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Acoustic and Gamma-ray attenuation studies of K_2O-PbO-SiO_2 glass system

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Abstract

Acoustic and gamma ray investigations of K_2O-PbO-SiO_2 glass system have been carried out to explore their structure and gamma-ray attenuation properties. Acoustic studies are carried out to study the effect of concentration of lead oxide on the connectivity of the glass structure. Elastic properties are estimated for getting information regarding the dimensionality and rigidity of the network. Gamma -ray mass attenuation coefficient is calculated theoretically as well as experimentally at 511KeV, 662KeV &1274.0KeV photon energy values. Experimental values of Gamma-ray attenuation coefficients are compared to theoretical values computed using NIST-XCOM software. Results of half value layer (HVL) for prepared glasses are compared with ferrite concrete to explore the scope of lead-based glasses as suitable candidates for radiation shielding materials.

Keywords: Glasses, Half Value Layer, Mass Attenuation Coefficient, Radiation Shielding Materials, Ultrasonic.

Introduction

Radiation is a form of energy that is emitted in the form of electromagnetic waves or particles from the source and the radiations emitting from these sources can penetrate depending on their energy through the given material on which they are incident.Various types of ionizing radiations like alpha particles, beta particles and gamma rays possess different characteristics and can have devastating effects on human beings as well as on the environment. Alpha particles consist of positively charged ions (Helium Nucleus) because of which these particles are considered to be heavier particles. As these particles are heavier and energetic their speed is less, and they utilize their energy over a short distance. Although, alpha particles can only affect the internal body of a human being but not the outer body because these particles don't have enough energy to penetrate the outer body of a human being. While inhaling or swallowing the alpha particle gets into the body it can damage the tissues and cells of the body. Beta particles are the fast-moving beam of electrons and are less harmful to tissues and cells, but these particles penetrate more as compared to alpha particles which may cause skin burns.

Gamma rays have much higher energy and are neutral. These rays are very harmful and can penetrate the barriers easily as compared to alpha and beta particles. Gamma rays have high speed and penetration power due to which these rays can travel a larger distance.

With the fast-growing technology, the amount of radiation used in everyday life is tremendously increasing, which is creating a disastrous effect on the environment and living organisms. Taking into concern the harmful effects of radiation, there's a great need to find promising and cost-effective shielding material to protect all of them[1].

The study of lead-based glasses is particularly important in the context of radiation shielding materials [2,3]. Due to their high density and effective attenuation of radiation, lead-based glasses have been used as a key component in radiation shielding for various applications, including medical imaging equipment, nuclear facilities, and industrial applications. Understanding their properties and behavior under radiation exposure is crucial for optimizing their effectiveness and ensuring the safety of personnel working in these environments. As advancements in radiation technology continue, the study of lead-based glasses remains vital for developing even more efficient and reliable radiation shielding materials.

Heavy metal oxide glasses consisting of Pb and Bi are drawing considerable interest and have been the subject of extensive research for several years due to their unique thermal, mechanical and optical properties. Moreover, these glasses are also advantageous over conventional materials used for the purpose of gamma ray attenuation due to their low weight requirement and transparency to visible light[4].

For technical applications of heavy metal oxide glasses the knowledge of elastic properties is important since it can provide us insight into understanding the rigidity, structure and dynamics of the system[5].

The author has undertaken the current research work to explore the scope of potassium lead silicate glasses as radiation shielding materials based upon Gamma (γ)–ray mass attenuation and acoustic investigations.

Materials and Methods

Theoretical Calculation

The attenuation coefficient can be expressed as per the following relation

$$\frac{\mu}{\rho} = \frac{\log\frac{I_0}{I}}{\rho t} \quad .... \quad 1$$

Where μ denotes linear mass attenuation coefficient, ρ denotes the density, I_0, I present intensity of incident and transmitted radiation. The thickness of the prepared system is presented by t.

Further, Half value layer (HVL) estimated from linear attenuation (μ) coefficient is given as:

$$HVLayer=0.6930/\mu \quad .... \quad 2$$

V_g(Molar Volume)of the prepared system estimated form molar mass (W) and density is given as

$$V_g=W/\rho \quad .... \quad 3$$

W is molar mass as per equation given below:

$$W=0.10W_1+yW_2+(1-0.10-y)\,W_3 \quad .... \quad 4$$

Where y is the mole fraction, W_1, W_2 and W_3 are the molar mass of oxides of potassium, lead and silicate respectively.

