ISSN 2229-5518

Elastic Properties of substituted 45S5 Bioactive Glasses and Glass - Ceramics

Ankesh Kumar Srivastava, Ram Pyare and S. P. Singh

Abstract — CuO, Fe_2O_3, MnO_2 and ZnO substituted 45S5 bioactive - glasses were prepared. Glass - derived Bioactive Glass - ceramics were obtained through controlled crystallization of bioactive glasses. The formed crystalline phases in bioactive glass - ceramics were identified using X - ray diffraction (XRD) analysis. Density and ultrasonic wave velocities of bioactive glasses and glass - ceramics were measured and used to study elastic properties: Young's modulus, shear modulus, bulk modulus and Poisson's ratio, of bioactive glasses and glass - ceramics.
The results indicate that the addition of CuO, Fe_2O_3, MnO_2 and ZnO contents in 45S5 bioactive glass enhances its density and elastic properties. The bioactive glass - ceramics exhibits higher density and elastic properties when compared with their corresponding bioactive glasses.

Index Terms — Bioceramics, Bioactive Glasses, Bioactive Glass - ceramics, Physical Properties, Bioactivity, Mechanical Properties, Elastic Modulus, Poisson's ratio

1 INTRODUCTION

The most widely researched bioactive material is 45S5 bioactive glass [Composition wt. % 45 SiO_2 - 24.5 Na_2O - 24.5 CaO - 6 P_2O_5], where S denotes the network former SiO_2 in 45% by weight followed by a specific Ca/P molar ratio 5 [1]. It was invented by Hench in 1969. The key compositional features that are responsible for the bioactivity of 45S5 bioactive glass are its low SiO_2 (glass network former) content, high Na_2O and CaO (glass network modifiers) content, and high CaO/P_2O_5 ratio [2].

An ideal bioactive material requires both good biochemical and biomechanical compatibility. A particular advantage of 45S5 bioactive glass is its ability to bond to both hard and soft tissues [3]. However, a disadvantage of 45S5 bioactive glass is its brittleness. As a consequence, it has poor mechanical properties and is generally restricted to clinical non - load bearing situation [4].

The mechanical strength of a glass depends on its elastic properties, shape, surface/internal defects and the character of the force to which it is subjected. These factors inevitably degrade the mechanical strength of a material to 1/10 or lower of its intrinsic (theoretical) strength [5]. Thus, one cannot obtain the intrinsic strength by using destructive mechanical test on a big specimen. The ultrasonic non - destructive testing has been found to be one of the best techniques to study the elastic properties of glasses.

The present work aims to measure the density and ultrasonic wave velocities (both longitudinal and shear) for CuO, Fe_2O_3, MnO_2 and ZnO substituted 45S5 bioactive glasses and glass - ceramics. These values have been used to evaluate Young's, bulk and shear modulus and Poisson's ratio of bioactive glasses and glass - ceramics.

2 EXPERIMENTAL

2.1 Preparation of Bioactive Glasses and Glass - ceramics

Fine grained quartz was used as the source of SiO_2 while Na_2O and CaO were introduced in the form of anhydrous sodium carbonate [Na_2CO_3] and anhydrous calcium carbonate [$CaCO_3$] respectively, P_2O_5 was added in the form of ammonium dihydrogen orthophosphate [$NH_4H_2PO_4$] and CuO, Fe_2O_3, MnO_2 and ZnO was added as such for preparation of bioactive glasses. All the batch materials were of analytical grade chemicals and used without further purification. The compositions of bioactive glasses are given in Table 1. The weighed batches were melted in alumina crucibles for 3 hours in an electric furnace at the temperature 1400 ± 10 ^{0}C. The homogeneous melts were cast into preheated stainless steel moulds of the required dimensions. The prepared bioactive glass samples were directly transferred to a regulated muffle furnace at the temperature 500 ^{0}C for annealing. After 1 h, the muffle furnace was left to cool to room temperature at a rate of 30 ^{0}C/ h.

In order to obtain the bioactive glass - ceramics, the bioactive glass samples were heated in the muffle furnace in two step regime at the deduced temperatures and times as shown in Table 2. These temperatures were obtained from differential thermal analysis (DTA) of bioactive glasses. Each bioactive glass sample was heated slowly to the first nucleation temperature for the formation of sufficient nuclei sites and after holding for the definite time, was then further heated to reach the second chosen crystal growth temperature for performing the perfect crystal growth process and after a second hold for the specific time, the sample was left to cool inside the muffle furnace to room temperature at a rate of 20 ^{0}C/h.

