Mechanical and Gamma-Ray Interaction Studies of PbO–MoO₃–Li₂O–B₂O₃ Glass System for Shielding Applications in The Low Energy Region: A Theoretical Approach

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Abstract: The mechanical and radiation shielding properties for the PbO–MoO₃–Li₂O–B₂O₃ glass system were theoretically investigated in this paper. The PbO–MoO₃–Li₂O–B₂O₃ glass system (coded as investigated glasses) was fabricated using the melt quenching mechanism. The optical packing density (OPD) increases from 75.563 to 84.366, and oxygen molar volume (OMV) decreases from 13.234 to 11.853 cm³/mol when increasing the PbO concentration. The values of elastic moduli decreased from 47.06 to 39.67 GPa for Young, from 33.51 to 32.41 GPa for bulk, from 19.82 to 16.29 GPa for shear and from 59.94 to 54.14 GPa for longitudinal moduli as the PbO is increased. The radiation attenuation characteristics were reported at the photon energies used in diagnostic radiology. The mass attenuation coefficient (MAC) was evaluated using the three photoatomic data libraries EPICS2017, EPDL97, and XCOM, available in the EpiXS and Phy-X programs. The MAC for the five investigated glasses at 20 keV was much higher than the MAC at 40, 60 and 80 keV. The MAC for investigated glasses increased with the addition of PbO, with Pb-S1 demonstrating the lowest MAC, and Pb-S5 demonstrating the highest MAC. Additionally, the rate of the increment of MAC at 20 keV as the concentration of PbO increased was higher than that at 40, 60 and 80 keV. The effective atomic number (EAN) was determined using Phy-X program. The EAN follows the trend: Pb-S5 > Pb-S4 > Pb-S3 > Pb-S2 > Pb-S1. The EAN results proved that the glass with low amounts of B₂O₃ and higher amounts of Pbo had good attenuation features. The EAN had the maximum values of 73.55–76.67 at 20 keV, whereas the lowest values occurred at 80 keV and varied between 53.63 and 63.39. The half-value layer (HVL) results showed that the Pb-S1 glass had the greatest HVL, while Pb-S5 had the least. There is a higher discrepancy between the tenth-value layer values at 80 keV than at 20 keV. At 20 keV, the difference between the highest and lowest TVL values (Pb-S1 and Pb-S5) was only 0.004 cm, while the difference at 80 keV was 0.152 cm. Pb-S5 is the most space-efficient radiation shield.

Keywords: diagnostic radiology; keV; glasses; radiation attenuation properties; mechanical properties

1. Introduction

The field of medicine uses radiation in radiology, cardiology, radiotherapy, and more, making it extremely beneficial for regular use. Many treatments rely on radiation to...
properly function. Excessive exposure to ionizing radiation may lead to permanent tissue damage, acute radiation syndrome and cancer. Radiation shields are used to protect patients from these side effects, minimizing the risk involved in these procedures. A radiation shield can protect humans by absorbing the incoming photons and reducing the intensity of radiation to safe levels [1,2].

Radiation shields can vary from metal sheets to concretes and glasses. Simple lead has historically been the most common radiation shield because its high density makes it highly effective at attenuating photons. Due to its toxic nature, its use should be restricted as much as possible, especially in medical treatment facilities. Therefore, researchers have been studying environmentally friendly substitutes to lead that are just as effective [3–5]. Concrete is a great candidate for this cause because of its low cost, simple manufacturing, and wide range of composition. The elements that typically compose concrete are often effective attenuators themselves, improving the properties of the material. Even though concrete is used as a radiation shield, it is prone to cracking and water loss over time, leading researchers to seek an alternative [6,7].

Radiation shielding glasses have similar benefits to concretes, except they offer the additional benefit of being transparent. Transparency can be useful to have the ability to view the adjacent room and allows the glasses to be used in non-medical applications as well [8,9]. Metal oxides, and heavy metal oxides especially, can alter the characteristics of the glass to fit its application. Metal oxides are broken up into three categories: glass formers, glass modifiers, and glass intermediates. Glass formers form the backbone of the glass network, glass modifiers alter the network but not the backbone, and intermediates can have the properties of each depending on the constituents of the glass [10–13].

