Applied Physics A (2022) 128:1058
https://doi.org/10.1007/s00339-022-06216-2

Applied Physics A
Materials Science & Processing

Gamma photons attenuation features of PbO-doped borosilicate glasses: a comparative evaluation

Mohammed J. R. Aldhuhaibat[1] · H. Saba Farhan[1] · Ruaa. H. Hassani[1] · Haider Majid Tuma[1] · H. Bakhtiar[2] · A. A. Salim[2]

Received: 29 July 2022 / Accepted: 3 November 2022 / Published online: 12 November 2022
© The Author(s), under exclusive licence to Springer-Verlag GmbH, DE part of Springer Nature 2022

Abstract

This paper demonstrates the possibility of improving the γ-photons attenuation traits of a new type of borosilicate glass system (x)PbO: $0.12B_2O_3$:(0.8-x) SiO_2: $0.08K_2O$ (where: $x = 0$, 0.05, 0.15, 0.3, 0.5 wt.) prepared using various doping concentrations of PbO. The mass attenuation coefficient (μ/ρ) of the proposed glass system over the entire γ-photon energy range (0.005–3 MeV) was improved due to doping. Glass with the highest doping concentration achieved the optimum values for μ/ρ, μ, α_a, Z_{eff} and $N_{eff.}$ The lowest values of MFP and HVL for the glasses were observed in the mid γ-photons energy region. In addition, the RPE values of the glasses were significantly enhanced with the increase in PbO content and reduced with the increase of γ-photons energy. The computed values of various radiative parameters like μ/ρ, μ, MFP, RPE, HVL, α_a, $Z_{eff.}$ and N_{eff} derived from XMuDat and XCOM programs were in good agreement with the theoretical values acquired using the Phy-X software. The proposed glass system may be useful as a high-performance radiation shield.

Keywords Borosilicate glass · Gamma photon · Attenuation coefficient · Effective atomic number · Protection efficiency

1 Introduction

In recent times, the cases of cancer due to exposure of high-energy radiation from various sources have become a major concern. For this reason, it is mandatory to control human exposures to radiation doses, thereby reducing them to the minimum level. This can be achieved via the implementation of the ALARA principle, which relies on shielding materials [1]. However, the major challenges faced by the researchers at present are the development of high-performance shields entirely different from the traditional ones. These shields must be made from novel elements of high-density (ρ), which are lighter than conventional lead-based heavy metals, more condensed and suitable for diverse radiological applications [2–4]. In radiological and nuclear physics, radiation protection, diagnosis, and treatment in the field of nuclear medicine, various physical parameters of shielding materials have widely been used for radiation protection. Amongst these quantities, the most significant ones are the linear attenuation coefficient (μ), mass attenuation coefficient (μ/ρ), mean free path (MFP), half value layer (HVL), effective atomic number ($Z_{eff.}$), and effective electronic number ($N_{eff.}$) [5–7].

It is established that various composite materials containing several elements cannot be described by a single atomic number. Therefore, the atomic number of these composite materials is referred to as the effective atomic number as well as the electronic number, wherein the value differs with the variation of the interacting radiation energy [8, 9]. Several studies related to radiation shielding have recently been considered with different inorganic oxide glass systems due to their distinct features compared to other materials or composites. These unique characteristics of glasses include the ease and diversity of their preparation methods in addition to their high transmittance in the visible wavelength region, enabling them to be advantageous for many special applications like the diagnostic and radiotherapy rooms' windowpanes and windows of some devices used in radiological appliances [10–13]. Many studies have been conducted

✉ A. A. Salim
asali@utm.my

H. Bakhtiar
hazri@utm.my

1 Department of Physics, College of Science, Wasit University, Kut, Iraq

2 Laser Center & Physics Department, Faculty of Science, Universiti Teknologi Malaysia, 80200 Bahru, Johor, Malaysia

using various types of doped glasses and composites to improve their radiative properties against high-energy radiation exposures. Generally, the radiative attenuation capacity of these materials was found to increase with the increase in dopants concentration [13–17].

Lately, many researchers have investigated distinctive kinds of sophisticated glassware and observed that the overall attenuation parameters improve with the doping of a glass and an increase in its density [18–20]. For instance, increasing the Cr_2O_3 content significantly decreased the mean free path of gamma rays and continued to increase the effective atomic number in the developed glass, leading to superior attenuation properties compared to conventional concrete, commercial glasses, and Pb-free glass [18]. Furthermore, improved radioactive attenuation properties of the fabricated glass were indeed explored by increasing the percentages of glass distortion in both the Ag_2O and WO_3 contents, which in turn enhanced the mass attenuation coefficient and effective atomic number values with a decrease in the mean free path and half value layer [19]. Mhareb [21] has shown that for a wide range of gamma-ray energies, increasing the concentration of Sm^{+3} ions in the lithium magnesium borate erbium oxide glass system increases the mass attenuation coefficient, effective atomic number, and effective electron densities, and decreases the mean free path and half value layers. The attenuation parameters and shielding efficiency of gamma rays and neutrons proposed by Al-Buriahi and his groups for a number of polymers [22], high Fe-content amorphous alloys [23], and various marble concretes [24] were comparable to those of ordinary concrete, commercial glass, and traditional materials and only suitable at low ray energies. In addition, earlier studies of epoxy composites reinforced with different concentrations of Fe_3O_4 [25], hybrid composites of epoxy reinforced with zirconium oxide and lead [26], and PMMA reinforced with zinc and bismuth oxides [27] showed similar results and compared the last hybrid compound to some traditional shields. The hybrid composite was less effective at attenuating X-rays than conventional concrete, barite concrete, and high-density polyethylene [24–27].