Table 1: Composition of bioactive glasses

Code for glasses	Composition (wt %)				
	CuO substituted 45S5 bioactive glasses				
	SiO_2	Na_2O	CaO	P_2O_5	CuO
C1	44.00	24.50	24.50	6.00	1.00
C2	43.00	24.50	24.50	6.00	2.00
C3	42.00	24.50	24.50	6.00	3.00
C4	41.00	24.50	24.50	6.00	4.00
	Fe_2O_3 substituted 45S5 bioactive glasses				
	SiO_2	Na_2O	CaO	P_2O_5	Fe_2O_3
F1	44.00	24.50	24.50	6.00	1.00
F2	43.00	24.50	24.50	6.00	2.00
F3	42.00	24.50	24.50	6.00	3.00
F4	41.00	24.50	24.50	6.00	4.00
	MnO_2 substituted 45S5 bioactive glasses				
	SiO_2	Na_2O	CaO	P_2O_5	MnO_2
M1	44.00	24.50	24.50	6.00	1.00
M2	43.00	24.50	24.50	6.00	2.00
M3	42.00	24.50	24.50	6.00	3.00
M4	41.00	24.50	24.50	6.00	4.00
	ZnO substituted 45S5 bioactive glasses				
	SiO_2	Na_2O	CaO	P_2O_5	ZnO
Z1	44.00	24.50	24.50	6.00	1.00
Z2	43.00	24.50	24.50	6.00	2.00
Z3	42.00	24.50	24.50	6.00	3.00
Z4	41.00	24.50	24.50	6.00	4.00
	Base 45S5 bioactive glass				
	SiO_2	Na_2O	CaO	P_2O_5	
45S5	44.00	24.50	24.50	6.00	

Table 2: Heat treatment schedule for crystallization of bioactive glasses

Sample	Nucleation		Growth	
	Temperature (^{0}C)	Time (hours)	Temperature (^{0}C)	Time (hours)
	CuO substituted 45S5 bioactive glasses			
C1	518	6	675	3
C2	510	6	651	3
C3	504	6	631	3
C4	499	6	616	3
	Fe_2O_3 substituted 45S5 bioactive glasses			
F1	527	6	682	3
F2	523	6	665	3
F3	519	6	650	3
F4	516	6	640	3
	MnO_2 substituted 45S5 bioactive glasses			
M1	525	6	678	3
M2	520	6	657	3
M3	517	6	640	3
M4	514	6	627	3
	ZnO substituted 45S5 bioactive glasses			
Z1	528	6	686	3
Z2	524	6	671	3
Z3	521	6	661	3
Z4	518	6	651	3
	Base 45S5 bioactive glass			
45S5	533	6	717	3

2.2 X - Ray Diffraction (XRD) Analysis

Identification of the crystalline phases after heat - treatment of bioactive glass samples was carried out by X - ray diffraction (XRD) analysis. The bioactive glass - ceramics were examined using a X - ray diffractometer, adopting Ni filter and Cu target with voltage of 40 KV and a current of 25 mA. The XRD patterns were recorded in a 2θ range of 10 - 70^0. The JCPDS - International Center for Diffraction Data Cards was used as a reference data for the interpretation of XRD patterns in the present work.

2.3 Density Measurements

Archimedes principle was employed to obtain the density of bioactive glass and glass - ceramic samples using distilled water as buoyant. All the weight measurements have been made using a digital balance having an accuracy of ± 0.0001 g. Density (ρ) of sample was obtained employing the relation [6] given below [6]:

$$\rho = \frac{w_a}{w_a - w_b}\rho_b$$

where w_a is the weight of sample in air, w_b is the weight of sample in buoyant and ρ_b is the density of buoyant.

2.4 Elastic Properties Measurements

The ultrasonic wave velocities propagated in the polished bioactive glass and glass - ceramic specimens were obtained by measuring the elapsed time between the initiation and the receipt of the pulse appearing on the screen of an ultrasonic flaw detector via a standard electronic circuit. The size of the specimen was 20 mm x 10 mm x 3 mm according to ASTM Standard: E494 - 10. Two quartz transducers in this machine, which are X - cut transducer and Y - cut transducer, with has a resonant frequency of 5 MHz and acts as transmitter - receiver at the same time, were required to generate longitudinal and transverse ultrasonic waves respectively Burnt honey was used as bonding material between samples and transducers. The ultrasonic wave velocity (V) can be calculated using the following equation [7]:

$$V = \frac{2X}{\Delta t}$$

where X is the sample thickness and Δt is the time interval. The elastic strain in an amorphous solid (such as glass) generated by a minor stress, can be described by two independent elastic constants, C_{11} and C_{44} [8]. For pure longitudinal ultrasonic waves, $C_{11} = \rho V_L^2$ and for pure transverse ultrasonic waves, $C_{44} = \rho V_T^2$, where V_L and V_T , respectively, are the longitudinal and transverse ultrasonic wave velocities. Elastic properties: Young's modulus (E), shear modulus (G), bulk modulus (K) and Poisson's ratio (σ), can be obtained by density (ρ) and longitudinal (V_L) and shear (V_S) ultrasonic wave velocities by using the following standard equations [9]:

$$E = \rho V_L^2 \frac{3V_L^2 - 4V_T^2}{V_L^2 - V_T^2}$$

$$G = \rho V_T^2$$

$$K = \frac{1}{3}\rho(3V_L^2 - 4V_T^2)$$

$$\sigma = \frac{V_L^2 - 2V_T^2}{2(V_L^2 - V_T^2)}$$

3 RESULTS

3.1. X - Ray Diffraction (XRD) Analysis

The X - ray diffraction (XRD) patterns for CuO substituted 45S5 bioactive glass - ceramics are shown in Figure 1. The XRD patterns of all the bioactive glass - ceramics show the presence of crystalline phase of sodium calcium silicate [$Na_2Ca_2Si_3O_9$ (card number: PDF # 01 - 1078 & PDF # 02 - 0961), $Na_2CaSi_3O_8$ (card number: PDF # 12 - 0671)]. Each CuO substituted bioactive glass - ceramics (C1, C2, C3 and C4) also, show the presence of crystalline phase of calcium silicate [$CaSiO_3$ (card number: PDF # 42 - 0550)].