Radiology uses average energies of 20 keV (dental), 30 keV (mammography), 40 keV (general), and 60 keV (computed tomography), respectively. Since these energies are the typically energy levels of photons used in the medical field, the glasses in this study will be examined under these energy ranges [14].

To evaluate the radiation shielding properties of glasses, researchers calculate and analyze several parameters. The typical method for obtaining these parameters is through an experimental study. To check the accuracy of the experiment, simulations are often used. Additionally, simulations also serve as an alternative method to investigate radiation shielding materials when it is not possible or practical to conduct actual experiments, such as during the COVID-19 pandemic. Previous studies have demonstrated the reliability of using simulations for shielding evaluations. MCNP-5 and Geant4 are two examples of simulation codes that use the Monte Carlo method [15–22]. It is good to note that the quality of data produced by modern simulation codes is limited to the quality of the embedded data libraries [23].

Electron Photon Interaction Cross Sections 2017 (EPICS2017) was released online by IAEA in 2018 [24,25]; it is the official electron-photon collection of ENDF/B-VIII [26]. The EPICS2017 is designated to replace all preceded electron and photon data embedded in the simulation codes. This release is important because several major codes (MCNP5, Geant4, PHITS, FLUKA, etc.) are based on the EPDL97 [27], released by LLNL more than two decades ago. The EPICS2017 has new and improved binding energies, absorption edges energies, and cross sections. Moreover, the extraction of cross sections or attenuation coefficients from EPICS2017 and EPDL97 was made convenient through developments of several software made to facilitate tedious interpolation and calculation [28,29].

In continuation of the previous work [30], the radiation shielding properties for the PbO–MoO$_3$–B$_2$O$_3$–Li$_2$O glasses was theoretically investigated at low energy (20–80 keV). The mass attenuation coefficient (MAC) was evaluated by three major photoatomic data libraries EPICS2017, EPDL97, and XCOM, using the EpiXS and Phy-X/PSD programs. Additionally, the mechanical properties of these glasses were examined.
2. Materials and Methods

2.1. Preparation of the Glass Samples

The details of the preparation of the Pb-SX glasses and Archimedes’ principle to measure the density \( (\rho) \) were discussed in our previous studies [30]. The glasses have been coded as Pb-SX glasses as:

Pb-S1: 30 PbO–5 MoO\(_3\)–25 Li\(_2\)O–40 B\(_2\)O\(_3\) (density = 4.354 g/cm\(^3\))

Pb-S2: 35 PbO–5 MoO\(_3\)–20 Li\(_2\)O–40 B\(_2\)O\(_3\) (density = 4.838 g/cm\(^3\))

Pb-S3: 40 PbO–5 MoO\(_3\)–15 Li\(_2\)O–40 B\(_2\)O\(_3\) (density = 5.327 g/cm\(^3\))

Pb-S4: 45 PbO–5 MoO\(_3\)–10 Li\(_2\)O–40 B\(_2\)O\(_3\) (density = 5.853 g/cm\(^3\))

Pb-S5: 50 PbO–5 MoO\(_3\)–5 Li\(_2\)O–40 B\(_2\)O\(_3\) (density = 6.578 g/cm\(^3\))

The chemical composition of the tested glasses are represented in Table 1.

| Glass Code | Mole % of Oxides Present | Density (g/cm\(^3\)) | \( V_m \) (cm\(^3\)/mol) | OPD (mol/L) | OMV (cm\(^3\)/mol) |
|------------|--------------------------|-----------------------|-----------------------------|-------------|---------------------|
| Pb-S1      | 30 PbO–5 MoO\(_3\)–25 Li\(_2\)O–40 B\(_2\)O\(_3\) | 4.354                 | 25.144                      | 75.563      | 13.234              |
| Pb-S2      | 35 PbO–5 MoO\(_3\)–20 Li\(_2\)O–40 B\(_2\)O\(_3\) | 4.838                 | 24.626                      | 77.151      | 12.962              |
| Pb-S3      | 40 PbO–5 MoO\(_3\)–15 Li\(_2\)O–40 B\(_2\)O\(_3\) | 5.327                 | 24.180                      | 78.575      | 12.727              |
| Pb-S4      | 45 PbO–5 MoO\(_3\)–10 Li\(_2\)O–40 B\(_2\)O\(_3\) | 5.853                 | 23.658                      | 80.307      | 12.452              |
| Pb-S5      | 50 PbO–5 MoO\(_3\)–5 Li\(_2\)O–40 B\(_2\)O\(_3\) | 6.578                 | 22.520                      | 84.366      | 11.853              |

2.2. Physical Properties

Molar volume \( (V_m) \) is obtained as [30]:

\[
V_m = \frac{M}{\rho}
\]  

(1)

where \( M \) is the molar mass and \( \rho \) is the density of the sample.