Based on the abovementioned factors, the radiative parameters like μ/ρ, μ, MFP, HVL, α_a, $Z_{eff.}$, N_{eff} and RPE of some PbO-doped borosilicate glasses of composition $0.12B_2O_3$:$0.8SiO_2$:$0.08K_2O$ were evaluated and compared to determine the feasibility of achieving their improved radiation shielding features. The main purpose of this research was to increase radiative attenuation and determine the effects of various doping contents (0.05, 0.15, 0.3, and 0.5 wt.%) on the improved γ-photons (energy ranged from 0.005 to 3 MeV) attenuation characteristics of the glasses, thereby establishing whether the proposed shields are appropriate for radiative uses and a wide range of gamma-ray energy. These parameters were theoretically determined using the XMuDat [28], XCOM [26], and Phy-X [29] programs. A comparison of the obtained radiation attenuation parameters for the proposed glass system revealed a significant improvement in the studied photon energy range, claiming the material to be a useful shielding material against high-energy radiation exposures.

2 Concepts and theoretical methods

The increasing use of γ-radiation in a variety of fields has prompted scientists and researchers to investigate various radiative attenuation parameters of various shielding materials such as μ/ρ, μ, MFP, HVL, Z_{eff}, and N_{eff}, among others, for hazards-free applications. In this perception, it became essential to predict these parameters theoretically, ascertaining the possibility of using them as high-performance radiation shields. Considering the immense importance and market demands of functional radiation shielding materials, we theoretically calculated various radiative attenuation parameters of (x) PbO: $0.12B_2O_3$: (0.8-x) SiO_2: $0.08K_2O$ glasses ($x=0$, 0.05, 0.15, 0.3, 0.5 wt.%). Table 1 reveals the compositions, densities, and weight fractions of these studied glasses obtained using the XMuDat, XCOM, and Phy-X programs in the γ-photons energy range of 0.005–3 MeV. These γ-photons energies are based on the emission spectra of radioactive elements of ^{22}Na, ^{55}Fe, ^{60}Co, ^{47}Ag, ^{109}Cd, ^{131}I, ^{137}Cs, ^{133}Ba, ^{152}Eu, and ^{241}Am as furnished in Table 2 [29].

The transmitted γ-rays intensity (I) of the incident beam of intensity (I_o) through a physical shield of thickness x and linear attenuation coefficient μ follows the Beer-Lambert formula as follows [30]:

$$I = I_o e^{-\mu x} \tag{1}$$

The value of μ/ρ of the shielding material can be calculated from the ratio of μ and density (ρ) [15]. The calculated values of μ are used to determine $MFP = 1/\mu$ of γ-photons within the material [28–31] and $HVL = \ln 2/\mu$ [10, 31]. The expression of $Z_{eff.}$ yields as follows [30, 32]:

Table 1 Details of the PbO-doped borosilicate glass system

Nominal compositions (wt.%)				
Dopant	Constituents			Density
PbO	B_2O_3	SiO_2	K_2O	(g/cm^3)
0	12	80	8	**2.24**
5	12	75	8	**2.33**
15	12	65	8	**2.52**
30	12	50	8	**2.88**
50	12	30	8	**3.54**

Table 2 Radioactive source and emitted γ-photons energies

Isotope (Z)	E_γ (MeV)	Isotope (Z)	E_γ (MeV)
^{22}Na (11)	0.511000	^{133}Ba (56)	0.302900
	1.275000		0.356000
^{55}Fe (26)	0.005888		0.383900
	0.005899	^{152}Eu (63)	0.039500
	0.006490		0.040120
	0.006536		0.045900
^{60}Co (27)	0.347100		0.047040
	1.333000		0.121800
	0.826100		0.244700
	1.173000		0.295900
	2.506000		0.344300
^{47}Ag (47)	0.022100		0.411100
^{109}Cd (48)	0.023100		0.444000
	0.025000		0.678000
	0.025500		0.688700
	0.088040		0.778900
^{131}I (53)	0.284000		0.867400
	0.364500		0.964100
	0.637000		1.005000
	0.723000		1.086000
^{137}Cs (55)	0.283500		1.090000
	0.661700		1.112000
^{133}Ba (56)	0.030820		1.299000
	0.035000		1.408000
	0.035400		1.458000
	0.035800	^{241}Am (95)	0.013810
	0.049620		0.026340
	0.053160		0.032180
	0.081000		0.033200
	0.160600		0.059540
	0.223400		0.098970
	0.276400		0.103000

$$Z_{eff.} = \frac{\alpha_a}{\alpha_e} \tag{2}$$

where α_a and α_e represent the atomic and electronic cross-section of the target (shielding) material, respectively, that are calculated via [26, 31]:

$$\alpha_a = \frac{(\mu/\rho)_c}{N_A \sum_i \frac{w_i}{A_i}} \tag{3}$$

$$\alpha_e = \frac{1}{N_A} \sum_i \frac{f_i A_i}{Z_i} (\mu/\rho)_i \tag{4}$$

where $(\mu/\rho)_c$ is the mass attenuation coefficient of the composite material, w_i and A_i are the corresponding weight fraction and atomic weight of the i^{th} constituent element in the composite material, N_A is the Avogadro's number, and f_i is the fractional abundance of the i^{th} constituent element obtained by dividing the total number of atoms of the constituent element i (n_i) by the total number of all the types of atoms that exist in the composite($\Sigma_j n_j$). The expression of N_{eff} is given by [26]:

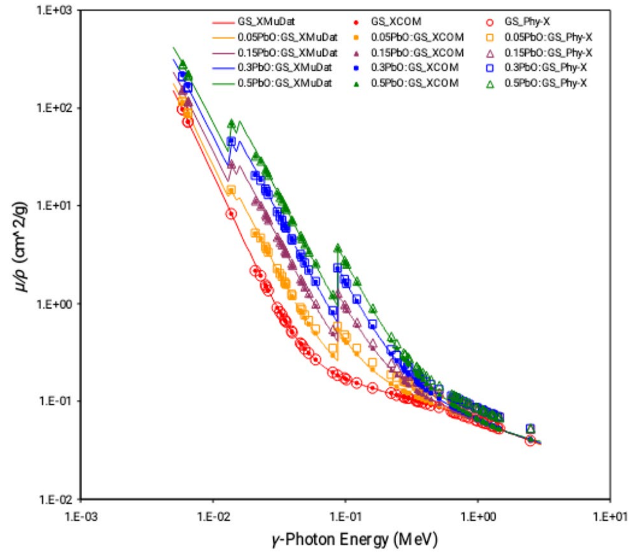

Fig. 1 γ-photons energy dependent variation of μ/ρ of the glasses

$$N_{eff.} = \frac{(\mu/\rho)_c}{\alpha_e} \tag{5}$$

The radiation protection efficiency (RPE) of the shielding material can be calculated using [29]:

$$RPE = (1 - e^{-\mu x}) \times 100 \tag{6}$$

3 Results and discussions

The values of μ/ρ for all glasses containing various amounts of PbO (0.05, 0.15, 0.3, 0.5 wt.%) of PbO under the γ-photons exposures in the energy range of 0.005–3 MeV were calculated using XMuDat XCOM and Phy-X programs. γ-photons of different energies (ranging from 0.005888–2.506 MeV) were obtained from the radioactive ^{22}Na, ^{55}Fe, ^{60}Co, ^{47}Ag, ^{109}Cd, ^{131}I, ^{137}Cs, ^{133}Ba, ^{152}Eu, and ^{241}Am sources. using. The values of μ, MFP, HVL, RPE, α_a, $Z_{eff.}$, and N_{eff} obtained from different programs were compared. Figures 1 and 2 show the effects of different γ-photons energies on the values of μ/ρ and μ of the proposed glasses. The calculated and theoretical results showed good agreement. In addition, both values were increased with the increase in doping concentration, indicating an increase in the glass density (Table 1). The