3.2 Density Measurements

Experimental values of density of bioactive glasses and glass ceramics are given in Table 3. It has been observed that the increase of CuO, Fe_2O_3, MnO_2 and ZnO contents in the base bioactive glass (45S5) causes an increase in its density. It also has been observed that the density of bioactive glass - ceramics are higher than their respective bioactive glasses.

3.3 Elastic Properties Measurements

Values of longitudinal and shear ultrasonic wave velocities of investigated bioactive glasses and glass - ceramics are given in Table 3 while values of Young's, shear and bulk modulus and Poisson's ratio are listed in Table 4. Variation in Young's, shear and bulk modulus and Poisson's ratio of investigated bioactive glasses and glass - ceramics are shown in Figures 2, 3, 4 and 5 respectively. Both longitudinal and shear ultrasonic wave velocities and Young's, shear and bulk modulus of base bioactive glass (45S5) increases with the incorporation of CuO, Fe_2O_3, MnO_2 and ZnO contents in it.while a slight decrease in Poisson's ratio was obtained. It also has been founded that the crystallization of bioactive glasses increases their both longitudinal and shear ultrasonic wave velocities, Young's, shear and bulk modulus while decreases the Poisson's ratio.

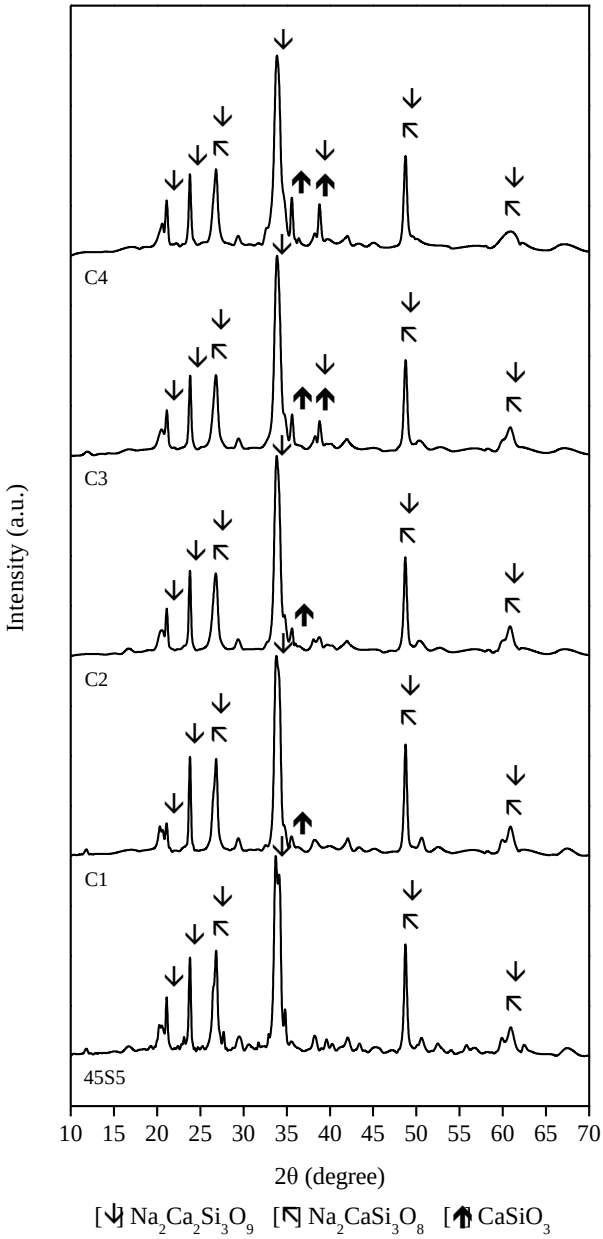


Figure 1: XRD Patterns for CuO substituted 45S5 bioactive glass - ceramics

Table 3: Density (ρ), longitudinal velocity (V_L) and transverse velocity (V_T) of bioactive glasses and glass ceramics

Sample	Glasses			Glass - ceramics		
	ρ (g/cm^3)	V_L (m/s)	V_T (m/s)	ρ (g/cm^3)	V_L (m/s)	V_T (m/s)
	CuO substituted 45S5 bioactive glasses			CuO substituted 45S5 bioactive glasses - ceramics		
C1	2.732	5915	3370	2.943	6519	3744
C2	2.742	5927	3381	2.954	6531	3757
C3	2.759	5940	3394	2.972	6547	3772
C4	2.772	5961	3411	2.986	6569	3789
	Fe_2O_3 substituted 45S5 bioactive glasses			Fe_2O_3 substituted 45S5 bioactive glasses - ceramics		
F1	2.723	5913	3368	2.925	6517	3743
F2	2.731	5925	3380	2.932	6530	3755
F3	2.746	5937	3393	2.946	6544	3770
F4	2.757	5958	3409	2.956	6562	3784
	MnO_2 substituted 45S5 bioactive glasses			MnO_2 substituted 45S5 bioactive glasses - ceramics		
M1	2.738	5927	3382	2.937	6533	3761
M2	2.749	5941	3397	2.947	6550	3775
M3	2.767	5965	3415	2.964	6571	3793
M4	2.781	5983	3431	2.977	6587	3807
	ZnO substituted 45S5 bioactive glasses			ZnO substituted 45S5 bioactive glasses - ceramics		
Z1	2.727	5912	3366	2.928	6515	3741
Z2	2.736	5921	3379	2.936	6527	3752
Z3	2.752	5933	3387	2.951	6541	3766
Z4	2.764	5947	3400	2.962	6556	3780
	Base 45S5 bioactive glass			Base 45S5 bioactive glass - ceramics		
45S5	2.707	5904	3353	2.912	6507	3728