OPD is given as [31]:

\[
OPD = \left( \frac{\rho}{M} \right) \times n \times 1000
\]  

(2)

where \( n \) is the total number of oxygen atoms.

OMV is given as [31]:

\[
OMV = \frac{V_m}{\sum x_i n_i}
\]  

(3)

where \( n_i \) represents the fraction of oxygen atoms.

2.3. Mechanical Properties

The average cross link density \( (\bar{n_c}) \) is given as [32]:

\[
\bar{n_c} = \frac{\sum x_i (n_c)_i (N_c)_i}{\sum x_i (N_c)_i}, \text{ where } (n_c = n_f - 2)
\]  

(4)

where \( n_f \) is the coordination numbers, \( x_i \) is the mole fraction and \( N_c \) is the number of cations present in the respective constituents of the fabricated glasses.

The number of bonds per unit volume of the glasses \( (n_b) \) is given as [33]:

\[
n_b = \frac{N_A}{V_m} \sum (n_f)_i x_i
\]  

(5)
According to the theoretical model of Makishima and Mackenzie (MM), the Young’s modulus \( E \), bulk modulus \( B \), shear modulus \( G \), longitudinal modulus \( L \), Poisson’s ratio \( \sigma \), fractal bond connectivity \( d \) and hardness \( H \) can be obtained as \([34,35]\):

\[
V_i = \left( \frac{1}{V_m} \right) \sum V_i x_i
\]

\[
V_i = N_A \left( \frac{4\pi}{3} \right) \left( xR_A^3 + yR_B^3 \right)
\]

\[
E = 8.36V_iG_i
\]

\[
B = 10V_i^2G_i
\]

\[
G = \frac{30V_i^2G_i}{(10.2V_i - 1)}
\]

\[
L = B + \left( \frac{4}{3} \right) G
\]

\[
\sigma = 0.5 - \left( \frac{1}{7.2V_i} \right)
\]

\[
d = 4 \left( \frac{G}{B} \right)
\]

\[
H = \frac{(1 - 2\sigma)E}{6(1 + \sigma)}
\]

2.4. Gamma Ray Shielding Properties

The photon attenuation characteristics were evaluated using data from the EPICS2017 and EPDL97. Both libraries can be interpolated manually. The interpolation of EPICS2017 total atomic cross sections can be made since this library is linearized. However, the interpolation of EPDL97 requires that all partial cross sections be interpolated to obtain the total atomic cross section, as follows:

\[
\sigma_T = \sigma_{coh} + \sigma_{incoh} + \sigma_{PP \text{ in Nuc}} + \sigma_{PP \text{ in Ele}} + \Sigma \sigma_{PE,i}
\]

where the total atomic cross section \( \sigma_T \) is the sum of the partial cross sections for different interaction processes.

A recent software was developed called EpiXS \([29]\) which facilitates the interpolations and calculations using EPICS2017 and EPDL97. The EpiXS software contains both photon libraries extracted in the international ENDF-6 format; it performs interpolation of all partial cross sections including each photoionization subshell cross section to calculate for total atomic cross sections. The cross sections are converted to attenuation coefficients using elemental masses from AME2016 considering the abundances in NUBASE2016. This EpiXS software was employed for the evaluation of MAC values based on EPICS2017 and EPDL97.

