Applied Physics A (2020) 126:301
https://doi.org/10.1007/s00339-020-03494-6

Applied Physics A
Materials Science & Processing

Impact of lead(II) iodide on radiation shielding properties of polyester composites

F. Akman[1,2] · H. Ogul[3,4] · M. R. Kaçal[5] · H. Polat[6] · K. Dilsiz[7] · M. F. Turhan[8]

Received: 11 February 2020 / Accepted: 23 March 2020 / Published online: 30 March 2020

Abstract

This paper investigates the radiation shielding properties, such as linear and mass attenuation coefficients, half and tenth value layers, effective atomic number and electron density, and radiation protection efficiency as a function of photon energy, of a new composite, PbI_2-doped polyester. The mentioned polyester composite was prepared with different proportions of lead(II) iodide (5% increments between 5 and 20%) so that impact of the dopant amount on radiation shielding could be properly analyzed. The prepared composites were tested in 22 different energies in the energy range of 59.5–1408.0 keV with the use of HPGe detector and eight radioactive point sources. The obtained results were further validated by comparing the results of XCOM computer program, and negligible discrepancies were observed. It was observed that PbI_2 (20%) composite is more effective gamma radiation shielding material than other produced composites. In light of this information, it can be said that the shielding efficiency increases with increasing lead(II) iodide amount.

Keywords Radiation shielding · PbI_2-doped polyester composite · Radiation protection efficiency · Mass attenuation coefficient · XCOM

1 Introduction

Radiation is simply defined as transmission of energy in a medium, but it means more than that for life. It could be encountered in some parts of daily life needs, such as in medical applications or in the generation of electricity at nuclear power plants, and so on. However, it could be harmful as much as it could be beneficial. While intended exposure of radiation could save lives, unwanted exposure could cost lives. Therefore, the term of radiation shielding takes duty at this point, which is the process of limiting the penetration of radiations, by blocking them with a barrier made of material attenuates radiation since unwanted exposure of radiation may be hazardous to life and required to be avoided. In this regard, to attenuate/absorb the undesired radiation and to provide radiation shielding for occupational or accidental hazards, researchers have used the traditional way: heavy metals or composites containing heavy metals [1] due to the fact that health risks associated with radiation exposure could threaten to life deathly. Here, it is very well known that heavy metal choice has further hazardous and important consequences, such as penetrative secondary radiations, massive gears or enormous volume of shields. Therefore, experts have focused on composites instead of

✉ F. Akman
fakman@bingol.edu.tr

1 Program of Occupational Health and Safety, Department of Property Protection and Security, Vocational School of Social Sciences, Bingöl University, 12000 Bingöl, Turkey

2 Central Laboratory Application and Research Center, Bingöl University, 12000 Bingöl, Turkey

3 Department of Nuclear Engineering, Faculty of Engineering and Architecture, Sinop University, Sinop, Turkey

4 Department of Physics and Astronomy, Faculty of Science, University of Iowa, Iowa City, IA, USA

5 Department of Physics, Faculty of Arts and Sciences, Giresun University, 28100 Giresun, Turkey

6 Department of Architecture and Urban Planning, Vocational School of Technical Sciences, Bingöl University, 12000, Bingöl, Turkey

7 Department of Physics, Faculty of Arts and Sciences, Bingöl University, 12000, Bingöl, Turkey

8 Department of Medical Imaging Techniques, Atatürk Vocational School of Health Service, Afyonkarahisar Health Sciences University, 03200 Afyonkarahisar, Turkey

only heavy metal usage. Concrete is a very well-known example of composite choice and accepted as the most advantageous option among other choices due to its ease of use and cost. In the past, tungsten and lead from heavy metal family were mixed into the concrete and used to attenuate/block undesired exposure of the radiation. Further discussions and studies revealed that this choice was found to be as disadvantageous since it has durability issue in addition to need of enormous volume to block the radiation completely [2]. Radiation shielding materials such as lead and concrete, which are traditionally used, are heavy because they are quite dense. It is tired to overcome this problem with new materials prepared by mixing heavy metals with lighter materials such as polymers. In addition, such materials/composites have a lower cost compared to lead price increases. In this study, a lighter and less costly new gamma radiation shielding material by adding PbI_2 into polyester resin was obtained.

Due to these well-known facts listed above, attention has recently been paid to production of flexible, cost-effective, lightweight and efficient radiation protection materials. In this regard, significant efforts have been made by researchers to obtain radiation protection materials with desired and needed properties [3–15]. Numerous studies have focused toward using polymer composites, such as polyester and epoxies, where the attenuation of composites is found by the combination of the structural material/s and filler/s. Many theoretical and experimental studies have discussed and reported the impact of these new trend radiation shielding composites [16–20]. Ahmed et al. [21] produced the flexible silicone/tungsten composites containing in different proportions tungsten. They investigated the gamma shielding properties of these composites and compared their results with a composite called T-Flex. They reported that the composite sample containing 88.1% tungsten was a better gamma shielding material than T-Flex. The gamma shielding feature of polyvinyl ester/Pb_2O_3 nanocomposite was investigated by El-Toony et al. [22]. They obtained the some radiation shielding parameters such as linear and mass attenuation coefficients, half and tenth value layers and mean free path for this composite in the energy range of 60–1333 keV. Kaçal et al. [23] investigated the radiation shielding characteristics of polyester composites reinforced with Zn at various photon energies between 59.5 and 1408.0 keV using an HPGe detector. They also checked the experimental results with theoretical and simulation results. All reports presented promising and good characteristics of polymer composites on radiation attenuation, and similar composites could compete with massive concrete and hazardous heavy metal blocks.