Various elastic properties for the prepared system mainly longitudinal modulus (L), Shear modulus (G), Bulk modulus (K), Young's modulus (E), Poisson's ratio (σ) and Debye temperature (θ_D)of the glasses are estimated as given below:

$$L=\rho V_L^2 \quad .... \quad 5$$

$$G=\rho V_T \quad .... \quad 6$$

$$K=L-(4/3)G \quad .... \quad 7$$

$$E=(1+\sigma)2G \quad .... \quad 8$$

$$\sigma=(L-2G)/2(L-G) \quad .... \quad 9$$

$$\theta_D=(h/k)[(3q\rho N_A)/(4\pi M)]^{1/3}V_m \quad .... 10$$

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where V_L, V_T and V_m are longitudinal, shear and mean velocities, respectively[1].

Experimental techniques

The melt and the quenching process was followed for the synthesis of $0.10K_2OxPbO(1-x) SiO_2$system. The mole fraction (x) for the component PbO chose from 0.45 to 0.65. Appropriate chemicals of AR grade were mixed and melted at 1100ºC followed by annealing at 250ºC to remove thermal residues. For gamma ray shielding samples were prepared for gamma ray shielding that was cylindrical and polished using SiC and Al paper.

To get an idea regarding the amorphous or crystalline nature of the prepared system powdered form of glass samples were taken for XRD studies. CuKα radiation with Philips (PW 1710) diffractometer utilized to scan at the rate (2h/s) of 0.03 in the angular region of 5.01º up to 60º. The absence of any peak in the diffraction pattern demonstrates the amorphous nature of the glass samples.

Acoustic measurements were performed by Pulse-Echo method for the cylindrical samples with Matec SR/9010 Digitizer and SR/9000 synthesizer) at 5MHertz. The order of time resolution was $5X10^{-9}$ sec and the measurement accuracy of the sound velocity was of the order ±0.20%.

NaI(TI) crystal having a resolution of 12.50% at 662.0 keV with Multichannel Analyzer using narrow beam transmission method was used for estimating attenuation coefficients of the synthesized glass system.The cylindrical container made up of lead was used to hold the radioactive sources (^{137}Cs and ^{60}Co). The sources used were having activities upto 5 mCi and the overall acceptance angle at the detector was 2.32º.

A narrow symmetrical area ranging centroid of the photo peak was selected for measuring intensities of the incident and transmitted gamma ray photons for a fixed preset time. The measure under each peak provides the intensity of gamma -ray photon.

Results and Discussion

Density and molar volume studies

Density and molar volume play crucial roles in lead-based glasses. The high density of lead contributes to their effective radiation shielding properties, making them suitable for various applications requiring gamma ray attenuation. Molar volume influences the glass's structure, affecting its properties like transparency and refractive index. Chemical compositions, density value and thickness of the glass system are given in Table 1.

Table 1. Constituents, density and thickness of the glasses

No.	Constituents (mole fraction)			Density (g/cm³)	Thickness t (cm)
	PbO	K_2O	SiO_2		
1	0.45	0.1	0.45	5.35	1.589
2	0.5	0.1	0.4	5.49	1.567
3	0.55	0.1	0.35	5.53	1.452
4	0.6	0.1	0.3	5.57	1.549
5	0.65	0.1	0.25	5.7	1.486

Elastic Properties

The elastic moduli are a function of the square of velocity and the variation of ultrasonic velocities as a function of composition provides important information regarding the dimensionality and rigidity of the network[6]. The variation of longitudinal (V_L) and transverse (V_T) sound velocities as a function of the mole fraction of PbO are shown in Fig. 1