The EpiXS software was designed to aid users in interpolating the EPICS2017 and EPDL97 and obtain the required photon attenuation and shielding quantities. Hence, the function and entry forms of the EpiXS is similar to that of the XCOM web program. The user gives the input of the material compositions, densities, and the energies required. Using the aforementioned atomic mass data, the material composition is converted into atom fractions per \( i \)th element. Subsequently, these atom fractions are used to obtain the material’s cross section \( \sigma_{mat} \) using the relationship \([29]\):

\[
\sigma_{mat} = \Sigma f_i \sigma_i
\]
where $\sigma_i$ is the cross section of the $i$th element and $f_i$ is the atom fraction of the $i$th element. The cross section data are chosen by the user from EPICS2017 or EPDL97 prior to the calculations. Therefore, the $x$ and $y$ scales of the linear spline interpolations will be dependent on the user-chosen photoatomic data library. The interpolated cross sections are used by EpiXS to derive the required parameters. All X-ray absorption edges per element are also tabulated by this software and can be viewed from both libraries.

The Phy-X/PSD program [36] is another program used for calculations, which is a WinXCom based software, hence performs evaluation using XCOM-NIST photoatomic library. It provides the output data in the form of an excel data sheet. The user must follow three successive steps using Phy-X/PSD program. These steps are summarized as the following: (I) define the materials: in this step, one can define the material by inputting the chemical composition in mole or weight fractions in the main page of the program, (II) define the energy: there are two options available in the software for the energy wide energy range or selected energy values emitted from the common radioactive sources such as $^{60}$Co, $^{109}$Cd, $^{133}$Ba, $^{137}$Cs and, (III) selection of the factors to be investigated: the user can select different factors (up to 18 factors) that are used for the radiation shielding investigation. Finally, the user can save the data in an excel file.

3. Results and Discussion

The measured values of densities have been accustomed to enumerate the molar volume, OPD and OMV have been obtained and listed in Table 1. The density and the molar volume values lies in the span of 4.354–6.578 g cm$^{-3}$ and 25.144–22.520 cm$^3$, respectively. Their variations with composition of PbO have already been discussed [30]. The OPD is another interesting parameter to identify the structure of the glass. It is observed that OPD increases from 75.563 to 84.366 with an upsurge in PbO content. The variation of OPD with percentage molar concentration of PbO is shown in Figure 1a. This increment may take place due to the enhancement in density due to the formation of the highly cross linked glass network [37]. The close packing of the glass network is further supported due to decreases of oxygen molar volume from 13.234–11.853 cm$^3$/mol with upsurge in PbO content as shown in Figure 1b [37].

![Figure 1. Cont.](image-url)
The obtained values of $n_b$ and $n_c$ are presented in Table 2. The $n_b$ upsurge from $1.030 \times 10^{23}$ cm$^{-3}$ to $1.257 \times 10^{23}$ cm$^{-3}$. The increase in PbO content increases the non-bridging oxygens (NBOs), that accounts for the cross linkage of the network resulting in an upsurge in $n_b$. The $n_c$ increases from 1.939 to 2.207. This means that as the value of $n_c$ rises, the network is becoming more stiff and more dimensional. More likely, this is related to the rise in NBOs.

### Table 2. Mechanical properties.

| Glass Code | $n_b$ (cm$^{-3}$) | $n_c$ | $E$ (GPa) | $B$ (GPa) | $G$ (GPa) | $L$ (GPa) | $\sigma$ | $d$ | $H$ (GPa) |
|------------|------------------|-------|-----------|-----------|-----------|-----------|---------|-----|-----------|
| Pb-S1      | $1.030 \times 10^{23}$ | 1.939 | 47.06     | 33.51     | 19.82     | 59.94     | 0.266   | 2.37| 2.89      |
| Pb-S2      | $1.076 \times 10^{23}$ | 2.000 | 45.17     | 33.07     | 18.93     | 58.30     | 0.273   | 2.29| 2.68      |
| Pb-S3      | $1.121 \times 10^{23}$ | 2.064 | 43.03     | 32.30     | 17.94     | 56.23     | 0.279   | 2.22| 2.48      |
| Pb-S4      | $1.171 \times 10^{23}$ | 2.133 | 40.89     | 31.59     | 16.96     | 54.21     | 0.285   | 2.15| 2.28      |
| Pb-S5      | $1.257 \times 10^{23}$ | 2.207 | 39.67     | 32.41     | 16.29     | 54.14     | 0.297   | 2.01| 2.07      |

