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NAZIRUL NAZRIN SHAHROL NIDZAM (✉ nazirulnazrin@gmail.com)

University Putra Malaysia

Amandeep Sharma

Akal University Talwandi Sabo (Bathinda)

M.S. Jufa

University Putra Malaysia

M.K. Izzaty

Imperial College London

Imed Boukhris

Université de Sfax

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Mechanical and radiation shielding properties of CuO doped TeO₂-B₂O₃ glass system

S.N. Nazrin^{1*}, Amandeep Sharma², M.S. Jufa¹, M.K. Izzaty³, Imed Boukhris^{4,5}

¹Department of Physics, Faculty of Science, University Putra Malaysia, 43400, Serdang, Selangor, Malaysia

²Department of Physics, Akal University Talwandi Sabo (Bathinda), Punjab, India

³Imperial College London, United Kingdom

⁴Department of Physics, Faculty of Science, King Khalid University; P.O. Box 9004, Abha, Saudi Arabia

⁵Université de Sfax, Faculté des Sciences de Sfax, Département de Physique, Laboratoire des matériaux composites céramiques et polymères (LaMaCoP) Faculté des sciences de Sfax BP 805, Sfax 3000, Tunisie

Correspondence should be addressed to **S. N. Nazrin**

***nazirulnazrin@ymail.com**

Abstract

A series of borotellurite glass system doped with copper oxide was synthesized using the method of melt quenching. The density of the glass decreases whereas its molar volume increases in respect to copper oxide concentration. The amorphous nature of prepared glasses was proven with the utilisation of XRD spectra. Meanwhile, the glass samples' elastic properties are determined from the measurement of longitudinal and shear velocities using ultrasonic technique. The longitudinal modulus, shear modulus, bulk modulus and Young's modulus will show an irregular trend that fluctuates. FLUKA Monte Carlo code is implemented to determine the shielding features at gamma energy 0.3565, 0.6616, 0.8348 and 1.3325 MeV. Linear attenuation coefficients acquired from FLUKA and XCOM are found to be in good agreement with relative difference < 1%. The glass sample B₂O₃TeO₂CuO1 (with highest percentage of TeO₂) is found to be the best shielding glass material in this study.

Keywords: Tellurite glasses, density and molar volume, gamma-ray shielding features, Monte Carlo code

1. Introduction

Over the years, tellurite glasses have accumulated a notable reputation especially in the application of non-linear optical devices, optical fibre amplifiers, lasers, and solid-state batteries. This reputation can be attributed to the benefits of tellurium oxide-based glasses which is its wide glass forming range as well as useful properties. Tellurium oxide-based glasses are commonly known to have a high dielectric constant, low melting point, low phonon energy and good transmittance of infrared radiation. Te–O network and its glass forming ability can be modified with addition of metal oxides [1].

Marzouk (2009) [2] had reported in his study that by adding copper oxide into the glass system, it allows for an increment in elastic moduli, due to existing changes in network bond per unit volume, as well as a decrement in non-bridging oxygen. Cu ions with small ionic radius are able to enter the network of glass in the exact position that creates a bond that cross-link among the phosphates tetrahedral, improving the mechanical properties as well as the stability of the glass sample.

Elastic properties of the glass samples are investigated using ultrasonic method. The ultrasonic measurement is tested by using ultrasonic waves such as sound wave. The waves are introduced into some parts using an ultrasonic transducer which converts it into electrical impulses from the machine and into sound waves that can be converted back into electric impulses [3]. Consequently, the study of some mechanical properties such as longitudinal, shear, Young's and bulk moduli are applicable in order to understand the strength and behaviour of the glasses.

Nowadays, Monte Carlo based computations are getting more acknowledgement within the progress of various simulation methods, especially for the recently developed radiation shielding materials. A considerable amount of software packages, based upon Monte Carlo executions, having distinct features are available for the modelling of radiation transportation through composite materials. FLUKA (FLUktuierende KAskade) simulation code is very reliable as a tool that could be employed for the radiation shielding features of newly developing glasses [4,5]. The

developments that have been administered in FLUKA code while outlining the significant medical applications and some concerns regarding to CERN has been reported by Bohlen et al. (2014) [6]. Due the user-friendly nature in designing diverse configurations/geometries, the FLUKA code is also used in new applications that are based on accelerator as well as dosimetry, radiotherapy and neutrino physics [7].