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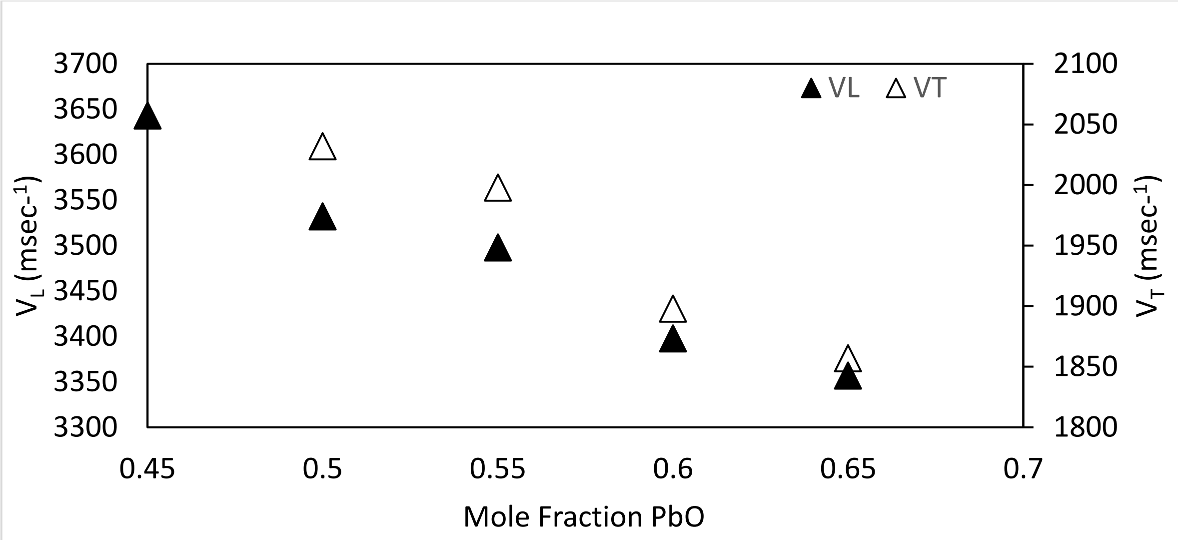

Figure 1. Longitudinal (V_L) and transverse (V_T) sound velocities as a function of mole fraction of PbO

Fig. 2 presents elastic moduli as a function of PbO content. As can be observed from Fig. 1 and 2 the longitudinal (V_L), transverse (V_T) and elastic moduli decrease with the addition of PbO content for investigated glass systems[7].

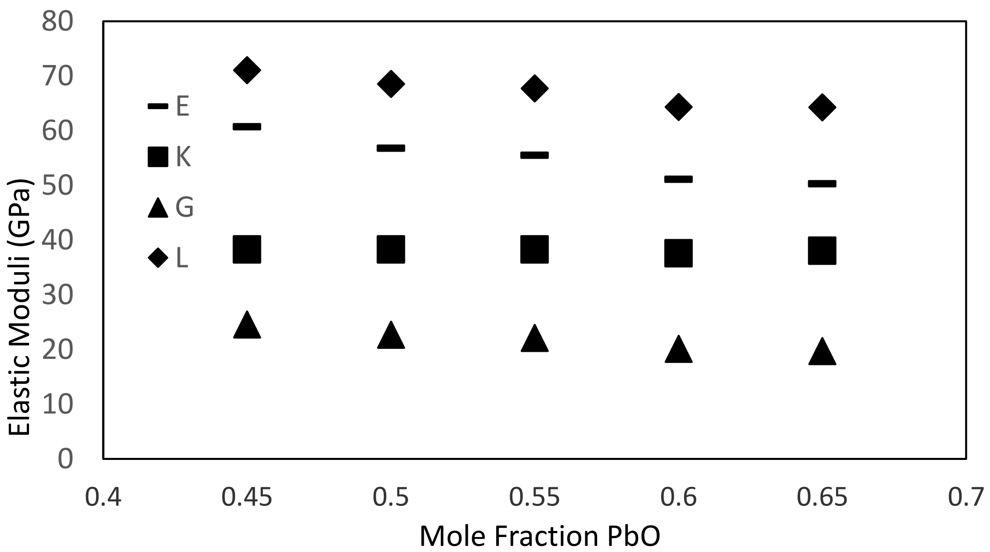

Figure 2. Elastic moduli as a function of mole fraction of PbO

The observed trends for the variation of acoustic velocities and elastic modulus are due to decrease in the network connectivity and dimensionality which can be assigned to the formation of non-bridging oxygen atoms (NBO's) [8].

The variation of Debye temperature and Poisson's ratio and with mole fraction of PbO is shown in Fig. 3. Ratio of transverse to linear strains for a linear stress gives the measure of Poisson's ratio. Further, Poisson's ratio gives the idea regarding the dimensionality of glass structure. The Poisson's ratio is having least value in the case of three-dimensional network and maximum value in the case of one-dimensional network structure. For two-dimensional network the value is more than three dimensional and less than one dimensional network. The above trends are due to reason that the bond concentration resisting a transverse deformation reduces from three-dimensional network to one dimensional network[9,10].