The mechanical properties are presented in Table 2. Their variation with PbO content is represented in Figure 2a. The values decrease from 47.06 to 39.67 GPa for $E$, from 33.51 to 32.41 GPa for $B$, from 19.82 to 16.29 GPa for $G$, and from 59.94 to 54.14 GPa for $L$, respectively, as the PbO upsurges. It is found that the values of the moduli are decreasing, which results in a decrease in their rigidity and mechanical strength [38,39]. The Poisson ratio ($\sigma$) possess an increasing trend from 0.266 to 0.297 with upsurge in PbO which is due to the lesser cross link density network and reduced rigidity [38,39]. The fractal bond connectivity ($d$) ranges from 2.01 to 2.37 which hints that the present glasses have chain structure [40–42]. The H decreases from 2.89 to 2.07 GPa with upsurge in PbO content which hints that the rigidity and connectivity of the selected glasses is diminished [39].
Figure 2. Variation of mechanical properties (a) elastic moduli (b) σ (c) d (d) H with PbO content.
The MAC for the five Pb-SX glasses in four equidistant photon energies between 20 and 80 keV was evaluated using three photoatomic libraries available through EpiXS and Phy-X/PSD programs. The MAC data is tabulated in Table 3, for each library used. On the other hand, the EPICS2017 (of ENDF/B-VIII.0) released by IAEA is the newest electron-photon data and is now being embedded into several major codes. From the results in Table 3, there was a slight difference among the libraries particularly in the 20 keV photon energy. This is because the glasses have some amount of molybdenum, and the K-edge energy of molybdenum lies near the 20 keV photon energy. This phenomenon is explained by Figure 3 which describes the photoelectric cross section of each library for the molybdenum element. The values for the K-edge of molybdenum, in each library, are 19.965 keV in EPDL97, 20.00 keV in XCOM-NIST, and 20.006 keV in EPICS2017. For both XCOM and EPDL97, the 20 keV energy appears after the Mo K-edge. Therefore, there is a higher value for MAC of the glasses at 20 keV using XCOM and EPDL97. This is the opposite for EPICS2017 since the Mo K-edge in this library is slightly higher than 20 keV. This results in lower MAC value at 20 keV for EPICS2017. Another slight difference among the libraries was found in the 80 keV photon energy MAC results. In this energy, the XCOM-NIST had a slight discrepancy with EPICS2017 and EPDL97, because the 80 keV energy is near the K-edge of Pb (~88 keV). It has been shown previously that MACs or cross sections vary among the libraries, especially in the photon energies near X-ray edges [24,29].

Aside from these slight differences, there was a good agreement found among all three libraries for the rest of the photon energies.

### Table 3. MAC (cm²/g) of the samples.

| Energy (keV) | Pb-S1 | Pb-S2 | Pb-S3 | Pb-S4 | Pb-S5 |
|--------------|-------|-------|-------|-------|-------|
|               | EPICS2017, ENDF/B-VIII (EpiXS) | EPDL97, ENDF/B-VI.8 (EpiXS) | Phy-X/PSD | EPICS2017, ENDF/B-VIII (EpiXS) | EPDL97, ENDF/B-VI.8 (EpiXS) | Phy-X/PSD | EPICS2017, ENDF/B-VIII (EpiXS) | EPDL97, ENDF/B-VI.8 (EpiXS) | Phy-X/PSD |
| 20           | 49.703 | 52.619 | 52.799 | 53.155 | 55.827 | 56.025 | 56.089 | 58.554 | 58.767 |
| 40           | 8.808  | 8.791  | 8.811  | 9.340  | 9.323  | 9.344  | 9.792  | 9.774  | 9.797  |
| 60           | 3.085  | 3.084  | 3.107  | 3.267  | 3.266  | 3.291  | 3.421  | 3.421  | 3.447  |
| 80           | 1.486  | 1.494  | 1.522  | 1.570  | 1.578  | 1.608  | 1.641  | 1.650  | 1.682  |