In this study, with the motivation of producing a new composite as a well radiation attenuator, a polymer composite, lead(II) iodide (PbI_2)-doped polyester, was produced and its gamma radiation shielding properties, such as linear (μ) and mass attenuation coefficients (μ/ρ), the effective atomic number (Z_{eff}), effective electron density (N_E) and radiation protection efficiency (RPE) with regard to specifically gamma radiation energy, were investigated since, in essence, the shielding efficiency of these composites largely depends on radiation energy and its type [24].

2 Materials and methods

2.1 Sample preparation

As motivated in "Introduction" section, polymer composites recently have been taking attention of many researches since they offer geometric conformability, low-cost and lightweight structure. In this regard, PbI_2-doped polyester composite was chosen as the material of the presented work. To obtain polyester matrix of the motivated study, unsaturated polyester was chosen as base resin, while initiator and accelerator were used as methyl ethyl ketone peroxide and cobalt octoate (6%), respectively. After the production of polyester matrix with resin, initiator and accelerator, PbI_2 was added as a phase material into the mixture at different proportions: 5, 10, 15 and 20%, so that impact of the dopant amount on the composites' radiation shielding property could be properly analyzed. The composites were produced in a mold with a diameter of 20 mm and a thickness of 10 mm. Table 1 further provides the percentage content of elements in polyester composite samples doped with different concentrations of PbI_2. More information can be found in our previous works for the production of doped composites [23, 25, 26].

Table 1 Percentage content of elements in polyester composites doped with different concentrations of PbI_2

Sample	Percent chemical composition						ρ (g/cm^3)
	H	C	O	Co	I	Pb	
PbI_2 (5%)	4.4475	56.9947	34.0057	0.0271	2.4912	2.0337	1.2969
PbI_2 (10%)	4.2550	54.5274	32.5336	0.0260	4.7667	3.8913	1.3122
PbI_2 (15%)	4.0785	52.2649	31.1837	0.0249	6.8533	5.5948	1.3402
PbI_2 (20%)	3.9160	50.1826	29.9413	0.0239	8.7737	7.1625	1.3530

2.2 Sample analysis

The investigation on the gamma radiation shielding properties of prepared PbI_2-doped polyester composite was performed experimentally at laboratory frame and theoretically at a computer-based program. The experimental setup illustrated in Fig. 1 was firstly established. Here, the experimental geometry of the analysis is simply consisting of preamplifier, linear amplifier, high voltage source, multi-channel analyzer (MCA), radioactive source and basic HPGe detector system. To adjust the beam shape, lead collimators were utilized as shown in the figure in addition to usage of sandwich collimator encircled with Pb (1.2 mm), Fe (1.1 mm) and Al (1.0 mm) in order to reduce possible backgrounds. Besides all these, the experiments were conducted with the support of liquid nitrogen to minimize the background noise and to ensure maximum efficiency of detector system. Afterward, the measurements of radiation intensities with the proposed setup were made at 22 different photon energies using the point sources of ^{22}Na, ^{54}Mn, ^{57}Co, ^{60}Co, ^{133}Ba, ^{137}Cs, ^{152}Eu and ^{241}Am, widely ranging from 59.5 to 1408.0 keV.

On the second step of the sample analysis, theoretical calculations were constructed as a function of photon energy using XCOM [27] computer program. The same photon energy range with experimental work was used so that the considered parameters for radiation attenuation determination were properly estimated and compared to the measurements. The theoretical predictions were additionally served to verify the accuracy of the experimental setup.

2.3 Analysis methodology

Using the energy peaks obtained from detector system, the calculations of linear and mass attenuation coefficients, half value layer (HVL), tenth value layer (TVL) and radiation protection efficiency were provided. μ is a measure of the decrease in radiation intensity passing through a target material and can be calculated using Eq. 1, where radiation intensities I_0 and I stand for "initial" and "transmitted" measurements, respectively. Both I and I_0 were obtained with the designed experimental setup and used in further calculations.

$$I = I_0 e^{-\mu x} \tag{1}$$

where x defines the absorber thickness.

In order to verify the precision of the experimental setup and radiation attenuation of the composite, μ/ρ was further calculated using a well-known mixture rule $\left((\mu/\rho)_{\text{comp.}} = \sum W_i(\mu/\rho)_i\right)$, and details of this calculation could be found in Ref. [28]. Other considered radiation attenuation parameters HVL and TVL simply define the required thickness of the sample in order to reduce initial radiation intensity to 1/2 and 1/10, respectively. In order to obtain the mathematical statements of HVL and TVL, Eq. 1 can be easily modified to $\ln 2/\mu$ and $\ln 10/\mu$, respectively.

The effective atomic number and effective electron density values are important radiation interaction parameters as much as linear and mass attenuation coefficients, which should be carefully examined before the application of any material as an attenuator. The calculation of these parameters can be followed by Eqs. (2) and (3) [29].

$$Z_{\text{eff}} = \frac{\sum_i f_i A_i \left(\frac{\mu}{\rho}\right)_i}{\sum_j f_j \frac{A_j}{Z_j}\left(\frac{\mu}{\rho}\right)_j} \tag{2}$$

$$N_E = \frac{Z_{\text{eff}}}{A_{\text{tot}}}\left(N_A n_{\text{tot}}\right) \tag{3}$$