From Fig. 3 the Poisson's ratio shows increment with the addition of more and more PbO content suggesting that the formation of more non-bridging oxygen atoms.

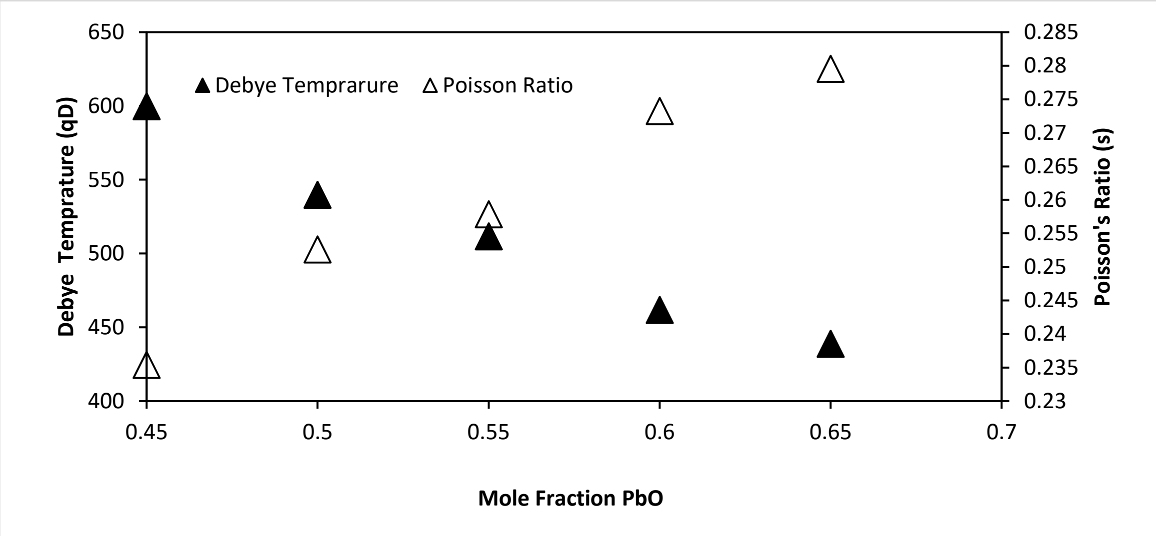

Figure 3. Debye temperature and Poisson's ratio as a function of mole fraction of PbO

The decrease in Debye temperature also depicts that the compactness of the structure decreases resulting in increase in mean sound velocity. The above observation is also consistent with the molar volume studies as shown in Fig. 4.