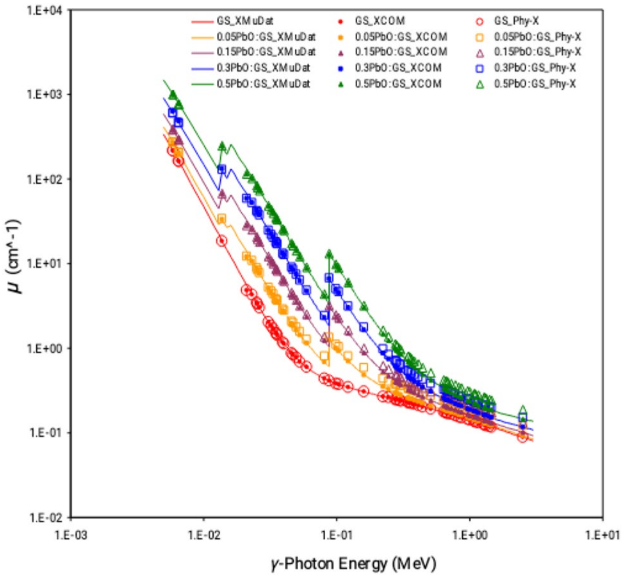

Fig. 2 γ-photons energy dependent variation of μ of the glasses

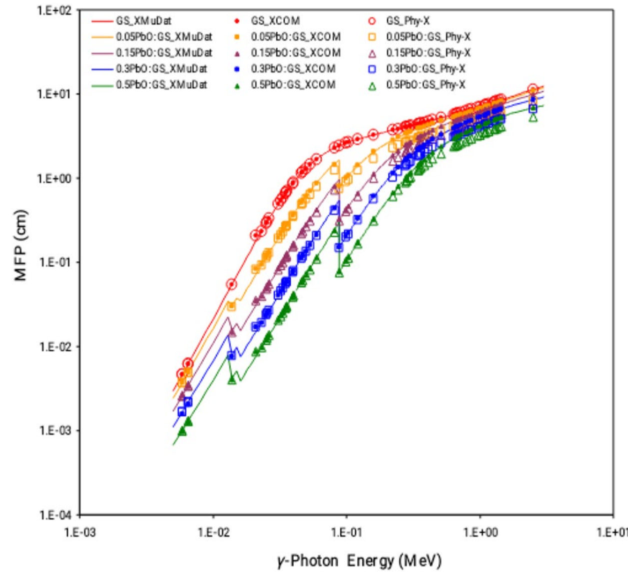

Fig. 3 γ-photons energy-dependent variation of MFP of the glasses

values of μ/ρ and μ of the glasses were strongly depended on the interacting γ-photons energies through different mechanisms such as photoelectric effects (dominant at low photons energies), Compton scattering (dominant at intermediate photons energies) and pair production (dominant at photons energies over 1.022 MeV) [33]. The calculated results were consistent with the theoretical values obtained using the Phy-X program. The observed sharp increase in the values of μ/ρ and μ at some specific γ-photons energy represents the absorption edge of the K-shell electron in Pb.

Figures 3 and 4 display various γ-photons energy-dependent changes in MPF and HVL values of the studied glasses. The calculated and theoretical results showed good agreement. Clearly, the behavior of these two parameters was opposite to that of μ (Fig. 2) but remained consistent with the theoretical results that showed the inverse relationship of these two quantities with μ. The values of both MFP and HVL were improved significantly at lower energies (below 0.1 MeV) and slightly at higher energies beyond this value. The values of both MFP and HVL were decreased with the increase of PbO doping content in the glass system, especially at the mid-energy range. This observation was ascribed to the dominance of the Compton scattering interaction plus the photoelectric effect.

Figure 5 illustrates the γ-photons energy dependent variation of α_a of the glasses obtained using the XMuDat and XCOM programs and compared with the theoretical results obtained using the Phy-X program. The values of α_a of the glasses revealed a behavior similar to that of both μ/ρ and μ. In addition, the values of α_a decreased with the increase of γ-photons energy. Conversely, the values of α_a were increased with the increase of PbO doping contents in the glass, particularly in the intermediate energy region.

Figure 6 presents the γ-photons energy-dependent variation of Z_{eff} of the glasses obtained using XMuDat and XCOM programs and then compared with the calculated results from the Phy-X program. The calculated values were found to behave irregularly with the increase of γ-photons energy, and they jumped suddenly at 0.01381 MeV due to the occurrence of the absorption edges in the L-shell of Pb. Then, it decreased with the further increase of γ-photons energy and again sharply increased at 0.08804 MeV due