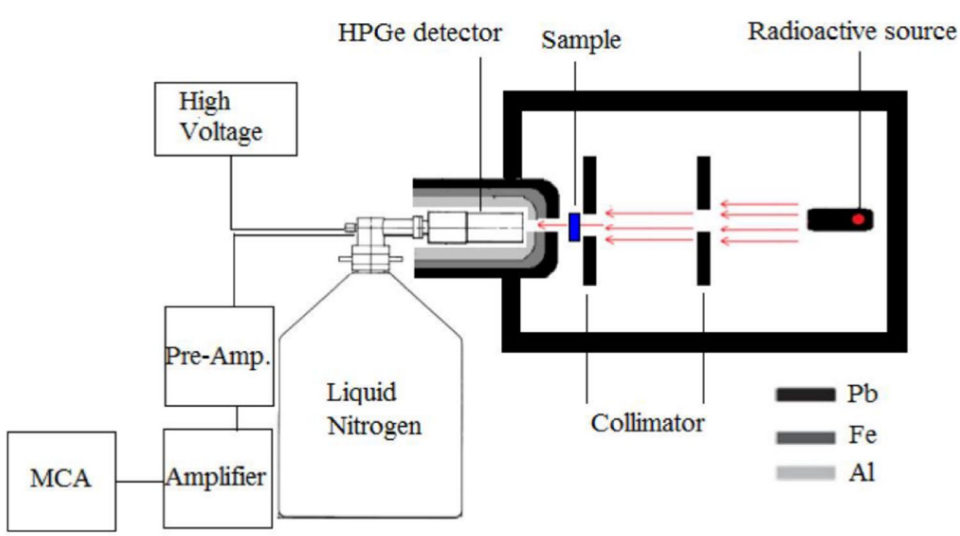

Fig. 1 Overview of experimental setup

where A_i, f_i, Z_j, N_A, A_{tot} and n_{tot} stand for the atomic weight, the fraction by mole of each constituent element of the prepared composite, the atomic number, Avogadro number, total atomic weight and total element number in the composites, respectively. The last analysis parameter considered in this study is radiation protection efficiency (RPE). RPE value of the prepared composite can be determined by employing Eq. 4.

$$\mathrm{RPE} = \left(1 - \frac{I}{I_0}\right) \times 100 \tag{4}$$

3 Results and discussion

As described in the section of analysis methodology, to assess the radiation attenuator, the linear attenuation coefficients were firstly obtained and plotted in a three-dimensional graph given in Fig. 2. The attenuation curves show a decrease in the coefficients exponentially by the increase in the radiation energy and the dopant amount enhancement of the linear attenuation property of the prepared composite. The reason for this exponential reduction is that it is the dominant interaction of photoelectric cross section at low energy levels, Compton scattering cross section at medium energy levels and pair production cross section at high energy levels. Energy dependency of photoelectric, Compton scattering and pair production cross sections is $E^{-3.5}$, E^{-1} and E, while their dependence on atomic number is Z^{4-5}, Z and Z^2, respectively. Besides, the attenuation examination of the materials is often made with the calculation of μ/ρ ratio as well since the linear attenuation depends largely on the density of the material. In this regard, Table 2 provides the experimental and theoretical (XCOM) μ/ρ values of the prepared composites, while Fig. 3 illustrates these numbers as a function of gamma energy. A remarkable agreement between experimental results and theoretical evaluations is found; the maximum disagreement within all considered energies and proportions is about 4.81%. The percentage differences between the experimental and theoretical mass attenuation coefficient values range from 0.45 to 4.77%, 0.31 to 4.70%, 0.26 to 4.81% and 0.20 to 4.79% for PbI_2 (5%), PbI_2 (10%), PbI_2 (15%) and PbI_2 (20%) samples, respectively. This proves the accuracy of the experimental setup, and this setup could be safely used to evaluate the radiation attenuation of PbI_2-doped polyester composites. In addition to accuracy information of the setup, the results highlight that the mass attenuation coefficient decreases exponentially with the increase in gamma radiation energy. In other words, shielding capability of the prepared composite is found to be higher at low energies. Increasing PbI_2 dopant amount was found to increase the mass coefficient almost for all considered energy ranges. This increase is higher at low energies compared to the region of high gamma radiation energy. The mass attenuation coefficient of the composite with PbI_2 (20%) is almost double of the value of the composite with PbI_2 (5%) dopant at low energies, while this difference decreases with the increase in the energy. Even, at higher values, the coefficients are almost the same. In Fig. 4, the mass attenuation coefficients for PbI_2-doped composites, A-, E- and S-type glass fibers [30] and ordinary concrete [31] samples are given comparatively. The mass attenuation coefficient of PbI_2 (5%) composite at 59.5 keV is 75%, 55%, 92% and 725 higher than that of A-glass fiber, E-glass fiber, S-glass fiber and ordinary concrete, respectively. This is calculated as 172%, 141%, 199% and 167% for PbI_2 (10%) composite. This trend increases with increasing PbI_2 in composite, namely 261%, 219%, 297% and 254% for PbI_2 (15%) and 341%, 290%, 385% and 333% for PbI_2 (20%). Accordingly, it can be said that PbI_2-doped composites are better radiation shielding materials than A-, E- and S-type glass fibers, and ordinary concrete at low energies. These percentages decrease rapidly in high energies. The difference between the mass attenuation coefficients of the PbI_2-doped composites and the mass attenuation coefficients of the compared samples is around 3–7%. The reason for this rapid decline in high energies is that the Compton cross section dominates these energy levels. It is directly proportional to the atomic number and inversely proportional to energy.