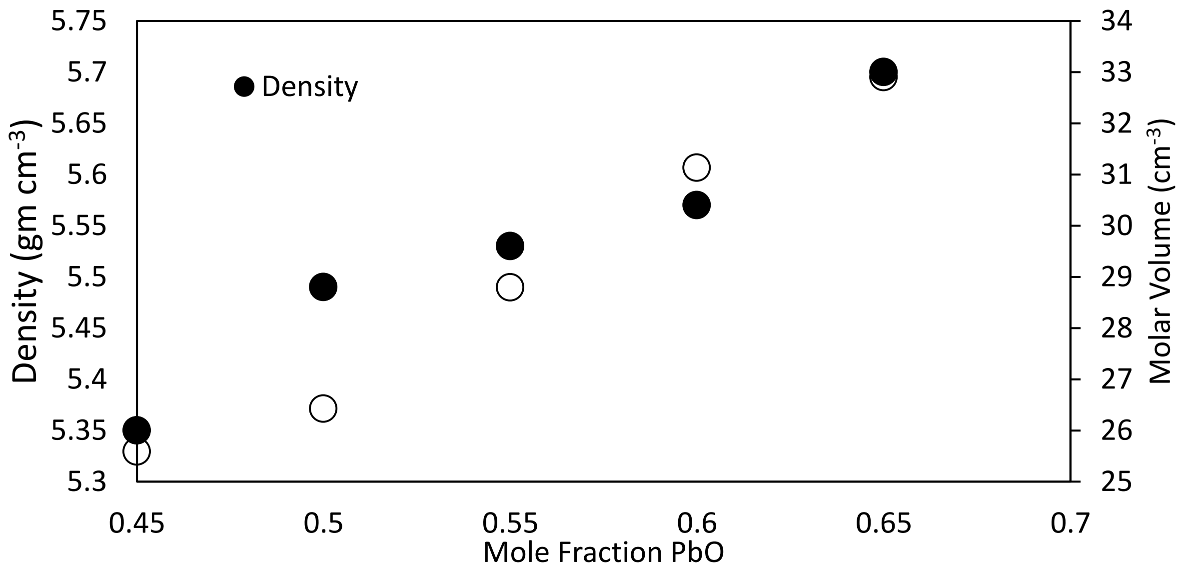

Figure 4. Density & molar volume vs mole fraction of Lead Oxide

Gamma-ray shielding properties

Incident and transmitted gamma ray intensities are estimated for finding mass attenuations [11-13]. The values have been compared with the theoretical results as shown in Fig. 5. NIST XCOM software has been used to estimate the theoretical values of mass attenuation coefficient[13-20]. The mass attenuation coefficient is a crucial parameter in the field of gamma ray shielding materials[21-23]. It quantifies the material's ability to attenuate or reduce the intensity of gamma rays as they pass through it. This coefficient takes into account both the material's density and its interaction properties with gamma rays, providing insight into the material's effectiveness as a shield. Selecting materials with higher mass attenuation coefficients ensures superior gamma ray absorption, aiding in the design and construction of efficient and safe shielding solutions for various applications, including nuclear facilities, medical imaging, and industrial settings. Fig.5 depicts that the mass attenuation coefficient increases with increase in mole fraction of PbO. This observation is due to the fact that with the addition of heavy metal the density of the system increases as shown in Fig. 4. Further the molar volume trends as shown in Fig. 4 depict that the compactness of the glass structure decreases and becomes more and more open with the addition of heavy metal oxide.

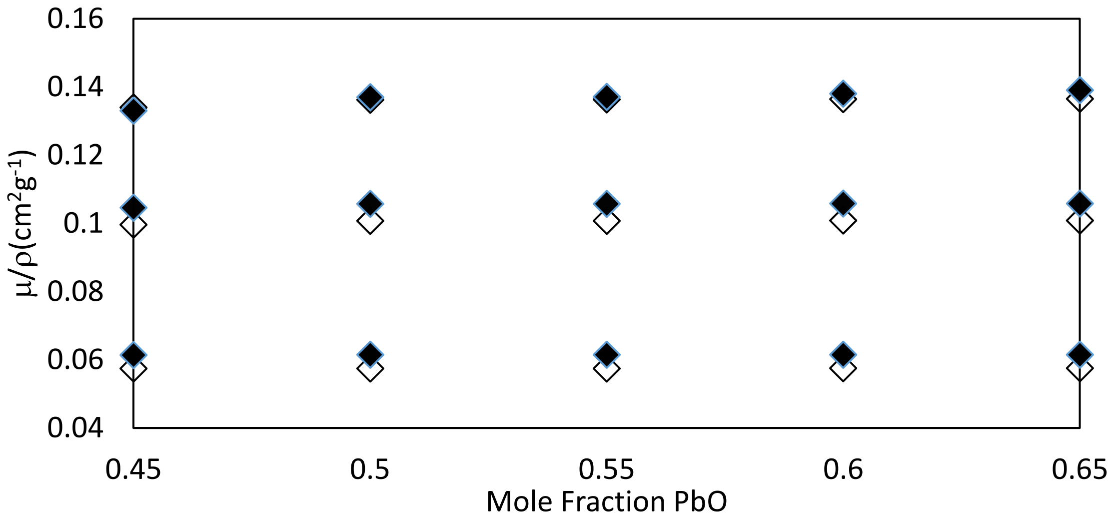

Figure 5. Experimental & theoretical attenuation coefficient vs Lead oxide at 511.0,662.0 and 1274.0 KeV photon energies.

Chemical compositions of some standard radiation shielding concrete ferrite is given in Table .2

Table 2. Chemical composition of Ferrite concrete

Concrete	Weight fraction of elements							
	H	O	Mg	Al	Si	S	Ca	Fe
Ferrite	0.028	0.4554	0.0019	0.0038	0.0128	0.0007	0.0595	0.4378

The half layer values for the ferrite at 511, 662 and 1274 KeV is compared with the prepared glass system as shown in Fig. 6.

