastic moduli, b) bulk and shear moduli and c) Poisson's ratio of borophosphosilicate glass samples.

Figure 9

Modeling and the assembly of the investigated plate mounted on the bone

Figure 10

Effect of the applied static load on the total deflection

Figure 11

(a) The relationship between the applied load and the critical point of failure and (b) effect of B_2O_3 (mol.%) contents on the buckling deflection mode

Figure 12

Buckling total deformation mode of the investigated glass samples

Figure 13

An equivalent stress under a 100N load applied to a compression plate supported on bone (a) S1 sample, (b) S2 sample, (c) S3 sample and (d) S4 sample

Figure 14

The mode shape of the investigated samples predicted from the modal analysis module

Figure 15

Mode shape and corresponding natural frequency

Figure 16

The FRF spectrum of the investigated glass compositions