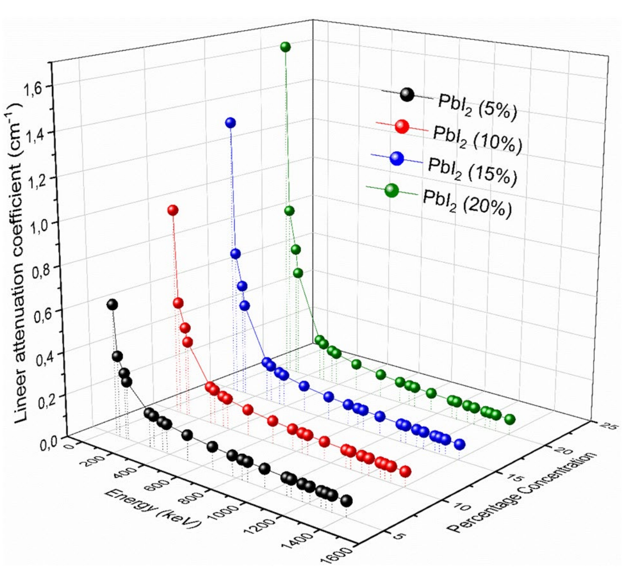

Fig. 2 The obtained linear attenuation coefficients versus different gamma radiation energies and PbI_2 concentrations

The HVL and TVL values should be further discussed since both of them are a good measure to depict the shielding effectiveness of a material against to gamma radiation. As can be seen above formulas, both HVL and TVL are a function of gamma radiation energy due to dependency of

Table 2 Mass attenuation coefficient results for polyester composites doped with different concentrations of PbI_2

Energy (keV)	PbI_2 (5%)		PbI_2 (10%)		PbI_2 (15%)		PbI_2 (20%)	
	Experimental	XCOM	Experimental	XCOM	Experimental	XCOM	Experimental	XCOM
59.5	0.4682 ± 0.0097	0.4768	0.7163 ± 0.0151	0.7415	0.9864 ± 0.0218	0.9828	1.1652 ± 0.0266	1.2015
81.0	0.3031 ± 0.0062	0.2943	0.4125 ± 0.0085	0.4088	0.5354 ± 0.0112	0.5131	0.6285 ± 0.0132	0.6076
122.1	0.2295 ± 0.0050	0.2399	0.3129 ± 0.0070	0.3244	0.4097 ± 0.0092	0.3993	0.4500 ± 0.0106	0.4679
136.5	0.2141 ± 0.0096	0.2118	0.2869 ± 0.0128	0.2745	0.3425 ± 0.0193	0.3300	0.3935 ± 0.0224	0.3809
276.4	0.1262 ± 0.0044	0.1245	0.1370 ± 0.0047	0.1335	0.1388 ± 0.0048	0.1414	0.1526 ± 0.0053	0.1486
302.9	0.1137 ± 0.0029	0.1185	0.1313 ± 0.0031	0.1254	0.1302 ± 0.0032	0.1315	0.1321 ± 0.0033	0.1371
356.0	0.1077 ± 0.0023	0.1091	0.1110 ± 0.0023	0.1135	0.1160 ± 0.0024	0.1173	0.1201 ± 0.0025	0.1207
383.9	0.1057 ± 0.0035	0.1052	0.1117 ± 0.0037	0.1086	0.1127 ± 0.0038	0.1116	0.1170 ± 0.0036	0.1144
511.0	0.0961 ± 0.0020	0.0918	0.0967 ± 0.0020	0.0932	0.0967 ± 0.0020	0.0944	0.0933 ± 0.0019	0.0955
661.7	0.0820 ± 0.0017	0.0812	0.0826 ± 0.0017	0.0817	0.0853 ± 0.0018	0.0821	0.0849 ± 0.0017	0.0825
778.9	0.0764 ± 0.0020	0.0751	0.0784 ± 0.0021	0.0753	0.0718 ± 0.0019	0.0755	0.0747 ± 0.0020	0.0756
834.8	0.0751 ± 0.0018	0.0726	0.0716 ± 0.0018	0.0727	0.0752 ± 0.0019	0.0728	0.0698 ± 0.0018	0.0728
867.4	0.0701 ± 0.0026	0.0713	0.0688 ± 0.0025	0.0713	0.0682 ± 0.0025	0.0713	0.0728 ± 0.0028	0.0714
964.1	0.0674 ± 0.0015	0.0677	0.0663 ± 0.0015	0.0676	0.0677 ± 0.0015	0.0675	0.0696 ± 0.0016	0.0675
1085.9	0.0614 ± 0.0016	0.0638	0.0664 ± 0.0017	0.0636	0.0614 ± 0.0015	0.0635	0.0625 ± 0.0016	0.0633
1112.1	0.0620 ± 0.0013	0.0630	0.0611 ± 0.0013	0.0628	0.0614 ± 0.0013	0.0627	0.0615 ± 0.0013	0.0625
1173.2	0.0591 ± 0.0013	0.0613	0.0613 ± 0.0013	0.0611	0.0637 ± 0.0013	0.0609	0.0580 ± 0.0012	0.0608
1212.9	0.0581 ± 0.0027	0.0602	0.0612 ± 0.0028	0.0600	0.0602 ± 0.0029	0.0599	0.0610 ± 0.0031	0.0597
1274.5	0.0612 ± 0.0013	0.0587	0.0601 ± 0.0013	0.0585	0.0573 ± 0.0012	0.0583	0.0609 ± 0.0013	0.0581
1299.1	0.0554 ± 0.0022	0.0581	0.0605 ± 0.0023	0.0579	0.0551 ± 0.0023	0.0577	0.0574 ± 0.0020	0.0576
1332.5	0.0581 ± 0.0012	0.0574	0.0548 ± 0.0011	0.0571	0.0583 ± 0.0012	0.0569	0.0566 ± 0.0012	0.0568
1408.0	0.0537 ± 0.0011	0.0558	0.0581 ± 0.0012	0.0555	0.0544 ± 0.0011	0.0553	0.0559 ± 0.0011	0.0552

the linear attenuation coefficient, μ. After the calculation of the linear attenuation coefficients, $\ln 2/\mu$ and $\ln 10/\mu$ formulas were satisfied to obtain desired parameters. Figures 5 and 6 present the outcomes of these calculations, and it is found that both HVL and TVL increase with the increase in radiation energy. The HVL value of the composite with PbI_2 (20%) is smaller than others, which means that this sample shows better attenuation of radiation. The HVL and TVL values of prepared composites at different proportions studied herewith were increased in the order as PbI_2 (20%) < PbI_2 (15%) < PbI_2 (10%) < PbI_2 (5%).