The utilisation of FLUKA code in assessing the shielding qualities of glasses [4,5], polymers [8] and wood composites [9] has already been recognized to be fruitful through previous works. In present study, the glass system of $B_2O_3TeO_2CuO$ has been reported with this well-established code. The FLUKA results have also been compared to the XCOM database based on National Institute of Standards and Technology (NIST) [10], to authenticate the simulated results on radiation shielding characteristics of new glass system.

For that reason, the study on borotellurite glass system doped with copper oxide is undertaken since no researchers have implemented the investigation into its mechanical and radiation shielding properties. The reaction of copper oxide and tellurium oxide will be used in this project with the purpose to determine the efficacy of these elements with the aforementioned application.

2. Materials and Methods

2.1 Sample preparation

The borotellurite glass system doped with copper oxide was prepared using chemical powder of boron oxide (B_2O_3), tellurium oxide (TeO_2) and copper oxide (CuO). The amount of stoichiometric mixture of B_2O_3 , TeO_2 and CuO was weighed about 10 g.

The chemical compositions were weighed accurately using a digital electronic balance at different molar fractions of dopants. All the compositions were mixed using mortar and pestle to ensure it was mixed homogeneously.

The mixture composition was transferred into an alumina crucible after the mixing phase. The alumina crucible was initially cleaned with acetone and purified water to ensure that it was sterile and free of impurities. The homogeneous mixture in the alumina crucible was heated in the

electrical furnace for one hour at 400°C to eliminate any remaining water vapours. Then, the alumina crucible was moved into a second electrical furnace and heated for two hours at 900°C. This is known as the melting process which was to ensure the complete reaction between the chemical compositions.

Following that melting stage, the molten material was poured into a stainless-steel mould. The mould had been polished beforehand to eliminate impurities from the surface using silicon carbide waterproof abrasive paper. The polished mould was preheated at 400°C to prevent thermal shock from the temperature differences between the molten and the mould. The transfer of molten into the stainless steel mould was executed quickly, where the formation of an amorphous solid glass sample would be obtained and prevented the process of crystallization to occur at the same time.

The molten set in the stainless steel mould was annealed at 400°C for two hours. The annealing process aimed to relieve residual internal stresses during the manufacture. Finally, the glass sample was set aside to cool at room temperature for the whole night.

The glass samples were polished up to a thickness averaging on 5.0 mm for its respective elastic measurement using silicon carbide paper at different grid until the glass sample has a flat, smooth, and parallel surface. This made the samples efficient to be used in the required method characterization. Meanwhile, density and atomic number of the samples are used for the radiation measurement application.

2.2 Elastic properties

The elastic properties of the glass samples were studied according to the pulse-echo method. All measurements of the glass samples were taken several times to obtain an accurate measurement. The measurement was obtained from the elapse between initial time and receipt time for the pulse that appeared on the flaw detector screen with the Ritec Ram-5000 Snap Ultrasonic System at room temperature on a frequency of 5 MHz. Both longitudinal and shear velocities were calculated by using:

$$U = \frac{2x}{\Delta t} \quad (1)$$

where U is the velocity for each longitudinal and shear, x is the thickness of glass samples and Δt is the time taken between two consecutive echoes.

According to Wang (2012) [11], when the repetition rate of the frequency synthesizer and the reciprocal of the travel time in the glass sample are in an equally similar order, there will be an obvious overlap of echoes appearing on the screen of the oscilloscope. Hence, adjusting the frequency synthesizer allows for the two selected echoes to overlap accurately. X- or Y- cut high frequency transducer for longitudinal and transverse waves were used to provide the excitation and detection of the ultrasonic pulses. Then, the transducers were bonded to the glass samples by using couplant for the experiments.

The variations of sound velocity are closely related to the elastic moduli, showing structural stability and rigidity. Previously obtained ultrasonic velocities and density of glass samples were utilised in calculating the elastic moduli that include bulk modulus, shear modulus, longitudinal modulus and Young's modulus [12].

2.3 Radiation attenuation simulations through FLUKA Monte Carlo code

The gamma-ray shielding features of $B_2O_3TeO_2CuO$ glass system was thoroughly studied using FLUKA Monte Carlo code. The FLUKA version 2011.2c, installed on Linux Mint 19 operating system, was used to compute the shielding features displayed by the newly developed glasses as tabulated in Table 1.