Table 4: Young's modulus (E), shear modulus (G), bulk modulus (K) and Poisson's ratio (σ) of bioactive glasses and glass ceramics

Sample	Glasses				Glass - ceramics			
	E (GPa)	G (GPa)	K (GPa)	σ	E (GPa)	G (GPa)	K (GPa)	σ
	CuO substituted 45S5 bioactive glasses				CuO substituted 45S5 bioactive glasses - ceramics			
C1	78.10	31.02	54.22	0.259	103.37	41.25	70.06	0.253
C2	78.85	31.34	54.53	0.258	104.39	41.69	70.40	0.252
C3	79.89	31.78	54.96	0.257	105.78	42.28	71.00	0.251
C4	81.01	32.25	55.49	0.256	107.15	42.86	71.70	0.250
	Fe_2O_3 substituted 45S5 bioactive glasses				Fe_2O_3 substituted 45S5 bioactive glasses - ceramics			
F1	77.75	30.88	54.02	0.259	102.67	40.97	69.59	0.253
F2	78.49	31.20	54.27	0.258	103.51	41.34	69.90	0.252
F3	79.46	31.61	54.64	0.257	104.75	41.87	70.32	0.251
F4	80.45	32.03	55.15	0.256	105.80	42.32	70.85	0.250
	MnO_2 substituted 45S5 bioactive glasses				MnO_2 substituted 45S5 bioactive glasses - ceramics			
M1	78.77	31.31	54.43	0.258	104.01	41.54	69.96	0.252
M2	79.74	31.72	54.72	0.257	105.05	41.99	70.44	0.251
M3	81.03	32.26	55.43	0.256	106.60	42.64	71.11	0.250
M4	82.15	32.73	55.90	0.255	107.76	43.14	71.64	0.249
	ZnO substituted 45S5 bioactive glasses				ZnO substituted 45S5 bioactive glasses - ceramics			
Z1	77.84	30.89	54.12	0.260	102.75	40.97	69.64	0.254
Z2	78.63	31.23	54.27	0.259	103.57	41.33	69.96	0.253
Z3	79.43	31.57	54.77	0.258	104.79	41.85	70.45	0.252
Z4	80.32	31.95	55.15	0.257	105.88	42.32	70.88	0.251
	Base 45S5 bioactive glass				Base 45S5 bioactive glass - ceramics			
45S5	76.74	30.43	53.77	0.261	101.57	40.47	69.33	0.255