Figure 4 shows the MAC for the five Pb-SX glasses at four energies (20, 40, 60 and 80 keV). The data exhibited in this figure reveals that the MAC at 20 keV is much higher than the MAC at 40, 60 and 80 keV. This is correct for the five Pb-SX glasses. This high value of MAC at 20 keV in comparison with the other energies can be directly related to the photoelectric interaction, in which the probability of this interaction is high at 20 keV and reduces with increasing energy. So, increasing the energy from 20 to 80 keV causes the MAC to drop. These results agree with the observation of Al-Hadeethi and Tijani where they observed that the MAC of the glasses is very high at 140 keV and the values reduce for the energy of 364 and 511 keV [43]. Additionally, we can observe from Figure 4 that the MAC for Pb-SX glasses improves with the addition of PbO; Pb-S1 had the lower MAC, while Pb-S5 had the highest MAC. The MAC increases from 52.79 to 63.18 cm²/g at 20 keV on increasing the PbO from 30 to 50 mol %. Additionally, at 40 keV, the MAC increases from 8.81 cm²/g (for Pb-S1) to 10.53 cm²/g (for Pb-S5), while at 80 keV, the MAC for Pb-S1 and Pb-S5 are 1.52 and 1.79 cm²/g, respectively. From these values, we can conclude that
the increment of MAC at 20 keV as the concentration of PbO increases is higher than that at 40, 60 and 80 keV.

It is important to remember that when the LAC values of the medium increases, its potency to attenuate the radiation also increases. In Figure 5 we exhibited the LAC for the five Pb-SX samples at the four tested energies. Glass codes Pb-S5 showed the highest LAC. This is due to the higher concentration of PbO in this glass (50 mol %). Moreover, from Figure 5 we can easily see that the LAC for the Pb-SX glasses were in reducing order from 20 keV to 80 keV. For instance, for a fix composition (e.g., 30PbO-5MoO₃-5Li₂O-40B₂O₃), the LAC takes the following values: 229.89 cm⁻¹ at 20 keV, 38.36 cm⁻¹ at 40 keV, 13.53 cm⁻¹ at 40 keV, and 6.63 cm⁻¹ at 80 keV. It is evident that there is high LAC for the glasses at 20 keV and these are accepted results as the photoelectric absorption dominates at such low energies. It can be concluded that the chosen glasses with high concentration of PbO must be selected for shielding aims when the radiations to be attenuated have average energy values between 20 and 80 keV.

Figure 3. Total photoelectric cross section of molybdenum (Z = 42) element by three different libraries with distinct K-absorption edge energies.

The effective atomic number (EAN) were plotted versus energy in Figure 6. From this figure we can understand the relationship between the EAN and the PbO content of the investigated samples in this study. Apparently, as the PbO content increases the EAN of the chosen glasses also increases. The replacement of the B₂O₃ by PbO is the reason for this trend in the EAN, since the atomic number of B is much less than that of Pb. The glass with a low amount of B₂O₃ and higher amount of PbO has high EAN in comparison with the glass with a high amount of B₂O₃. The outcome of the EAN data suggests that Pb-SX samples will perform optimally in shielding the radiation with energy of 20–80 keV when using a high amount of PbO. Additionally, we can see that the EAN has the maximum values of 73.55–76.67 at 20 keV, whereas the lowest values occurred
at 80 keV and varied between 53.63 and 63.39. The EAN decreases when increasing the energy from 20 to 80 keV implying that the shielding performance of the Pb-SX glasses becomes worse when increasing the energy.

Figure 4. The MAC for the Pb-SX glasses at four energies (20, 40, 60 and 80 keV).

Figure 5. Cont.
Figure 5. The LAC for the Pb-SX glasses at (a) four energies 20, 40, 60 and 80 keV and (b) at 40, 60 and 80 keV (In order to show the values at the three energies more clearly).

Figure 6. The EAN for the Pb-SX glasses at four energies (20, 40, 60 and 80 keV).
The half-value layer (HVL) were graphed in Figure 7. At all four energies, the HVL values followed the trend of Pb-S1 > Pb-S2 > Pb-S3 > Pb-S4 > Pb-S5. These results demonstrate that the Pb-S1 glass has the greatest HVL at all the tested energies, while Pb-S5 has the least. This trend is due to the greater PbO content of the Pb-S5 glass (50 mol%) compared to the Pb-S1 glass (30 mol%), causing an increase in density which correlates with a decrease in HVL. Pb-S5 is the most space-efficient radiation shield. The figure also reveals the correlation between energy and HVL. When observing any glass at increasing energy, the HVL values can be seen to greatly increase. The HVL of the Pb-S2 glasses increases from 0.003 cm to 0.015 cm, 0.044 cm, and 0.089 cm for energies of 20, 40, 60, and 80 keV, respectively. However, it should be observed that the HVL of Pb-S1 can be seen to increase at a much greater rate than the HVL of Pb-S5, for instance, which signifies that even though the HVL of Pb-S5 increases with increasing energy, the rate of the increase is much smaller, or the ability of the glass to absorb radiation becomes increasingly better at higher energies.