Table 1: The elemental composition of investigated $B_2O_3TeO_2CuO$ glass system.

Glass name	Mass fraction of elements (%)			Density(g/cm ³)
	TeO ₂	B ₂ O ₃	CuO	
B ₂ O ₃ TeO ₂ CuO1	84.2469	15.7504	0.000	4.3725
B ₂ O ₃ TeO ₂ CuO2	83.9964	15.7031	0.3005	4.1005
B ₂ O ₃ TeO ₂ CuO3	83.7422	15.6555	0.6023	3.7091
B ₂ O ₃ TeO ₂ CuO4	83.4870	15.6078	0.9052	3.6444
B ₂ O ₃ TeO ₂ CuO5	83.2307	15.5599	1.2094	3.5042

Several useful commands that was used in designing the present simulation set-up includes BEAM (for defining the beam energy and particle type), BEAMPOS (for the direction and starting position of particles) and MATERIAL (for defining a chosen material and its properties). A user-friendly interface known as '*Flair*' have been used to handle the input/output data files [13]. A cubic sample material ($B_2O_3TeO_2CuO$ glass system) was considered through this interface by choosing gamma photons transporting along Z-direction. Typically, a beam consisting of 10^5 gamma photons at the specific energy (and momentum) of choice was projected onto the target glass composition. The chosen glass sample is the cause for attenuation in projected gamma photons. For this study specifically, the target glass cube with desired thickness was chosen with 10 cm in dimensions (each for height and breadth) along X and Y direction. Using *Flair*, the splash screen showing target geometry for a typical target composition with a thickness of 1 cm is presented in Figure 1.

With USRBDX score card used in defining a detector for assessment of fluence, the output results were collected for a run consisting of 5 cycles. All the data received through FLUKA were recorded with less than 1% statistical uncertainty. A deeper technicality of the code used in preparing input files are presented in FLUKA [14] and our recently published work [4,8,9].

The intensity of gamma radiations decreases when incident beam traverses via an absorbing material. This is attributed to the interaction processes, where the majority are photoelectric absorption, pair production, and Compton scattering, allowing for a complete or partial transfer of energy to atomic electrons of the interacting material. The decrement in the intensity of gamma through this interaction is shown by Lambert-Beer's law as follows:

$$\mu = -\frac{1}{x} \ln \frac{I}{I_0} \quad (2)$$

where ' μ ' denotes the linear attenuation coefficient (LAC) of the material [4, 8]. I_0 and I are the incident and the transmitted gamma intensities respectively, and ' x ' is thickness in cm of the material. From this equation, the slope of fitted lines derived from plotting fractional transmission intensity, $\ln(I/I_0)$, versus absorber (glass) thickness (x), gives the value of 'linear attenuation coefficient (μ)'.

Figure 1: Splash screen of *Flair*, for absorber sample (glass) having thickness 1 cm.

Another parameter that is important in identifying radiation shielding features is the Half-value layer (HVL). It is the required thickness of the absorbing material to reduce the incident intensity by 50% and is expressed mathematically as follow:

$$\text{HVL} = \frac{\ln 2}{\mu} \quad (3)$$

The value of this parameter is very useful to estimate a quick shielding calculation for newly developing shielding materials.

3. Results and Discussion

3.1 Structural Analysis: X-ray Diffraction (XRD)

In order to define the purity of the glass samples, XRD analysis is used in this study to identify whether the materials are in crystalline or amorphous state in nature. The determination is made by referring to the non-existence of peaks. In this study, the x-ray diffraction pattern of prepared glass sample, borotellurite glass system doped with copper oxide, was obtained through characterizing the powder form in the range of $20^\circ \leq \theta \leq 80^\circ$. Figure 2 show the XRD pattern for different composition of $[(\text{B}_2\text{O}_3)_{0.3}(\text{TeO}_2)_{0.7}]_{1-x}(\text{CuO})_x$ with molar fraction, $x=0, 0.005, 0.010, 0.015$ and 0.020 mol.