In addition, to identify the prepared composites' radiation shielding property, effective atomic number and electron density parameters are crucial knowledge. In essence, the higher effective atomic number means the higher number of electrons per atom; both parameters are related to each other [32]. These parameters are calculated by following Eqs. (2) and (3) and illustrated in Figs. 7 and 8, respectively. The obtained results show distinctive differences for the considered composites. As expected, Z_{eff} and N_E behave the same, and they decrease with an increase in the gamma radiation energy for all samples. Besides, a remarkable difference between the values of Z_{eff} for PbI_2 (5%) and PbI_2 (20%) was found, where the values were increased in the order of PbI_2 (5%) < PbI_2 (10%) < PbI_2 (15%) < PbI_2 (20%), where Z_{eff} for PbI_2 (20%) is about two times of Z_{eff} for PbI_2 (5%) at low energies and about 15% higher than Z_{eff} for PbI_2 (5%) at high energies. Here, all evaluations for Z_{eff} are valid for N_E parameter as well. Based on the evaluation of Z_{eff} and N_E, PbI_2 (20%) indicates a better radiation attenuator property.

The last parameter investigated in this work is RPE determination of prepared composites as a function of radiation energy. It was calculated for four different prepared composites with the proportions of PbI_2 (5%), PbI_2 (10%), PbI_2 (15%) and PbI_2 (20%). The obtained results are shown in Fig. 9, and it is easily seen that RPE is inversely proportional to the radiation energy. Besides, it is found that the maximum RPE value is observed with the composite consisting of PbI_2 (20%).

4 Conclusions

PbI_2-doped polyester composites were produced at different proportions of lead iodide to depict their gamma radiation shielding effectiveness. The prepared composites placed into a narrow-beam geometry and the radiation intensities have been investigated at different gamma radiation energies ranging from 59.5 to 1408.0 keV. Based on the obtained radiation intensities, linear attenuation coefficient, mass

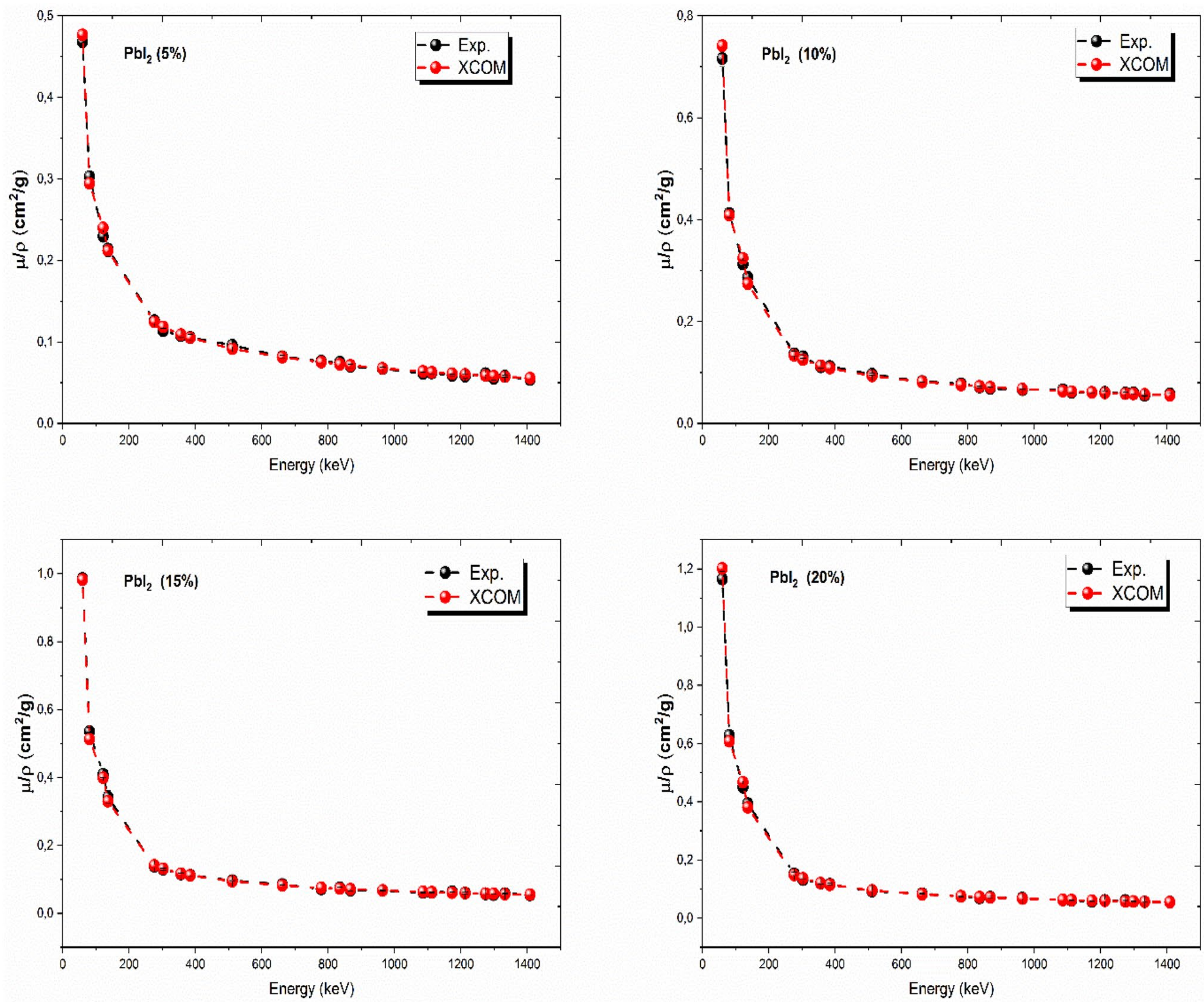

Fig. 3 Comparison of theoretical and experimental mass attenuation coefficients as a function of gamma energy

