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Comprehensive study on physical, elastic and shielding properties of ternary $BaO\text{-}Bi_2O_3\text{-}P_2O_5$ glasses as a potent radiation shielding material

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ABSTRACT

Recent research studies have been carrying out to characterize the structural, elastic and shielding properties of novel ternary $BaO\text{-}Bi_2O_3\text{-}P_2O_5$ glasses. The glass series having composition $BaO{\cdot}(50-x)\ Bi_2O_3{\cdot}50P_2O_5$ ($10 \le x \le 40$ wt%) were prepared by conventional melt-quenching technique and the variation in density (ρ), molar volume (V_m), X-ray diffraction (XRD) and ultrasonic velocities has also been studied and correlated with the structural modifications in the glasses. The shielding parameters, effective atomic numbers, half value layers, and exposure buildup factor values have been computed using WinXCom program and G-P fitting method. The variations of shielding parameters were discussed for the effect of Bi_2O_3 addition into the glasses. The density, ultrasonic velocity and the calculated elastic moduli are found to be composition dependent and discussed in terms of Bi_2O_3 modifiers. The replacement of BaO by Bi_2O_3 causes an increase in effective atomic number, while the half value layer and the exposure buildup factor are decreased. This indicates that the increment in the content of Bi_2O_3 improves the gamma ray shielding characteristics.

1. Introduction

Increasing progress in radiation shielding technology leads to the extreme use of gamma radiation in several industrial sectors including agriculture, engineering and medical treatment. These gamma radiations are very dangerous not only for human but also for sensitive laboratory equipment. To deal with these current issues, exploration and innovation of new possible and effective gamma radiation shielding material is very essential. Generally, concrete is the common material used as shielding material in nuclear reactors and other civil uses [1]. This is because the concrete is low-cost, flexible and easy to handle for any construction design. Besides, concrete also has an acceptable density and structure strength for the attenuation of gamma rays but it has several disadvantages properties such as crack formation, variability in water content due to evaporation process with high gamma ray energies and non-transparency to visible light [2]. In consideration of this situation, it is necessary to develop and design a superior gamma radiation shielding material which can act better compared to the concrete.

Glass is an amorphous material that commonly transparent (excellent material for the transmission of visible light) and hard. For that reason, glass has been used in various applications such as coatings, semiconductor microelectronics, optical lenses, scintillation detectors and hard nuclear waste materials [3–7]. Additionally, the composition of the glass can be varied to provide suitable accommodations for large quantity of heavy metal oxides [8]. Glass can be a suitable replacement for the concrete as gamma ray shielding material. For this reason, it is an important area of research to investigate the structural, elastic and shielding properties of potential glass for gamma ray shielding industries which provide the evidences to improve the properties of the gamma ray shielding materials.

Phosphate glasses are interesting glass system that can be used for fast ion conducting material, biomedical applications and bio-compatible materials such as bio glass, ceramic bone regeneration application, and shielding materials [9]. Phosphate glasses also have been studied comprehensively in developing new glasses suited to the demands of both industry and technology, because of their low glass transition temperatures, low optical dispersions and relatively high thermal expansion coefficients and high refractive indices [10]. Besides, these glasses has been nominated for gamma ray shielding materials by their properties such as high dielectric constant, good transmission for infrared rays with a wide range of wavelengths, high thermal stability and low phonon energy [11]. However, the information of phosphate glass used in the radiation shielding material is very limited. The

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properties of the phosphate glass such as low chemical durability, high hygroscopic and volatile has limited their uses compared to other glass system [12]. However, the properties of phosphate glasses can be improved by addition of suitable oxides into the glass structure [13]. In addition, the combination of ionic species such as alkali metal ions into the phosphate glass structure produces ionically conducting materials for planar solid-oxide fuel cells [14]. Moreover, the properties of phosphate glasses such as high thermal expansion coefficients, low melting and softening temperatures and good transparency to visible light make these glasses very interesting to studies [15].