Figure 2 represent the absence of sharp peaks or any discrete sharp peaks for all molar fractions except for molar fraction at 0.000 mol. The appearance of broad hump can be seen at the position of 2θ between 20° to 30° . Rosmawati *et al.*, (2008) [15] had stated that if the constituent atoms are not regularly arranged, there will be no well-defined plane in or around the structure. Hence, the presence of XRD patterns of the glass sample indicates the amorphous nature of the glass system. However, in the case of molar fraction value of 0.000 mol, it shows a single crystalline peak in an amorphous matrix. According to Baizura and Yahya (2011) [16], the crystalline peak is suggested either due to the existence of formation $\alpha - \text{TeO}_2$ phase or $\gamma - \text{TeO}_2$ phase. Besides that, the existence of the peak can also be attributed to the insufficient length of time for the melting process during the synthesis of the glass samples to allow it to melt completely and form the molten.

Figure 2: XRD pattern for borotellurite doped copper oxide

3.2 Physical Analysis: Density and Molar Volume

The density of glass is a practical indicator to determine the degree of structural compactness, coordination change, the modification of geometrical configuration of glass network, and the variation of interstitial holes. Other than that, it is also required for the mechanical and radiation shielding properties application [17]. In this study, the density of the glass samples is determined with the application of Archimedes Principle at room temperature, in which distilled water are used as the immersion liquid. The results of molar volume and density are presented in Table 2.

Table 2: Density and molar volume of borotellurite glass system doped with various concentration of copper oxide

Molar Fraction, x (mol)	Density, (g/cm ³)	Molar Volume, (cm ³ /mol)
0.000	4.3725	30.3269
0.005	4.1005	32.4364
0.010	3.7091	35.9655
0.015	3.6443	36.7142
0.020	3.5042	38.2955

Based on Figure 3, the density of borotellurite glass system doped with copper oxide shows a decreasing trend as the concentration of copper oxide increases. According to Pavani *et al.*, (2011) [18], by introducing copper oxide, there is a change to the density of that glass system which is related to the density of structural units' formation. This is due to the contribution of additive property from each oxide within the glass system into the density of overall system. When a substance with lower molecular weight is substituted with substance that has a higher molecular weight, the net molecular weight decreases which results in a weak connectivity within the glass network. The molecular weight of copper used as glass modifier is 79.545 g/mol which is lighter in comparison to borotellurite that has a molecular weight of 229.217 g/mol. Therefore, the glass density will decrease as CuO content in borotellurite glass system increase. Besides that, Begum and Rajendran (2006) [19] had reported that the addition of small quantity of modifier content in the glass network will sever the Te-O-Te linkages. Depolymerisation of network based on the alteration of this linkage leads to the creation of Te-O-Te bridges with the emergence of non-bridging oxygen. As a result, this linkage will continue to break by the addition of the modifier content which causes the glass network to loosen in structure and reduce the density at the same time.

In this study, Figure 4 shows the increase in molar volume of the glass sample as the content of the copper oxide increases. The density and molar volume have shown opposite behaviour

(Eevonet *al.*, 2010) [20] and therefore when the density decreases, the molar volume will increase since molar volume is inversely proportional to the density.

Figure 3: Density of borotellurite doped copper oxide

Figure 4: Molar volume of borotellurite doped copper oxide

Apart from that, Halimah *et al.*, (2005) [3] had reported that the increasing bond length and interatomic spacing between atoms may affect the molar volume as it also increases. This is due to the more open ions being opened in the network as an effect of adding modifier ions into the glass spaces. On top of that, based on Azianty *et al.*, (2012) [21], the increasing numbers of non-bridging oxygen (NBO) that exists within the glass network also contributes to the increment of molar volume. Other than that, the differences in metal-oxygen bond were also proposed to give a similarly increasing effect to the molar volume of a glass system.

3.3 Elastic Properties

The ultrasonic echo overlap method of velocity is used in this study to obtain the elasticity parameters of present glass. From the pulse-echo technique, Y-cut transducer was employed for transverse modes while X-cut transducer for longitudinal mode [22]. According to Marzouk (2009) [2], the ultrasonic velocities were obtained through measuring time from the beginning to the receiving of pulse on the screen of a flaw detector.

The variations of longitudinal velocity, shear velocity and elastic moduli of the glass system with the function of glass modifier CuO content had been listed in Table 3.