attenuation coefficients, half value layer, tenth value layer, the effective atomic number (Z_{eff}), effective electron density (N_E) and radiation protection efficiency (RPE) parameters were obtained to determine whether the proposed composite was applicable as radiation attenuator. The accuracy of the experimental setup was cross-checked with theoretical predictions computed using XCOM computer program, and negligible discrepancies were observed. The results confirmed the attenuation ability of PbI_2-doped polyester composites in the considered gamma energies. Effectiveness in radiation attenuation/absorption increases with increasing the concentration of PbI_2. In addition, it was observed that the linear and mass attenuation coefficients, effective atomic number and electron density, and radiation protection efficiency parameters decrease exponentially with increasing photon energy, while the half and tenth value layers parameters increase with increasing photon energy. The increase in half and tenth value layers parameters means that a thicker material is needed at high energies. According to the determined radiation shielding parameters, it can be said that PbI_2 (20%) composite is a more capable gamma-ray attenuation material than other produced PbI_2-doped composites. The presented experimental and theoretical data will provide a significant contribution to health physics, research in nuclear physics, X-ray and radiation oncology units of hospitals, radiation physics, nuclear power plants, etc.

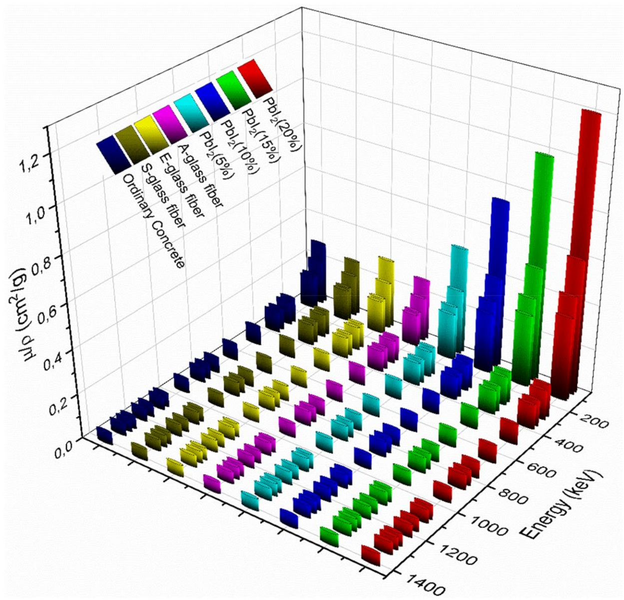

Fig. 4 Comparison of mass attenuation coefficients of produced composites with that of ordinary concrete and some glass fibers