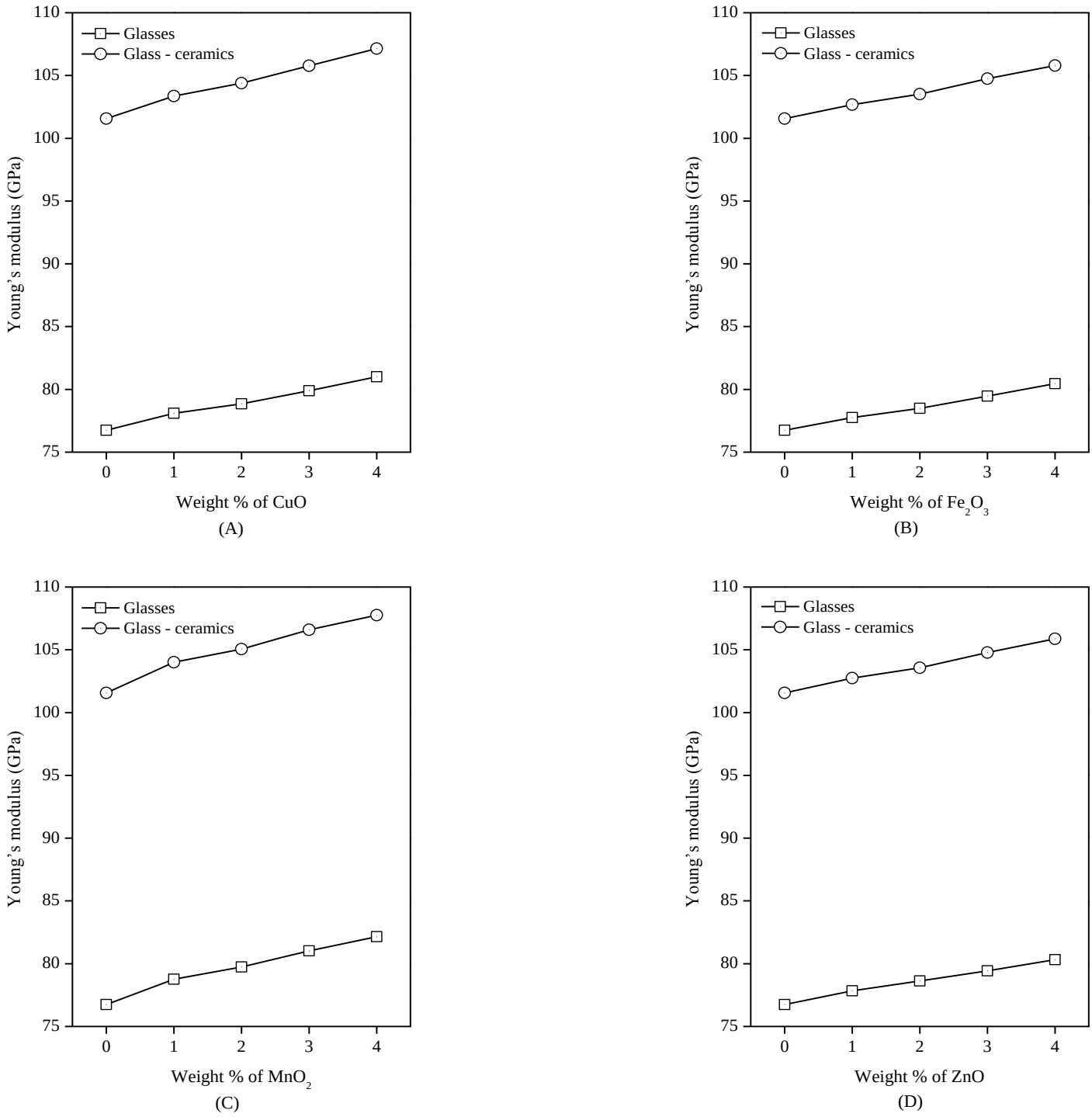


Figure 2: Variation in Young's modulus for (A) CuO, (B) Fe_2O_3, (C) MnO_2 and (D) ZnO substituted 45S5 bioactive glasses and glass - ceramics

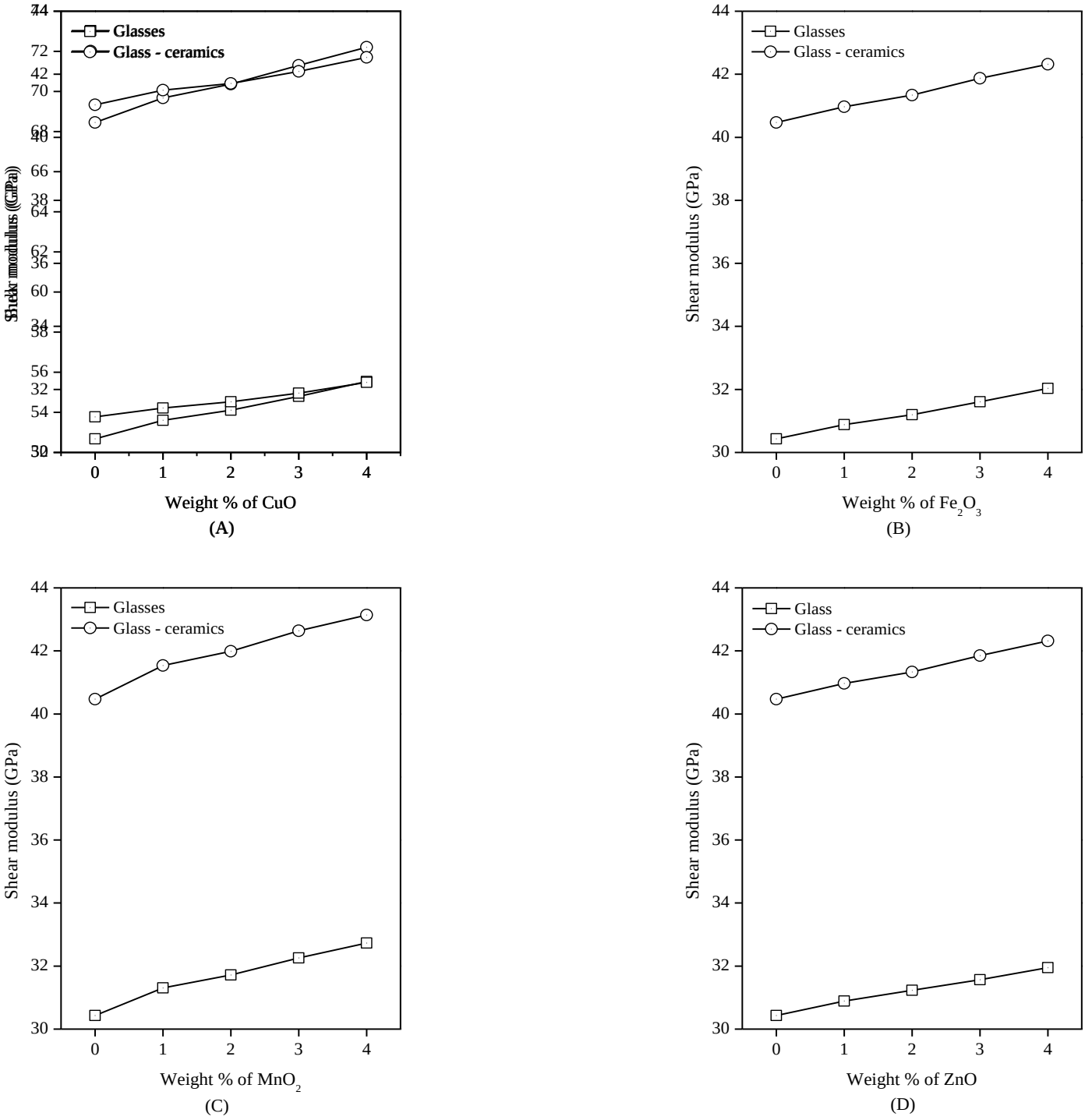


Figure 3: Variation in shear modulus for (A) CuO, (B) Fe_2O_3, (C) MnO_2 and (D) ZnO substituted 45S5 bioactive glasses and glass - ceramics