Table 3: Longitudinal velocity (V_L), shear velocity (V_S), longitudinal modulus (L), shear modulus (G), bulk modulus (K), Young's modulus (E), Poisson's ratio (σ), hardness (H) and softening temperature T_s of borotellurite glass system doped with various concentration of copper oxide

x (mol)	V_L (m/s)	V_S (m/s)	L (GPa)	G (GPa)	K (GPa)	E (GPa)
0.000	8499	4788	315.84	100.20	182.2	254.11
0.005	7140	4288	209.04	75.39	108.5	183.65
0.010	7411	4351	203.72	70.22	110.1	173.72
0.015	7463	4355	202.97	69.12	110.8	171.66
0.020	7612	4387	203.04	67.44	113.1	168.78

According to Khanisani and Sidek (2014) [23], the basic structural consideration of glass networks will result in variations in the ultrasonic velocities and the elastic moduli of the glass sample due to its bond strength, packing density, cross-linking of units, and coordination number.

As shown in Figure 5, ultrasonic velocities among all of the present glass systems are seen to fluctuate according to the content of modifier oxide. The value of longitudinal velocity is seen to decrease from 8499 ms^{-1} at $x=0.000 \text{ mol}$ to 7140 ms^{-1} at $x=0.005 \text{ mol}$, and then increase at $x=0.005$ until 0.020 mol with longitudinal value from 7140 to 7612 ms^{-1} . Meanwhile for shear velocity, it follows the similar trend to longitudinal velocity as the modifier content increases. At $x=0.000$ to $x=0.005 \text{ mol}$, the longitudinal velocity decreases from 4788 to 4288 ms^{-1} and increase from 4288 to 4387 ms^{-1} at molar fraction $x=0.005$ until $x=0.020 \text{ mol}$.

Figure 5: Longitudinal velocity (V_L) and shear velocity (V_S) of borotellurite doped copper oxide

The variations of shear and longitudinal velocity depend on the elastic properties and the rigidity of glass as it changes. Therefore, the decrement in value for longitudinal and shear velocities can be attributed to the decreasing rigidity and hardness of the glass sample. The effect of chemical composition causes for the bridging oxygen to be converted into non-bridging oxygen (NBO) in which the tellurite network bond is further broken down by the lack rigidity of the glass sample.

Besides that, the conversion of NBO prompted for more open ions to be opened within the network as more modifier ions are added into the glass system [24]. Khanisani and Sidek (2014) [23] had reported that adding oxides into a glass network will cause the cation ions of oxides to enter interstitially in the glass networks in order to modify the B-O-B linkage to B-O-Cu bonds. This conversion of linkage leads to the decreasing of packing density as well as an increment in molar volume, further expanding the glass network.

Hence, the decreasing ultrasonic velocity in this study can be due to the reduction of rigidity and contribute to the formation of new linkage. Besides that, Elok and Aboudeif (2016) [22] had stated that the increment of the concentration molar fraction tends to be of a higher rigidity of the glass network and decreases the NBO concentration which results to an increment of both ultrasonic velocities. Both velocities in the studied glass system were found to be increasing due to the transformation of coordination that affects the formation of more bridging oxygen [25].

Shear modulus, G from Figure 6 shows a large decrease initially from 100.20 GPa at $x=0.000$ mol to 75.39 GPa at $x=0.005$ mol and remains mostly constant for molar fraction greater than $x=0.010$ mol. Meanwhile, the longitudinal modulus, L also exhibit a large decrease initially from $x=0.000$ mol to $x=0.005$ mol with the value of 315.84 to 209.04 GPa, followed by further decrement until at $x=0.015$ mol which the value is 202.97 GPa. However, a small increment can be observed from 202.97 GPa at $x=0.015$ mol to 203.04 GPa at $x=0.020$ mol.

Figure 6: Longitudinal modulus (L) and shear modulus (G) of borotellurite doped copper

The initial drop in both shear and longitudinal modulus is due to increasing numbers of NBO. This reduces the connectivity and the rigidity of the glass network that distract the environment of the network glass structure. Meanwhile, according to Table 3, an increment at $x=0.020$ mol for longitudinal modulus indicates some formation of competition between non-bridging oxygen and bridging oxygen within the glass network due to the increase intensity of TeO_4 and accompanied by TeO_3 trigonal pyramid [16]. In general, the elastic moduli of shear modulus and longitudinal modulus decreases with the increase of CuO concentration in this present glass which can also be connected to the average strength of the bond [26].

The trend for bulk modulus, K and Young's modulus, E in this study is obtained from Figure 7. Bulk modulus shows decreasing trend from 182.20 to 108.50 GPa at the initial molar fraction of $x=0.000$ mol to $x=0.005$ mol. However, further increment on the concentration of CuO content up to $x=0.020$ mol resulted to the increment of bulk modulus which reached up to 113.10 GPa. Meanwhile for Young's modulus, as the concentration of CuO increases from $x=0.000$ mol until $x=0.020$ mol, the value for Young's modulus decreases.