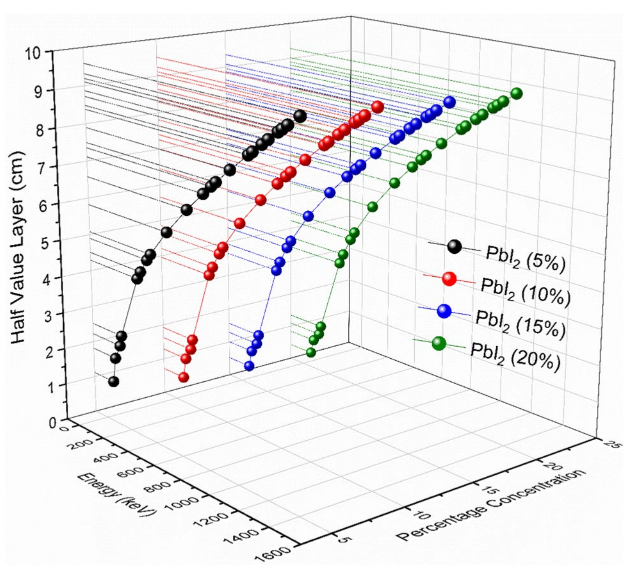

Fig. 5 Three-dimensional HVL distribution for the prepared composites

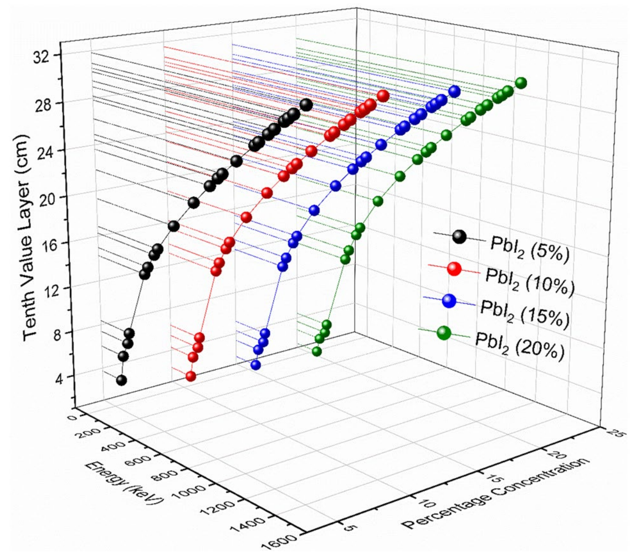

Fig. 6 Three-dimensional TVL distribution for the prepared composites

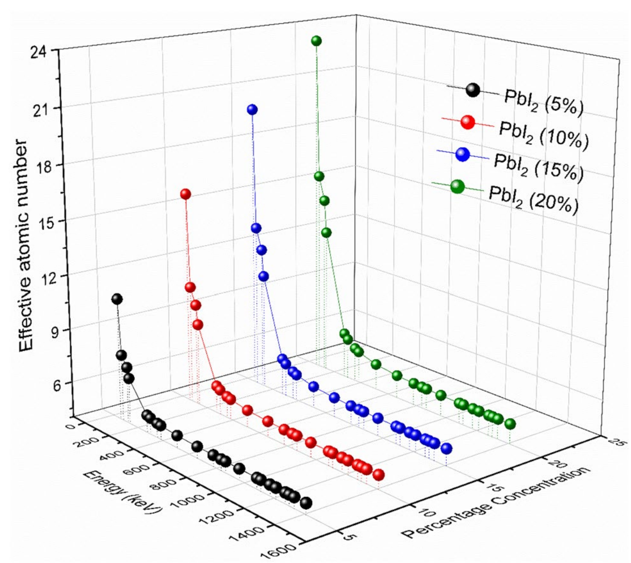

Fig. 7 The effective atomic number for prepared composite samples

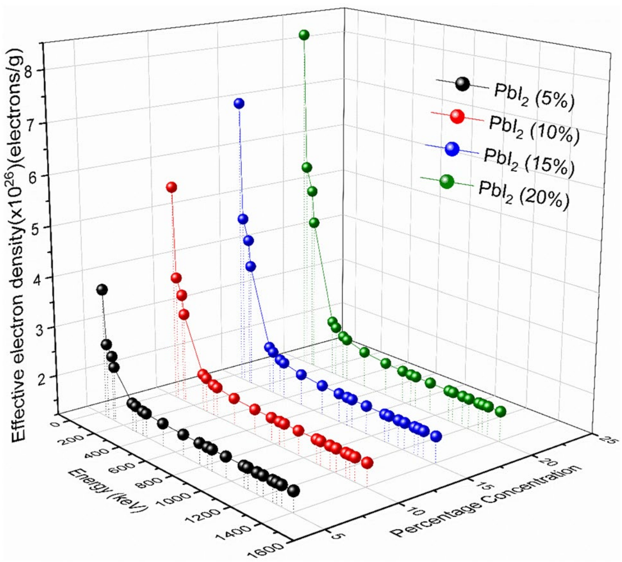

Fig. 8 The effective electron density for prepared composite samples

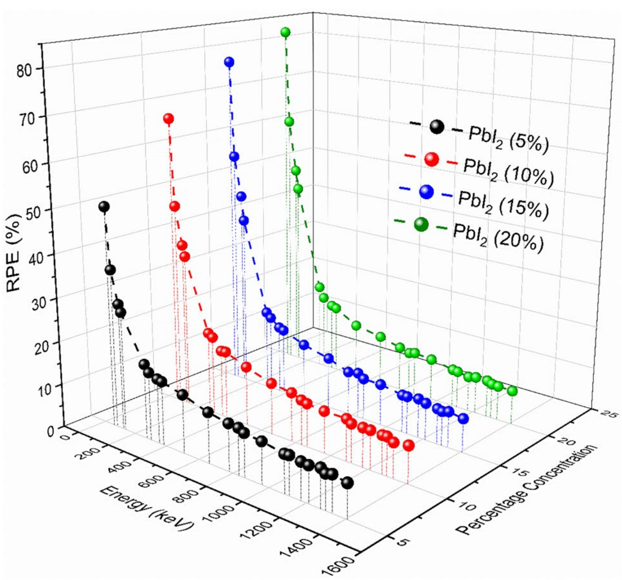

Fig. 9 The radiation protection efficiency as a function of gamma radiation energy