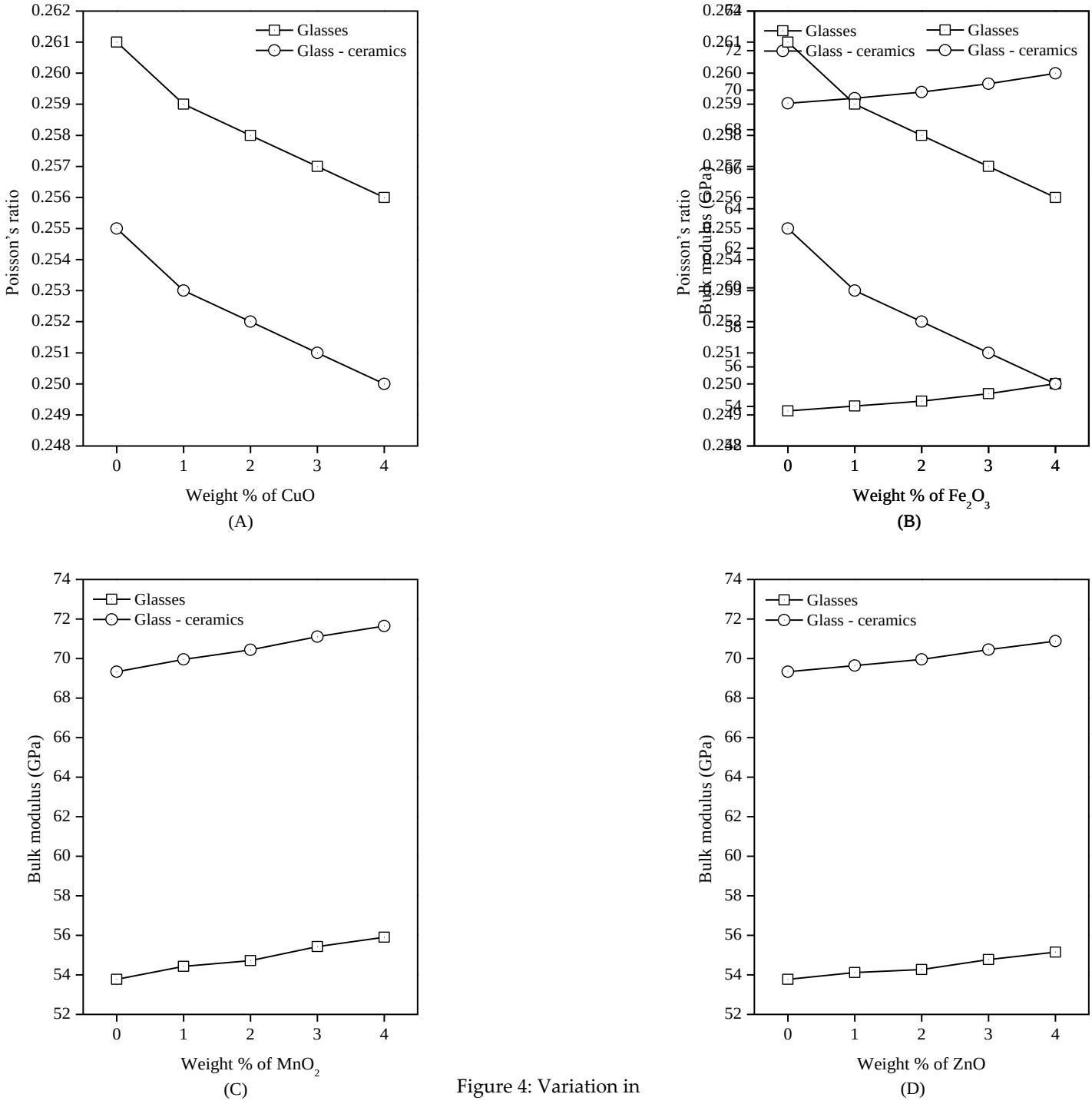
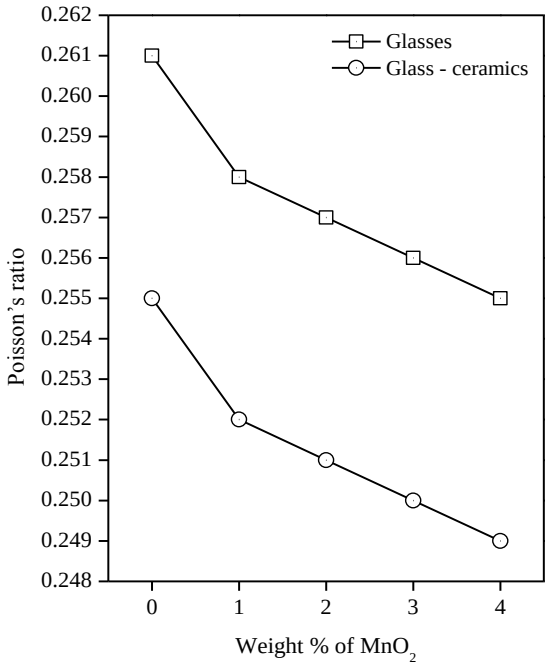
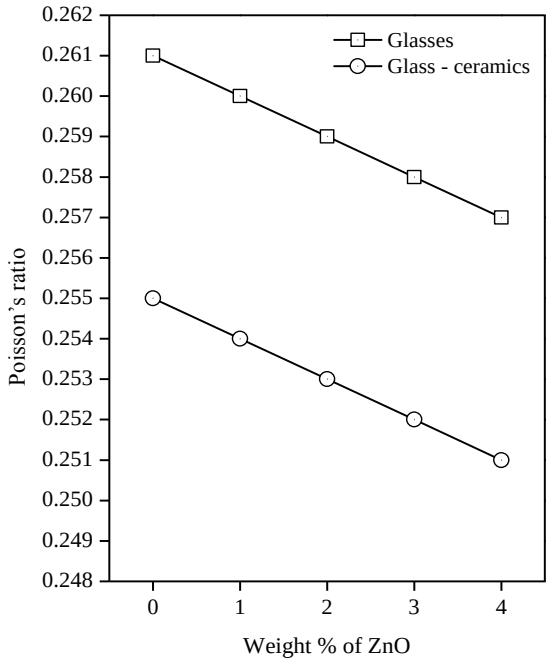