Figure 7: Bulk modulus (K) and Young's modulus (E) of borotellurite doped copper oxide

In the present glass system, the bulk modulus initially decreases as the concentration of CuO increases. Based on Begum and Rajendran (2006) [27], it can be observed that the bulk modulus is dependent to the bond stretching force constant, the cross-link density of the glass system and the molar atomic volume. Apart from that, the bonding type may also play an important role to determine the bulk modulus. Thus, the change in coordination number of Te from 4 to 3, known as the TeO_3 trigonal pyramid is due to the addition of the modifier content. Hence, reducing the rigidity of the network. According to Halimah *et al.*, (2010) [12], the decrease in bulk modulus and Young's modulus is a result of the increasing group of non-bridging oxygen that have more open structure. Based on this present glass study, the CuO functions as network modifier and thus breaking the network structure. Besides the rigidity of the glass system, the increment of bulk modulus can also be conducted by strong covalent bond formed which result to the effect of increasing bridging oxygen [21]. The strong Cu-O ion covalent bond in borotellurite glass system doped with copper oxide had been influenced by the bridging oxygen.

3.4 Radiation shielding characteristics of $\text{B}_2\text{O}_3\text{TeO}_2\text{CuO}$ glasses

Alternatively, the employment of FLUKA based simulation code is an equally essential aspect in this study in order to calculate the linear attenuation coefficients for $\text{B}_2\text{O}_3\text{TeO}_2\text{CuO}$ glass system. From equation 2, the transmission value of fractional intensity decreases with the increase of absorber thickness, presented in negative sign for the slope (attenuation coefficient). For example, in Figure 8, at 0.3565 MeV, the best fit equation of obtained straight line is $y = -0.53114x - 9.38417\text{E-}4$, where the value of slope (0.53114) is the linear attenuation coefficient (cm^{-1}) of $\text{B}_2\text{O}_3\text{TeO}_2\text{CuO1}$. The plots of fractional transmission intensity with sample thickness corresponding to gamma energies is displayed in Figure 8 for glass sample $\text{B}_2\text{O}_3\text{TeO}_2\text{CuO1}$. The parameters of differently fitted straight lines through obtained data points have been listed in Table 4 and shown through Figure 9 for all the samples prepared belonging to $\text{B}_2\text{O}_3\text{TeO}_2\text{CuO}$ glass system.

Figure 8: Representation of fractional transmission intensity of gamma-rays as a function of glass ($B_2O_3TeO_2CuO_1$) thickness

Table 4: Parameters of data fitting for plots of sample thickness versus $\ln(I/I_0)$ for different glasses, as shown through figures 8 and 9 for $B_2O_3TeO_2CuO$ system.

	B₂O₃TeO₂CuO1			B₂O₃TeO₂CuO2			B₂O₃TeO₂CuO3			B₂O₃TeO₂CuO4			B₂O₃TeO₂CuO5		
Ener gy (Me V)	Intercep t	Slope	R- Squar e	Intercept	Slope	R- Squar e	Intercep t	Slope	R- Squar e	Intercep t	Slope	R- Squa re	Intercep t	Slope	R- Squa re
0.356 5	- 9.38417E -4	- 0.531 14	1	0.00136	- 0.498 97	0.999 98	0.00203	- 0.451 22	0.999 99	0.00127	- 0.442 79	0.999 99	-0.00422	- 0.423 19	0.999 98
0.661 6	-0.00109	- 0.327 2	1	0.00267	- 0.308 45	0.999 99	-0.00251	- 0.277 08	0.999 95	- 3.11071 E-4	- 0.272 95	1	3.10781 E-4	- 0.263 4	0.999 98
0.834 8	5.83895E -4	- 0.284 68	0.999 98	-0.00203	- 0.266 11	0.999 99	- 8.76511 E-4	- 0.241 31	0.999 99	- 3.42525 E-4	- 0.237 51	0.999 99	-0.00116	- 0.227 67	0.999 98
1.332 5	-0.00228	- 0.217 74	0.999 99	-0.00155	- 0.204 46	1	-0.0011	- 0.185 15	0.999 97	-0.00211	- 0.181 47	0.999 99	- 3.71836 E-5	- 0.175 26	0.999 98

Figure 9: Variation of fractional transmission intensity of gamma-rays due to absorption in B₂O₃TeO₂CuO₂, B₂O₃TeO₂CuO₃, B₂O₃TeO₂CuO₄ and B₂O₃TeO₂CuO₅ samples

Table 5: Comparison of linear attenuation coefficients (LAC) obtained from FLUKA and XCOM database.