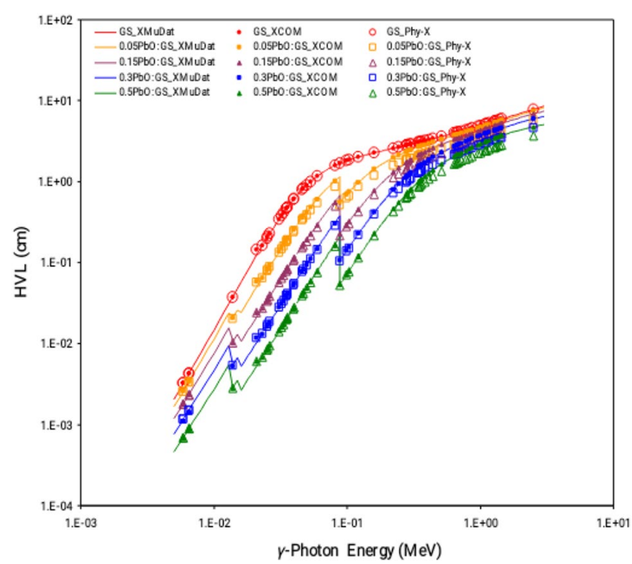

Fig. 4 γ-photons energy dependent variation of HVL of the glasses

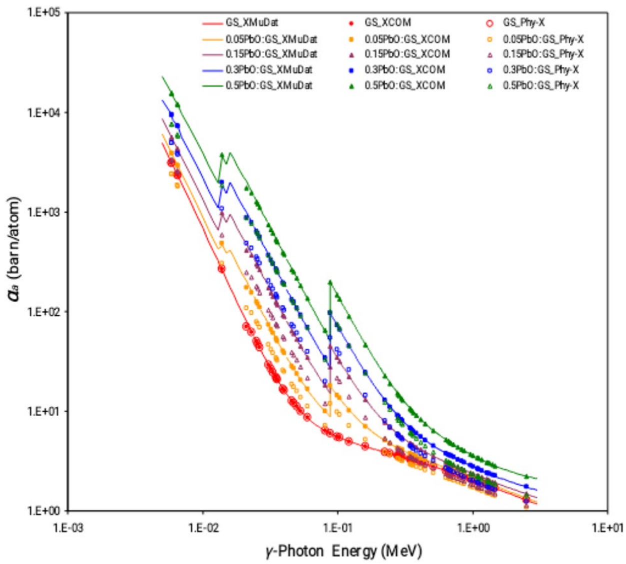

Fig. 5 γ-photons energy dependent variation of α_a of the glasses

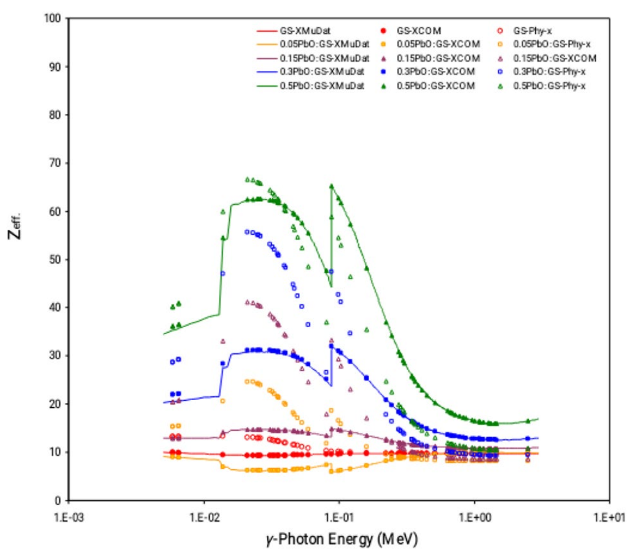

Fig. 6 γ-photons energy dependent variation of $Z_{eff.}$ of the glasses

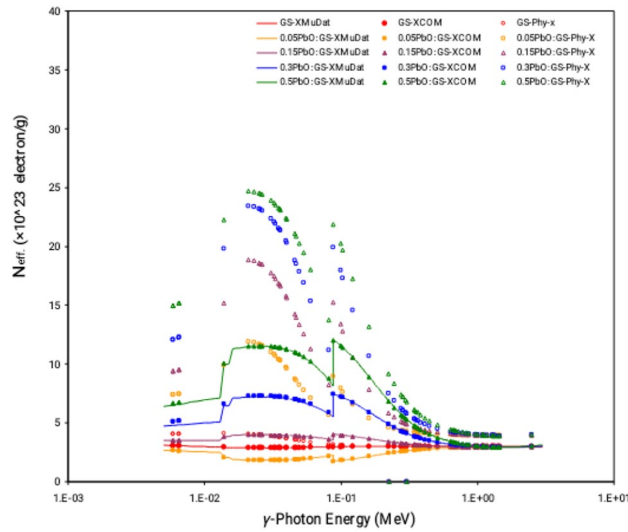

Fig. 7 γ-photons energy dependent variation of $N_{eff.}$ of the glasses

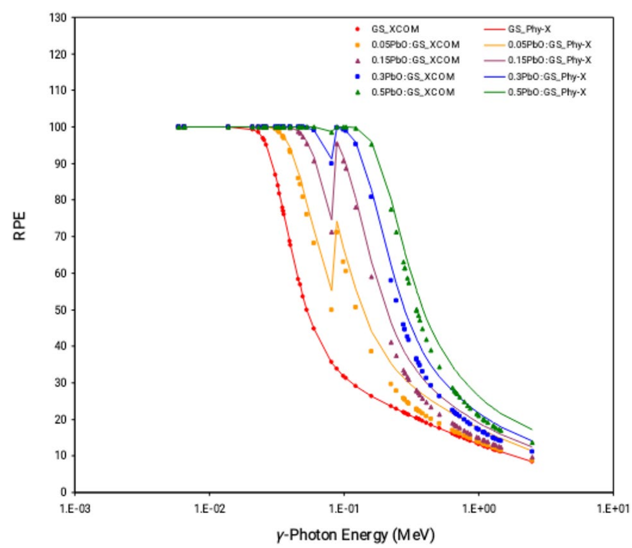

Fig. 8 γ-photons energy-dependent variation of RPE of the glasses

to the absorption edge of the K-shell of Pb atoms in the borosilicate glasses prepared with PbO content above 15%. In addition, the values of Z_{eff} of the glasses were decreased significantly at energies above 0.08804 MeV, wherein the calculated values were less consistent with the theoretical values. Overall, both results for Z_{eff} showed similar behavior except for the glass containing 5% of PbO where the behavior was opposite and incompatible with the theoretical values. In the low energy region, the values of Z_{eff} generally showed a maximum and then decreased to a minimum in the intermediate energy region close to 1 MeV. Later, the values of Z_{eff} began to increase slightly at the higher energies. The reason for this is that the interaction cross-sections of γ-photons strongly depended on the Z values of the glass constituents wherein different interaction processes were involved. In addition, the interaction cross-sections depended on Z as Z^{4-5} in the low-energy region, linearly in the intermediate energy region, and as Z^2 in the high-energy region [34–37].

Figure 7 displays the γ-photons energy-dependent variation of $N_{eff.}$ of the glasses. The values of N_{eff} changed similarly to those of Z_{eff} as a function of the γ-photon energy and PbO content in the glasses. In addition, the calculated and theoretical results were slightly deviated from one another. Figure 8 shows the γ-photons energy-dependent variation of the RPE of the glasses. The RPE values were calculated to evaluate the radiation protection efficiency of the proposed borosilicate glass system as an effective shield. The values of this parameter were calculated based on the values of μ calculated by the XCOM program and on those obtained using the Phy-X program for the values of γ-photons energies emitted from the radioactive sources (Table 2), which were obtained from the Phy-X program. All glasses displayed maximum values for RPE at γ-photons energies up to 0.025 MeV and then the RPE values decreased significantly with the increase of the γ-photons energy. Finally, the values of RPE of the glasses were converged to each other at γ-photons energies close to the end of the studied energy range [38–40].