![Figure 7. The HVL for the Pb-SX glasses at four energies (20, 40, 60 and 80 keV).](image)

The advantage of the Pb-S5 glass at greater energies is demonstrated in Figure 8, where the tenth-value layer, or TVL, of the glasses are illustrated against incoming photon energy. The differences between the two parameters signifies that TVL will logically be greater than HVL, but the values are still trying to be minimized. Similar to HVL, the TVL values increase when increasing the energy. The TVL of the Pb-S3 glass increases from 0.007 cm at 20 keV to 0.044 cm at 40 keV, 0.125 cm at 60 keV, and 0.257 cm at 80 keV. The increment of the values can be justified with the same reasoning used in the Figure 7. If the data are analyzed at a single energy, the same order of values is obtained once again, with S5 demonstrating the lowest values and Pb-S1 demonstrating the greatest. It is important to observe, however, that there is a higher discrepancy between the values at 80 keV than at 20 keV. At 20 keV, the difference between the highest and lowest TVL values (Pb-S1 and Pb-S5) is equal to 0.004 cm, while the difference at 80 keV is 0.152 cm. The fact that the difference is much greater at 80 keV highlights the superior shielding ability of the Pb-S5 glass. At the same time though, if the glasses are being used against radiation energies of 20 keV, the discrepancy between the shielding ability of the glasses is
practically negligible. The advantage of the Pb-S5 glass over the other samples can only be observed as energy further increases.

![Graph showing TVL vs Energy for Pb-SX glasses](image)

**Figure 8.** The TVL for the Pb-SX glasses at four energies (20, 40, 60 and 80 keV).

4. Conclusions

The mechanical and gamma-ray interaction parameters of PbO–MoO$_3$–Li$_2$O–B$_2$O$_3$ glass system for shielding applications in the low energy region was reported. The role of different contents of PbO on the mechanical properties of the proposed glasses was examined. The increase in OPD and decrease in OMV when increasing the PbO concentration, indicating towards the formation of highly cross-linked glass network. The rigidity and mechanical strength of glasses with increasing the PbO concentration. The values of elastic moduli decreased from 47.06 to 39.67 GPa for Young, from 33.51 to 32.41 GPa for bulk, from 19.82 to 16.29 GPa for shear and from 59.94 to 54.14 GPa for longitudinal moduli as the PbO is increased. The MAC values between the three distinct libraries EPICS2017, EPDL97, and XCOM have been compared. The MAC at 20 keV is much higher than the MAC at 40, 60 and 80 keV, and the MAC decreases with increasing energy from 20 to 80 keV. Both MAC and LAC for the Pb-SX glasses increase with the addition of PbO. Pb-S1 possesses the lower MAC, LAC as well as EAN, and Pb-S5 has the highest values of these three factors. The EAN has the maximum values of 73.55–76.67 at 20 keV, whereas the lowest values occurred at 80 keV and varied between 53.63 and 63.39. These HVL results demonstrate that the Pb-S1 glass has the greatest HVL at all the tested energies, while Pb-S5 has the least. Additionally, we found that the HVL of Pb-S1 increases at a much greater rate than the HVL of Pb-S5. The HVL results demonstrated that Pb-S5 is the most space-efficient radiation shield. Additionally, there is a higher discrepancy between the TVL values at 80 keV than at 20 keV, and the difference between the highest and lowest TVL values (Pb-S1 and Pb-S5) at 20 keV is equal to 0.004 cm, while the difference at 80 keV is 0.152 cm. It can be concluded that the chosen PbO–MoO$_3$–Li$_2$O–B$_2$O$_3$ glasses with high concentration of PbO must be selected for shielding aims when the radiations to be attenuated have average energy values between 20 and 80 keV.
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