Energy (MeV)	Linear attenuation coefficient (cm ⁻¹)														
	B ₂ O ₃ TeO ₂ CuO1			B ₂ O ₃ TeO ₂ CuO2			B ₂ O ₃ TeO ₂ CuO3			B ₂ O ₃ TeO ₂ CuO4			B ₂ O ₃ TeO ₂ CuO5		
	FLUKA	XCOM	RD*	FLUKA	XCOM	RD	FLUKA	XCOM	RD	FLUKA	XCOM	RD	FLUKA	XCOM	RD
0.3565	0.5311	0.5330	0.36	0.4990	0.4999	0.18	0.4512	0.4518	0.13	0.4428	0.4435	0.16	0.4232	0.4265	0.77
0.6616	0.3272	0.3286	0.43	0.3084	0.3082	0.06	0.2771	0.2787	0.57	0.2729	0.2738	0.33	0.2634	0.2633	0.04
0.8348	0.2846	0.2853	0.25	0.2661	0.2676	0.56	0.2413	0.2420	0.29	0.2375	0.2378	0.13	0.2277	0.2286	0.39
1.3325	0.2177	0.2191	0.64	0.2045	0.2054	0.44	0.1851	0.1859	0.43	0.1815	0.1826	0.60	0.1753	0.1756	0.17

*Percentage relative difference (RD) between FLUKA and XCOM data

The linear attenuation coefficient, derived from FLUKA computations, of the five studied sample glasses and four different energies has been shown through Table 5 and in Figure 10. The NIST: XCOM based linear attenuation coefficient values are also provided in this table. The relative difference of FLUKA values with respect to XCOM data is found to be <1% for all of the cases.

Figure 10: Comparison of linear attenuation coefficients (cm^{-1}) of prepared glasses at gamma-ray energies 0.3565, 0.6616, 0.8348, 1.3325 MeV

The agreement of LAC values through two different approaches validates the simulation results reported for new glass system. The LAC describes the general capability for a material to attenuate penetrating radiation, with a larger value signifying a better protection. The greatest LAC values occur at the lowest tested energy 0.3565 MeV, while the smallest values occur at the highest tested energy i.e. 1.3325 MeV. Meanwhile at 0.3565 MeV, B₂O₃TeO₂CuO₁'s LAC is equal to 0.5311 cm^{-1} and B₂O₃TeO₂CuO₅'s LAC is equal to 0.4232 cm^{-1} , while at 1.3325 MeV, their LAC values are equal to 0.2177 cm^{-1} and 0.1753 cm^{-1} , respectively. Within this energy range, the LAC values

decrease gradually along with increasing energy. For instance, the LAC values for $B_2O_3TeO_2CuO_3$ decreases from 0.4512 cm^{-1} to 0.2771 cm^{-1} , 0.2413 cm^{-1} , and 0.1851 cm^{-1} at energies of 0.3565, 0.6616, 0.8348 and 1.3325 MeV, respectively. These trends are the result of greater penetration power of gamma photons at greater energies. Conclusively, it is understood that the shielding capability of these glasses decreases as the gamma photons energy increases. On the other hand, at any single energy, the LAC values follow the sequence of $B_2O_3TeO_2CuO_5 < B_2O_3TeO_2CuO_4 < B_2O_3TeO_2CuO_3 < B_2O_3TeO_2CuO_2 < B_2O_3TeO_2CuO_1$, such as at 0.6616 MeV, where the LAC values are 0.2634 cm^{-1} , 0.2729 cm^{-1} , 0.2771 cm^{-1} , 0.3084 cm^{-1} , and 0.3272 cm^{-1} for $B_2O_3TeO_2CuO_5$, $B_2O_3TeO_2CuO_4$, $B_2O_3TeO_2CuO_3$, $B_2O_3TeO_2CuO_2$, $B_2O_3TeO_2CuO_1$ respectively. These results prove that $B_2O_3TeO_2CuO_1$, the glass with the highest TeO_2 content, has the greatest LAC at all tested energies, therefore possess the best shielding characteristics.