In short, the increase of doping concentration in the borosilicate glass system significantly improved the RPE values, especially in the energy region of 0.081–0.511 MeV. In addition, the results obtained using the XCOM and Phy-X programs showed good agreement when compared [34–42]. The current investigation demonstrated that HVL, MFP and RPE were greatly improved compared to the P_2O_5–SrO–Sb_2O_3 glass system [40], novel Pb–Al alloys [41], and MgO-Al_2O_3-SiO_2-Li_2O-Na_2O glass system [42], which obtained much smaller values for half-thickness layers and greater values for protection efficiency at the corresponding energies. Earlier studies [22, 43, 44] reported similar alterations in the values of the analysed attenuation parameters in response to variations in impurity concentration, doped glass sample density, and gamma-ray energy.

4 Conclusions

A comparative evaluation was made to examine the γ-photons energy attenuation efficacy of some PbO-doped borosilicate glasses. Programs such as XMuDat, XCOM, and Phy-X were used to calculate various radiative parameters (μ/ρ, μ, $\alpha_{a,}$ and RPE) of the proposed glasses as a function of γ-photons energy obtained from diverse radioactive sources. With the increase of PbO doping contents, the radiation attenuation capability of the glasses was improved. Conversely, the radiation attenuation capacity of the glasses was decreased with the increase of γ-photon energy. The values of both MFP and HVL of the glasses were reduced to the lowest possible values at the highest PbO doping content, showing a significant increase with the increase of γ-photons energy. Theoretically obtained (using the Phy-x program) values of the radiative parameters exhibited good agreement with the ones calculated using XMuDat and XCOM programs. The values of Z_{eff} and N_{eff} displayed random behavior with a very poor agreement between the calculated and theoretical results, wherein the highest values were achieved in the intermediate energy region (0.01–0.1 MeV). Doping borosilicate glass with lead oxide significantly increased its radioactive attenuation capacity, particularly in the region of the medium energies of γ-rays within the range of 0.01–0.25 MeV. It was asserted that the studied PbO-doped borosilicate glass system of the form $0.5PbO:0.12B_2O_3:0.3SiO_2:0.08K_2O$ could be a potential candidate for γ-radiation shielding applications.

Acknowledgements Authors are extremely thankful to Universiti Teknologi Malaysia (UTM), Ministry of Higher Education Malaysia (MOHE), and RMC for research grant FRGS Q.J130000.2509.21H11, and UTM RA ICONIC GRANT Q.J130000.4354.09G60, FRGS-04E86 and UTMFR 21H78. Authors are also grateful to Research Management Centre-Universiti Teknologi Malaysia (RMC-UTM) for supporting them under the Postdoctoral fellowship scheme.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval Authors declare that this manuscript is original, has not been published before, and is not currently being considered for publication elsewhere.

References

1. A.J. Gislason-Lee, Patient X-ray exposure and ALARA in the neonatal intensive care unit: Global patterns. Pediatr. Neonatol. **62**(1), 3–10 (2021)
2. C. Lee, H.R. Kim, S.J. Lee, Comparison of occupational exposure according to dismantling strategy of Kori nuclear power plant unit# 1 bio-shield. Ann. Nucl. Energy **157**, 108227 (2021)
3. M. Dong, X. Xue, H. Yang, D. Liu, C. Wang, Z. Li, A novel comprehensive utilization of vanadium slag: as gamma ray shielding material. J. Hazard. Mater. **318**, 751–757 (2016)
4. M.I. Sayyed, J.F.M. Jecong, F.C. Hila, C.V. Balderas, A.M. Alhuthali, N.R.D. Guillermo, Y. Al-Hadeethi, Radiation shielding characteristics of selected ceramics using the EPICS2017 library. Ceram. Int. **47**(9), 13181–13186 (2021)
5. S.R. Manohara, S.M. Hanagodimath, Studies on effective atomic numbers and electron densities of essential amino acids in the energy range 1 keV–100 GeV. Nucl. Instrum. Methods Phys. Res., Sect. B **258**(2), 321–328 (2007)
6. J. Kaewkhao, J. Laopaiboon, W. Chewpraditkul, Determination of effective atomic numbers and effective electron densities for Cu/Zn alloy. J. Quant. Spectrosc. Radiat. Transfer **109**(7), 1260–1265 (2008)
7. M. Kurudirek, İ Türkmen, Y. Özdemir, A study of photon interaction in some building materials: high-volume admixture of blast furnace slag into Portland cement. Radiat. Phys. Chem. **78**(9), 751–759 (2009)
8. M.J. Aldhuhaibat, M.S. Amana, H. Aboud, A.A. Salim, Radiation attenuation capacity improvement of various oxides via high density polyethylene composite reinforcement. Ceram. Int. **48**(17), 25011–25019 (2022)
9. K. Kirdsiri, J. Kaewkhao, P. Limsuwan, Photon interaction in borate glass doped with Bi2O3 at different energies. Procedia Eng. **32**, 727–733 (2012)