Figure 4: Variation in bulk modulus for (A) CuO, (B) Fe_2O_3, (C) MnO_2 and (D) ZnO substituted 45S5 bioactive glasses and glass - ceramics



(C)



(D)

Figure 5: Variation in Poisson's ratio for (A) CuO, (B) Fe_2O_3, (C) MnO_2 and (D) ZnO substituted 45S5 bioactive glasses and glass - ceramics

4 DISCUSSIONS

4.1 X – Ray Differaction (XRD) Analysis

The XRD patterns of all the bioactive glass - ceramics show the presence of crystalline phases. The reason for the ease of

crystallization of bioactive glasses can be correlated with the presence of silicate and phosphate network, as well as the possible phase separation even in micro scale of the two phases on heat - treatment. It is well known that the addition of a few percentage of P_2O_5 to silicate glass compositions, promotes the volume nucleation and glass - ceramic formation [10]. There is some evidence for precipitation of phosphate crystals which subsequently act as heterogeneous nucleation sites for the subsequent crystallization of the major phases, although the detailed role of P_2O_5 remains to be discussed [11]. Previous studies [12], [13], [14] have shown that the heat - treatment of 45S5 bioactive glass at a nucleation temperature of 550 ^{0}C and followed by heating at a crystallization temperature of 680 ^{0}C produces a bioactive glass - ceramic containing the sodium calcium silicate [$Na_2Ca_2Si_3O_9$] as main crystallline phase. In all the bioactive glass - ceramics sodium calcium silicate [Na_2Ca_2 Si_3O_9 & $Na_2CaSi_3O_8$] is present as main crystalline phase. Crystalline phase of calcium silicate [$CaSiO_3$] is also observed in each CuO substituted bioactive glass - ceramics (C1, C2, C3 and C4). The studied bioactive glass - ceramics did not contain Cu, Fe, Mn and Zn as separate crystalline phases. This can be related to their relatively low content in bioactive glass composition.

4.2 Density Measurements

. The increase of CuO, Fe_2O_3, MnO_2 and ZnO contents in the base bioactive glass (45S5) leads to an increase its density because of replacement of a lighter element, Si (density = 2.33 g/cm^3) with a heavier element, Cu (density = 8.96 g/cm^3), Fe (density = 7.86 g/cm^3), Mn (density = 7.21 g/cm^3) and Zn (density = 7.14 g/cm^3). The density of bioactive glass - ceramics are higher than their respective bioactive glasses due to densification.

4.3 Elastic Properties Measurements

In general, the increase in ultrasonic wave velocities (longitudinal and shear) and elastic modulus of glasses are related to the increase in connectivity of the glass network [15], [16]. An increase in longitudinal and shear ultrasonic wave velocities and Young's, shear and bulk modulus of 45S5 bioactive glass due to increase of CuO, Fe_2O_3, MnO_2 and ZnO contents in it, can be explained by the decrease in the inter - atomic spacing which means that the copper, iron, manganese and zinc ions with octahedral coordination are involved in the glass network as modifiers by occupying the interstitial positions which cause the increase in the average number of the network bonds per unit volume. Therefore, it can be suggested that CuO, Fe_2O_3, MnO_2 and ZnO modification leads to an increase in the network connectivity of the studied bioactive glasses. A decrease in Poisson's ratio of 45S5 bioactive glass with increasing of network modifiers is attributed to increase the crosslink density (defined as the number of bridging bonds per cation) of glass network [17].

It is generally accepted that the controlled heat treatment of glasses above the glass transition temperature and crystallisation temperature leads the possible formation of crystalline phases along with the residual glassy phases [18]. The observed increase in ultrasonic wave velocities and elastic modulus, and decrease in Poisson's ratio of bioactive glass - ceramics is mainly due to the densification during thermal treatments.