Other equally vital parameter in estimating any shielding requirement is half-value layer (given through equation 3), which corresponds to the thickness of absorbing material that will faithfully attenuate half of the original gamma intensity. Lowering the value of half value layer (HVL) infers that a thinner glass thickness is required to lower the intensity of photon by 50%. The calculated values of HVL as a function of gamma energy for five glass samples have been shown in Figure 11. The value of HVL at 1.3325 MeV is greater than those of 0.3565, 0.6616, 0.8348 MeV, while the value at 0.3565 MeV energy corresponds to the lowest value of HVL. As an example, the glass sample $B_2O_3TeO_2CuO_1$ has the HVL values that are about 1.31, 2.12, 2.44 and 3.18 cm at 0.3565, 0.6616, 0.8348 and 1.3325 MeV respectively.

Among the five glass samples investigated in this study, the HVL values increases following the sequence as such: $B_2O_3TeO_2CuO_1$, $B_2O_3TeO_2CuO_2$, $B_2O_3TeO_2CuO_3$, $B_2O_3TeO_2CuO_4$ and $B_2O_3TeO_2CuO_5$. Thus, on the basis of thickness (cm) of the glass, the best shielding material is able to be determined from the aforementioned sequence. Glass sample $B_2O_3TeO_2CuO_1$ was found to have smaller HVL values at all investigated energies because of the higher percentage of Tellurium, higher Z (52) relatively to other elements in this study. Thus, amplifying the possibilities of interaction between gamma-rays and absorbing glass material.

Figure 11: Comparison of Half Value Layer (HVL) of $B_2O_3TeO_2CuO$ glass system at different gamma-ray energies

In conjunction, it can also be inferred that high density glasses have smaller value of HVL, thus agreeing with the preceding findings on $(100-x)[0.5Li_2O-0.1B_2O_3-0.4P_2O_5]-xTeO_2$ glass system done by Askin et al (2019) [5]. The overall trend of LAC and HVL indicates that the decreasing density of glass composition, done by adding more CuO, deteriorates the attenuation capability of $B_2O_3TeO_2CuO$ glass system. Thus, it is worth to mention here that $B_2O_3TeO_2CuO1$ sample, among the investigated glasses, has the greatest potential for gamma radiation shielding.

4. Conclusion

A series of borotellurite glass system doped with copper oxide, denoted by a chemical formula $[(B_2O_3)_{0.3}(TeO_2)_{0.7}]_{1-x}(CuO)_x$ where $x = 0, 0.005, 0.010, 0.015$ and 0.020 were synthesized by the method of melt quenching. In general, certain characteristics of the glass samples, such as the structural, physical, mechanical and radiation shielding properties, are dependent on the composite that makes up the glass system. The X-ray diffraction (XRD) analysis proved that the glass samples

were all amorphous in nature as the observation showed no sharp peak is seen except for molar fraction at $x = 0$ mol. The glass samples decreased in density whereas increased in molar volume when the concentration of copper oxide was increased from $x = 0$ until $x = 0.020$ mol. It is a result of the increasing number of non-bridging oxygen and the lighter atomic mass of copper in comparison to boron and tellurium. Furthermore, the elastic properties were studied by the evaluation of longitudinal and shear velocities employing pulse echo overlap technique at 5 MHz. The initial decrease or highest concentration of tellurium oxide represented outstanding mechanical properties employing the elastic moduli parameters (bulk modulus (182.20 GPa), longitudinal modulus (315.84 GPa), shear modulus (100.20 GPa) and Young's modulus (254.11 GPa)). FLUKA Monte Carlo code was employed for the shielding features of $B_2O_3TeO_2CuO$ glass system at gamma energy 0.3565, 0.6616, 0.8348 and 1.3325 MeV. Linear attenuation coefficients obtained with FLUKA and XCOM are found to be in a good agreement with relative difference $< 1\%$. The prepared glass sample $B_2O_3TeO_2CuO1$ (with highest percentage of TeO_2) is found to be the best shielding glass material out of all samples investigated in this study.

Therefore, borotellurite without existence of copper oxide has brought upon the most efficient glass sample for mechanical properties (strength of the glass) and radiation shielding properties as well. Also, tellurium oxide is believed to promote the radiation shielding applications of new glasses.

Declarations

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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