10. A.H. Almuqrin, M.I. Sayyed, Gamma ray shielding properties of Yb3+-doped calcium borotellurite glasses. Appl. Sci. **11**(12), 5697 (2021)
11. N. Singh, K.J. Singh, K. Singh, H. Singh, Comparative study of lead borate and bismuth lead borate glass systems as gamma-radiation shielding materials. Nucl. Instrum. Methods Phys. Res., Sect. B **225**(3), 305–309 (2004)
12. J. Kaewkhao, A. Pokaipisit, P. Limsuwan, Study on borate glass system containing with Bi2O3 and BaO for gamma-rays shielding materials: comparison with PbO. J. Nucl. Mater. **399**(1), 38–40 (2010)
13. K. Kirdsiri, J. Kaewkhao, N. Chanthima, P. Limsuwan, Comparative study of silicate glasses containing Bi2O3, PbO and BaO: radiation shielding and optical properties. Ann. Nucl. Energy **38**(6), 1438–1441 (2011)
14. A. Saeed, Y.H. Elbashar, A.M. Abou El-azm, M.M. El-Okr, M.N.H. Comsan, A.M. Osman, A.M. Abdal-monem, A.R. El-Sersy, Gamma ray attenuation in a developed borate glassy system. Radiat. Phys. Chem. **102**, 167–170 (2014)
15. K. Siengsanoh, W. Chaiphaksa, R. Rajaramakrishna, W. Cheewasukhanont, J. Kaewkhao, Radiation shielding properties of BaO:WO3:Na2O:B2O3 glass system using WinXCom program in the range of 1 keV to 100 GeV: theoretical calculation. J. Phys Conf. Ser. **1259**, 012009 (2019)
16. H. Al-Ghamdi, A.H. Almuqrin, M.I. Sayyed, A. Kumar, The physical, structural and the gamma ray shielding effectiveness of the novel Li2O-K2O–B2O3–TeO2 glasses. Results in Physics **29**, 104726 (2021)
17. M.I. Sayyed, Y. Al-Hadeethi, M.M. AlShammari, M. Ahmed, S.H. Al-Heniti, Y.S. Rammah, Physical, optical and gamma radiation shielding competence of newly borotellurite based glasses: TeO2–B2O3–ZnO–Li2O3–Bi2O3. Ceram. Int. **47**(1), 611–618 (2021)
18. M.S. Al-Buriahi, Y.S.M. Alajerami, A.S. Abouhaswa, A. Alalawif, T. Nutarog, B. Tonguc, Effect of chromium oxide on the physical, optical, and radiation shielding properties of lead sodium borate glasses. J. Non-Cryst. Solids **544**, 120171 (2020)
19. M.S. Al-Buriahi, V.P. Singh, A. Alalawi, C. Sriwunkum, B.T. Tonguc, Mechanical features and radiation shielding properties of TeO2–Ag2O-WO3 glasses. Ceram. Int. **46**, 15464–15472 (2020)
20. M.S. Al-Buriahi, H.H. Hegazy, F. Alresheedi, H.H. Somaily, C. Sriwunkum, I.O. Olarinoye, Effect of Sb2O3 addition on radiation attenuation properties of tellurite glasses containing V2O5 and Nb2O5. Appl. Phys. A **127**(2), 1–12 (2021)
21. M.H.A. Mhareb, Physical, optical and shielding features of Li2O–B2O3–MgO–Er2O3 glasses co-doped of Sm2O3. Appl. Phys. A **126**, 71 (2020)
22. M.S. Al-Buriahi, C. Eke, S. Alomairy, A. Yildirim, H.I. Alsaeedy, C. Sriwunkum, Radiation attenuation properties of some commercial polymers for advanced shielding applications at low energies. Polym. Adv. Technol. **32**(6), 2386–2396 (2021)
23. B. Alshahrani, I.O. Olarinoye, C. Mutuwong, C. Sriwunkum, H.A. Yakout, H.O. Tekin, M.S. Al-Buriahi, Amorphous alloys with high Fe content for radiation shielding applications. Radiat. Phys. Chem. **183**, 109386 (2021)
24. M.S. Al-Buriahi, V.P. Singh, Comparison of shielding properties of various marble concretes using GEANT4 simulation and experimental data. J. Aust. Ceram. Soc. **56**(3), 1127–1133 (2020)
25. H.O. Kathem, M.J. Resen, N.J. Jubier, Characterization of radiation attenuation properties of 0.662 MeV gamma ray energy for epoxy Fe3O4 composite shields. Indian J. Nat. Sci **9**, 14609–14615 (2018)
26. M.J. Aldhuhaibat, M.S. Amana, N.J. Jubier, A.A. Salim, Improved gamma radiation shielding traits of epoxy composites: Evaluation of mass attenuation coefficient, effective atomic and electron number. Radiat. Phys. Chem. **179**, 109183 (2021)
27. M.S. Al-Buriahi, M. Hessien, F. Alresheedi, A.M. Al-Baradi, Z.A. Alrowaili, I. Kebaili, I.O. Olarinoye, ZnO–Bi2O3 nanopowders: fabrication, structural, optical, and radiation shielding properties. Ceram. Int. **48**(3), 3464–3472 (2022)