References

1. S. Nambiar, J.T.W. Yeow, Polymer-composite materials for radiation protection. Appl. Mater. Interfaces **4**, 5717–5726 (2012)
2. I. Akkurt, H. Akildirim, B. Mavi, S. Kilincarslan, C. Basyigit, Photon attenuation coefficients of concrete includes barite in different rate. Ann. Nucl. Energy **37**, 910–914 (2010)
3. M.I. Sayyed, F. Akman, V. Turan, A. Araz, Evaluation of radiation absorption capacity of some soil samples. Radiochim. Acta **107**, 83–93 (2019)
4. M.R. Kaçal, F. Akman, M.I. Sayyed, Investigation of radiation shielding properties for some ceramics. Radiochim. Acta **107**, 179–191 (2019)
5. F. Akman, Z.Y. Khattari, M.R. Kaçal, M.I. Sayyed, F. Afaneh, The radiation shielding features for some silicide, boride and oxide types ceramics. Radiat. Phys. Chem. **160**, 9–14 (2019)
6. O. Agar, H.O. Tekin, M.I. Sayyed, M.E. Korkmaz, O. Culfa, C. Ertugay, Experimental investigation of photon attenuation behaviors for concretes including natural perlite mineral. Results Phys. **12**, 237–243 (2019)
7. M.G. Dong, O. Agar, H.O. Tekin, O. Kilicoglu, K.M. Kaky, M.I. Sayyed, A comparative study on gamma photon shielding features of various germanate glass systems. Compos. Part B Eng. **165**, 636–647 (2019)
8. A. Sharma, M.I. Sayyed, O. Agar, M.R. Kaçal, H. Polat, F. Akman, Photon-shielding performance of bismuth oxychloride-filled polyester concretes. Mater. Chem. Phys. **241**, 122330 (2020)
9. H.O. Tekin, V.P. Singh, T. Manici, Effects of micro-sized and nano-sized WO_3 on mass attenuation coefficients of concrete by using MCNPX code. Appl. Radiat. Isot. **121**, 122–125 (2017)
10. H.O. Tekin, T. Manici, Simulations of mass attenuation coefficients for shielding materials using the MCNP-X code. Nucl. Sci. Technol. **28**, 95 (2017)
11. B. Oto, A. Gür, E. Kavaz, T. Çakır, N. Yaltay, Determination of gamma and fast neutron shielding parameters of magnetite concretes. Prog. Nucl. Energy **92**, 71–80 (2016)
12. A. Levent, E. Kavaz, Y. Özdemir, An experimental study on the investigation of nuclear radiation shielding characteristics in iron-boron alloys. J. Alloy. Compd. **819**, 152946 (2020)
13. B.O. El-Bashir, M.I. Sayyed, M.H.M. Zaid, K.A. Matari, Comprehensive study on physical, elastic and shielding properties of ternary $BaO–Bi_2O_3–P_2O_5$ glasses as a potent radiation shielding material. J. Non-Cryst. Solid **468**, 92–99 (2017)
14. S.S. Obaid, D.K. Gaikwad, P.P. Pawar, Determination of gamma ray shielding parameters of rocks and concrete. Radiat. Phys. Chem. **144**, 356–360 (2018)
15. M.A.M. Uosif, A.M.A. Mostafa, S.A.M. Issa, H.O. Tekin, Z.A. Alrowaili, O. Kilicoglu, Structural, mechanical and radiation shielding properties of newly developed tungsten lithium borate glasses: an experimental study. J. Non-Cryst. Solid **532**, 119882 (2020)
16. M.A. El-Sarraf, A. El-SayaedAbdo, Insulating epoxy/barite and polyester/barite composites for radiation attenuation. Appl. Radiat. Isot. **79**, 18–24 (2013)
17. A. El-Sayed, M.A.M. Ali, M.R. Ismail, Natural fibre high-density polyethylene and lead oxide composites for radiation shielding. Radiat. Phys. Chem. **66**, 185–195 (2003)
18. C. Zeitlin, S.B. Guetersloh, L.H. Heilbronn, J. Miller, Measurements of materials shielding properties with 1 GeV/nuc ^{56}Fe. Nucl. Instrum. Methods Phys. Res. Sect. B **252**, 308–318 (2006)
19. M. Tajiri, Y. Tokiya, J. Uenishi, M. Sunoka, K. Watanabe, New shielding materials for clinical electron beams. Radiother. Oncol. **80**, 391–393 (2006)
20. D.Y. Stewart, P.F. Harrison, B. Morgan, Y. Ramachers, Radiation shielding for underground low-background experiments. Nucl. Instrum. Methods Phys. Res. Sect. A **571**, 651–662 (2007)
21. B. Ahmed, G.B. Shah, A.H. Malik, M.R. Aurangzeb, Gamma-ray shielding characteristics of flexible silicone tungsten composites. Appl. Radiat. Isot. **155**, 108901 (2020)
22. M.M. El-Toony, Gh Eid, H.M. Algarni, T.F. Alhuwaymel, E.E. Abelhady, Synthesis and characterisation of smart poly vinyl ester/Pb_2O_3 nanocomposite for gamma radiation shielding. Radiat. Phys. Chem. **168**, 108536 (2020)
23. M.R. Kaçal, H. Polat, M. Oltulu, F. Akman, O. Agar, H.O. Tekin, Gamma shielding and compressive strength analyses of polyester composites reinforced with zinc: an experiment, theoretical, and simulation based study. Appl. Phys. A **126**, 205 (2020)

24. M. Erdem, O. Baykara, M. Dogru, F. Kuluozturk, A novel shielding material prepared from solid waste containing lead for gamma ray. Radiat. Phys. Chem. **79**, 917–922 (2010)
25. F. Akman, M.R. Kaçal, N. Almousa, M.I. Sayyed, H. Polat, Gamma-ray attenuation parameters for polymer composites reinforced with $BaTiO_3$ and $CaWO_4$ compounds. Prog. Nucl. Energy **121**, 103257 (2020)
26. A. Sharma, M.I. Sayyed, O. Agar, M.R. Kaçal, H. Polat, F. Akman, Photon-shielding performance of bismuth oxychloride-filled polyester concrete. Mater. Chem. Phys. **241**, 122330 (2020)
27. L. Gerward, N. Guilbert, K. Jensen, H. Levring, WinXCom—a program for calculating X-ray attenuation coefficients. Radiat. Phys. Chem. **71**, 653–654 (2004)
28. D.F. Jackson, D.J. Hawkes, X-ray attenuation coefficients and elements and mixtures. Phys. Rep. **70**, 169–233 (1981)
29. S.R. Manohara, S.M. Hanagodimath, K.S. Thind, L. Gerward, On the effective atomic number and electron density: a comprehensive set of formulas for all types of materials and energies above 1 keV. Nucl. Instrum. Methods B **266**, 3906–3912 (2008)
30. T.P. Sathishkumar, S. Satheeshkumar, J. Naveen, Glass fiber-reinforced polymer composites—a review. J. Reinf. Plast. Compos. **33**(13), 1258–1275 (2014)
31. I.I. Bashter, Calculation of radiation attenuation coefficients for shielding concretes. Ann. Nucl. Energy **24**(17), 1389–1401 (1997)
32. U. Cevik, H. Baltas, Measurement of the mass attenuation coefficients and electron densities for BiPbSrCaCuO superconductor at different energies. Nucl. Instrum. Methods Phys. Res. Sect. B **256**, 619–625 (2007)