Glasses containing high-Z number elements (the element that has high atomic number and should be of high gamma ray cross-section), such as Ba (Z = 56), W (Z = 74), Pb (Z = 82) and Bi (Z = 83) are the suitable choice to shelter peoples from interference radiation like X-ray, gamma-ray and neutron. The shielding materials against mixture of gamma and neutron require an adequate composition of low-and high-Z elements [16]. In order to make the phosphate glasses effective for gamma-ray shield, the composition of the parent glass should alter with heavy metal oxides element such as bismuth oxide (Bi_2O_3). Addition of Bi_2O_3 in phosphate glasses may lower the phonon energy and hence the radiative properties of the glasses can be improved [17–19]. Marzouk and coworkers proposed that the addition of glass intermediate oxides such as Bi_2O_3 may results in the formation of P—O—Bi bonds [20]. This bonding formation may leads to improve the chemical durability and stability of the phosphate glasses. Normally, the linkages between PO_4 tetrahedra are dominate in phosphate glass network and these groups are connected to adjacent units by three out of four vertices; one unit may being place occupied by a terminal double-bonded oxygen's atom [21]. The networks of phosphate glasses can be classified by the oxygen-to-phosphorus ratio, which sets the number of linkages through bridging oxygens to neighboring P-tetrahedra. Thus, metaphosphate (O/P = 3) and polyphosphate (O/P > 3) glasses have structures that are based on chain-like phosphate anions that are themselves interconnected through terminal oxygens by ionic bonds with modifying cations. Q2 tetrahedra form the links within the chains and Q1 tetrahedra terminate the chains. The chain length of the average phosphate anion decreases with increasing O/P [22]. Even though the structure of the phosphate glasses is modified with the addition of heavy metal oxides, the glass structure still retains fourfold coordination throughout the full composition range from pure phosphate glass to the fully alkali oxide saturated orthophosphate MPO_4 (M = heavy metal). As heavy metal oxide is added to phosphate, the P_2O_5 structural group passes from P_3 to P_2 to P_1 to P_0 (the subscripts correspond to the number of bridging oxygens present in the phosphate tetrahedron) as the molar ratio of alkali oxide to P_2O_5 ($R = M_2O/P_2O_5$) passes from 0 to 1 to 2 and finally to 3 [23]. These modifications are similar to those taking place in a silicate network upon the addition of alkali oxide. The studies on optical, spectral and radiation shielding properties of high lead phosphate glasses have been characterize by some researcher [24]. This glass has radiation resistance at doses up to 107 R and has an optical transmission edge at 360 nm. The absorption coefficient of gamma radiation for the new glass is larger than that of dense silicate flints. Taking into account of this situation, these glasses can be potential candidates for applications as gamma ray radiation shielding materials.

The purpose of this research is to fabricate and characterize the physical, elastic and shielding properties of the novel ternary BaO-Bi_2O_3-P_2O_5 glass system. Phosphate glass containing alkali and alkaline earth metal oxides as modifiers have been found to be a stable glass system. Phosphorus is a solid glass former with polymer like structure of regular tetrahedron of PO_4^{3-} groups which are linked together with covalent bonding in chains or rings. These chains of phosphate have been subjected to modifications to various extents with addition of glass modifier. This is attended by decisive the shielding properties of the glass system in terms of the values of the mass attenuation coefficient and half value layer parameters which have been calculated using WinXCom software. Therefore, this BaO-Bi_2O_3-P_2O_5 glass system appears to be promising for use in the radiation shielding industry.

2. Materials and methods

2.1. Sample preparation

Glass samples of the system xBaO·(50 − x)Bi_2O_3·50P_2O_5 ($10 \le x \le 40$ wt%) were prepared by conventional melt quenching technique. Firstly, a suitable amounts of barium oxide, BaO (98.0% purity), bismuth oxide, Bi_2O_3 (98.0% purity) and phosphorus pentoxide, P_2O_5 (98.5% purity) were used to prepare the glass samples. About 30 g of batch for each different composition was mixed and dry mill to obtain homogenous mixture powder. Then, the mixture was melted in 50 ml porcelain crucible above 1000 °C for 2 h until homogeneous melt was obtained. The melt was poured onto stainless steel plate mold and annealed around 350 °C in pre-heated stainless steel mold for 30 min followed by slow cooling to room temperature in order to remove the internal stress of the glasses to avoid it from cracking. The glass samples were then cut by using the Isomet Low Speed Saw machine and polished using various grades of silicon carbide abrasive paper to obtain the parallel, smooth and clear surface for the ultrasonic measurement. The chemical composition of the glass samples are provided in Table 1.

2.2. Density and molar volume studies

Density and molar volume is the best implement to study the structural changes occurring in the glass matrix. These parameters are pretentious by the structural softening or compactness of the materials. The density of glass samples was measured and calculated by Archimedes principle using acetone as immersion liquid. Acetone was chosen as an immersion liquid because it has low surface tension. Due to this reason, it will discourage the air bubbles from stick to the sample during immersion. Besides, it will not react with or be absorbed by the glass samples. Archimedes principle is a well-established technique to analyze the density of glass samples. Generally, the density (ρ) of the glasses can be calculated as per the following relation:

Table 1
Chemical composition (in wt%), density (ρ) and molar volume (V_m) of BaO-Bi_2O_3-P_2O_5 glass system.

Glass sample	Composition in wt%			Density (ρ) (g/cm^3) ± 0.001	Molar volume (V_m) (cm^3) ± 0.04	Longitudinal (V_L) (m/s) ± 1	Shear (V_S) (m/s) ± 1
	BaO	Bi_2O_3	P_2O_5				
G1	40	10	50	2.82	73.03	4711	2722
G2	35	15	50	3.28	64.08	4345	2500
G3	30	20	50	3.65	58.95	4032	2270
G4	25	25	50	4.08	54.20	3750	2088
G5	20	30	50	4.41	51.78	3568	1983
G6	15	35	50	4.82	49.23	3394	1881
G7	10	40	50	5.25	47.35	3204	1792