28. B.T. Tonguc, H. Arslan, M.S. Al-Buriahi, Studies on mass attenuation coefficients, effective atomic numbers and electron densities for some biomolecules. Radiat. Phys. Chem. **153**, 86–91 (2018)
29. E. Şakar, Ö.F. Özpolat, B. Alım, M.I. Sayyed, M. Kurudirek, Phy-X/PSD: development of a user friendly online software for calculation of parameters relevant to radiation shielding and dosimetry. Radiat. Phys. Chem. **166**, 108496 (2020)
30. M.B.Z. Gili, F.C. Hila, Investigation of gamma-ray shielding features of several clay materials using the EPICS2017 library. Philipp. J. Sci. **150**(5), 1017–1026 (2021)
31. M.S. Al-Buriahi, B.T. Tonguc, Mass attenuation coefficients, effective atomic numbers and electron densities of some contrast agents for computed tomography. Radiat. Phys. Chem. **166**, 108507 (2020)
32. M.S. Al-Buriahi, C. Eke, Sultan alomairy., Micro-hardness and gamma-ray attenuation properties of lead iron phosphate glasses. J. Mater. Sci.: Mater. Electron. **32**(10), 1–11 (2021)
33. I. Akkurt, B. Mavi, A. Akkurt, C. Basyigit, S. Kilincarslan, H.A. Yalim, Study on Z dependence of partial and total mass attenuation coefficients. J. Quant. Spectrosc. Radiat. Transfer **94**(3–4), 379–385 (2005)
34. M.S. Al-Buriahi, Z.A. Alrowaili, C. Eke, J.S. Alzahrani, I.O. Olarinoye, C. Sriwunkum, Optical and radiation shielding studies on tellurite glass system containing ZnO and Na2O. Optik **257**, 168821 (2022)
35. A. Edukondalu, S. Stalin, M.S. Reddy, C. Eke, Z.A. Alrowaili, M.S. Al-Buriahi, Synthesis, thermal, optical, mechanical and radiation-attenuation characteristics of borate glass system modified by Bi2O3/MgO. Appl. Phys. A **128**(4), 1–12 (2022)
36. F. Chen, S. Dai, Q. Nie, T. Xu, X. Shen, X. Wang, Glass formation and optical band gap studies on Bi2O3-B2O3-BaO ternary system. Journal of Wuhan University of Technology-Mater. Sci. Ed. **24**(5), 716–720 (2009)
37. J.S. Alzahrani, Z.A. Alrowaili, C. Eke, Z.M. Mahmoud, C. Mutuwong, M.S. Al-Buriahi, Nuclear shielding properties of Ni-, Fe-, Pb-, and W-based alloys. Radiat. Phys. Chem. **195**, 110090 (2022)
38. M.S. Al-Buriahi, Z.A. Alrowaili, S. Alomairy, I.O. Olarinoye, C. Mutuwong, Optical properties and radiation shielding competence of Bi/Te-BGe glass system containing B2O3 and GeO2. Optik **257**, 168883 (2022)
39. O.B. Aljewaw, M.K.A. Karim, H.M. Kamari, M.H.M. Zaid, A.A. Salim, M.H.A. Mhareb, Physical and spectroscopic characteristics of lithium-aluminium-borate glass: Effects of varying Nd2O3 doping contents. J. Non-Cryst. Solids **575**, 121214 (2022)
40. G.A. Alharshan, C. Eke, M.S. Al-Buriahi, Radiation-transmission and self-absorption factors of P2O5–SrO–Sb2O3 glass system. Radiat. Phys. Chem. **193**, 109938 (2022)
41. J.S. Alzahrani, Z.A. Alrowaili, H.H. Saleh, A. Hammoud, S. Alomairy, C. Sriwunkum, M.S. Al-Buriahi, Synthesis, physical and nuclear shielding properties of novel Pb–Al alloys. Prog. Nucl. Energy **142**, 103992 (2021)
42. M.A. Alothman, I.O. Olarinoye, C. Sriwunkum, S. Alomairy, J.S. Alzahrani, M.S. Al-Buriahi, Study of the radiation attenuation properties of MgO-Al2O3-SiO2-Li2O-Na2O glass system. J. Aust. Ceram. Soc. **58**, 267–273 (2022)
43. P. Kaur, K.J. Singh, S. Thakur, M. Kurudirek, Investigation of a competent nontoxic Bi2O3− Li2O− CeO2− MoO3− B2O3 glass system for nuclear radiation security applications. J. Non-Cryst. Solids **545**, 120235 (2020)
44. A. Alalawi, C. Eke, S. Alomairy, O. Alsalmi, C. Sriwunkum, Z.A. Alrowaili, M.S. Al-Buriahi, Attenuation properties and radiation

protection efficiency of Tb2O3-La2O3-P2O5 glass system. J. Aust. Ceram. Soc. **58**(2), 511–519 (2022)

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.