5 CONCLUSIONS

Addition of CuO, Fe_2O_3, MnO_2 and ZnO contents in 45S5 bioactive glass increases its density and elastic modulus: Young's, shear and bulk modulus while a decreases its Poisson's ratio. Crystallization of bioactive glasses enhances their density and elastic properties.

References

[1] S.M. Best, A.E. Porter, E.S. Thian and J. Huang, "Bioceramics: Past, present and for the future", Journal of the European Ceramic Society, vol. 28, pp. 1319 - 1327, 2008.

[2] M.N. Rahaman, D.E. Day, B.S. Bal, Q. Fu, S.B. Jung, L.F. Bonewald and A.P. Tomsia, "Bioactive glass in tissue engineering", Acta Biomaterialia, vol. 7, pp. 2355 - 2373, 2011.

[3] L.L. Hench and O. Andersson, "An Introduction to Bioceramics", editors, L.L. Hench and J. Wilson, World Scientific, Singapore, pp. - 41, 1993.

[4] V. Aina, G. Malavasi, A.F. Pla, L. Munaron and C. Morterra, "Zinc - containing bioactive glasses: Surface reactivity and behaviour towards endothelial cells", Acta Biomaterialia, vol. 5, pp. 1211 - 1222, 2009.

[5] C.C. Lin, L.C. Huang and P. Shen, "$Na_2CaSi_2O_6$ - P_2O_5 based bioactive glasses. Part 1: Elasticity and structure", Journal of Non - Crystalline Solids, vol. 351, pp. 3195 - 3203, 2005.

[6] V. Rajendran, A.N. Begum, M.A. Azooz and F.H. ElBatal, "Microstructural dependence on relevant physical - mechanical properties on SiO_2 - Na_2O - CaO - P_2O_5 biological glasses", Biomaterials, vol. 23, pp. 4263 - 4275, 2002.

[7] K.A. Matori, M.H.M. Zaid, H.A.A. Sidek, M.K. Halimah, Z.A. Wahab and M.G.M. Sabri, "Influence of ZnO on the ultrasonic velocity and elastic moduli of soda lime silicate glasses", International Journal of the Physical Sciences, vol. 5(14), pp. 2212 - 2216, 2010.

[8] B. Eraiah, M.G. Smitha and R.V. Anavekar, "Elastic properties of lead - phosphate glasses doped with samarium trioxide", Journal of Physics and Chemistry of Solids, vol. 71, pp. 153 - 155, 2010.

[9] M.H.M. Zaid, K.A. Matori, L.C. Wah, H.A.A. Sidek, M.K. Halimah, Z.A. Wahab and B.Z. Azmi, "Elastic moduli

prediction and correlation in soda lime silicate glasses containing ZnO", International Journal of the Physical Sciences, vol. 6(6), pp. 1404 - 1410, 2011.

[10] F.H. ElBatal and A. ElKheshen, "Preparation and characterization of some substituted bioglasses and their ceramic derivatives from the system SiO_2 - Na_2O - CaO - P_2O_5 and effect of gamma irradiation", Materials Chemistry and Physics, vol. 110, pp. 352 - 362, 2008.

[11] P.F. James, "Glass ceramics: new compositions and uses", Journal of Non - Crystalline Solids, vol. 181, pp. 1 - 15, 1995.

[12] L.L. Hench, R.J. Splinter, T.K. Greenlee and W.C. Allen, "Bonding mechanisms at the interface of ceramic prosthetic materials", Journal of Biomedical Materials Research, vol. 2 (part 1), pp. 117 - 141, 1971.

[13] L.L. Hench and H.A. Paschall, "Direct chemical bonding of bioactive glass - ceramic materials and bone", Journal of Biomedical Materials Research: Symp., vol. 4, pp. 25 - 42, 1973.

[14] V.R. Mastelaro, E.D. Zanotto, N. Lequeux and R. Cortes, "Relationship between short - range order and ease of nucleation in $Na_2Ca_2Si_3O_9$, $CaSiO_3$ and $PbSiO_3$ glasses", Journal of Non - Crystalline Solids, vol. 262, pp. 191 - 199, 2000.

[15] M.S. Gaafar, F.H. ElBatal, M. ElGazery and S.A. Mansour, "Effect of Doping by Different Transition Metals on the Acoustical Properties of Alkali Borate Glasses", Acta Physica Polonica A, vol. 115, pp. 671 - 678, 2009.

[16] A.N. Kannappan, S. Thirumaran and R. Palani, "Elastic and Mechanical Properties of Glass Specimen by Ultrasonic Method", ARPN Journal of Engineering and Applied Sciences, vol. 4(1), pp. 27 - 31, 2009.

[17] A. Higazy and B. Bridge. "Elastic constants and structure of the vitreous system Co_3O_4 - P_2O_4", Journal of Non - Crystalline Solids, vol. 72, pp. 81 - 108, 1985.

[18] A.V. Gayathri Devi, V. Rajendran and N. Rajendran, "Ultrasonic characterisation of calcium phosphate glasses and glass - ceramics with addition of TiO2", International Journal of Engineering Science and Technology vol. 2(6), pp. 2483-2490, 2010.

■ Ankesh Kumar Srivastava, Ram Pyare and S. P. Singh
Department of Ceramic Engineering,
Institute of Technology
Banaras Hindu University, Varanasi - 221005: INDIA
■ Corresponding Author
Ankesh Kumar Srivastava
E - mail: ankesh.000@gmail.com