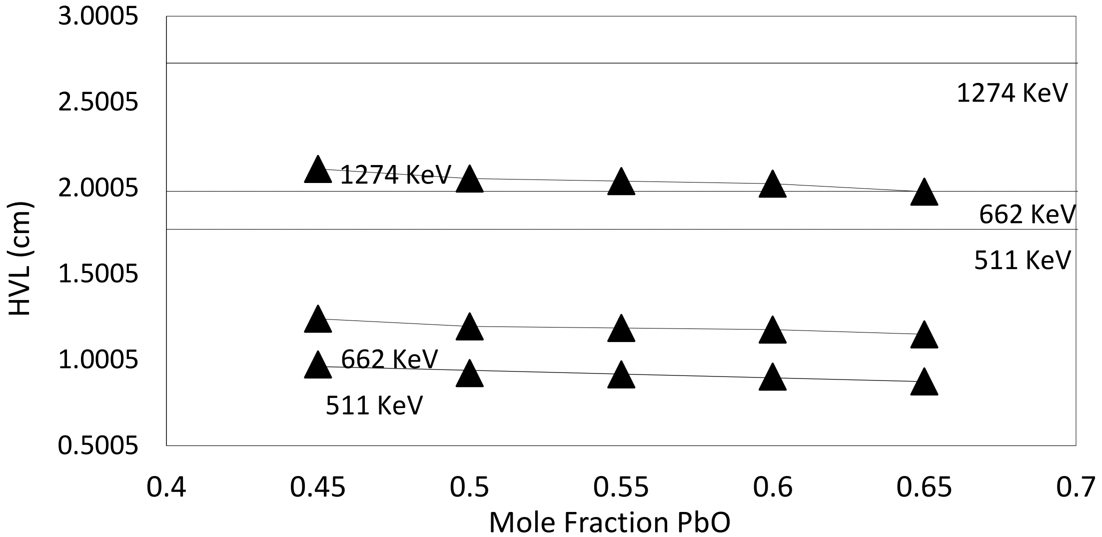

Figure 6. Half Vale Layer (HVL) of prepared samples and ferrite concrete vs lead oxide at 511.0,662.0 and 1274.0 KeV.

Conclusions

γ–ray investigation for K_2O PbO SiO_2 glasses is undertaken experimentally and theoretically at various gamma ray photon energy values. The half value layer for the prepared glasses decreases with an increase in the mole fraction of lead indicating that a lower thickness of the material is required to reduce the intensity of the gamma rays to 50% of its initial value. Comparison of gamma-ray shielding properties with ferrite shows that these prepared glass systems have improved γ–ray shielding properties as evidenced by their low thickness as well as a large value of mass attenuation coefficient.

Further, acoustic investigations reveal that with an increase in the lead content the connectivity of the network structure decreases and the structure becomes more open as evident from molar volume studies.

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Author's declaration:

- Conflicts of Interest: None.
- I hereby confirm that all the Figures and Tables in the manuscript are mine. Furthermore, any Figures and images, that are not mine, have been included with the necessary permission for re-publication, which is attached to the manuscript.
- Ethical Clearance: The project was approved by the local ethical committee at University of Phagwara.

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استكشاف خصائص التوهين الصوتي وأشعة جاما داخل النظام الزجاجي-K2O-PbO SiO2

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الخلاصة

تم إجراء فحوصات صوتية وأشعة جاما لنظام الزجاج K2O-PbO-SiO2 لاستكشاف بنيته وخصائص التوهين بأشعة جاما. أجريت دراسات صوتية لدراسة تأثير تركيز أكسيد الرصاص على توصيل الهيكل الزجاجي. تم تقدير الخصائص المرنة للحصول على معلومات تتعلق بأبعاد الشبكة وصلابتها. تم حساب معامل التوهين الشامل لأشعة جاما نظريًا وتجريبيًا عند قيم طاقة الفوتون 511 كيلو فولت، 662 كيلو فولت و1274.0 كيلو فولت. تم مقارنة القيم التجريبية لمعاملات توهين أشعة جاما بالقيم النظرية المحسوبة باستخدام برنامج NIST-XCOM. تمت مقارنة نتائج طبقة نصف القيمة (HVL) للزجاج المحضر مع خرسانة الفريت لاستكشاف نطاق الزجاج الذي يحتوي على الرصاص كمرشح مناسب لمواد الحماية من الإشعاع.

الكلمات المفتاحية: النظارات, طبقة نصف القيمة, معامل التوهين الشامل, مواد الحماية من الإشعاع, الموجات فوق الصوتية.