EFFECT OF Pbo INCORPORATION WITH DIFFERENT PARTICLE SIZE ON X-RAY ATTENUATION OF POLYSTYRENE

by

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> Scientific paper https://doi.org/10.2298/NTRP2201018O

Lead oxide (PbO) bulk and nanoparticles of two different sizes (A = 78 nm and B = 54 nm) are incorporated separately into the polystyrene matrix at various concentrations (0, 10, 15, 25, and 35 %) using roll mill mixing and compressing molding techniques. The X-ray narrow-spectrum series (N-series / ISO 4037-1) is then used to investigate the radiation attenuation capability of the novel polymer composite PS/PbO, as well as the effect of varying PbO particle sizes on shielding performance. The filler dispersion and chemical elemental analysis of the synthesized composite are investigated using scanning electron microscopy and energy-dispersive X-ray spectroscopy. To determine the mass attenuation coefficients m, samples with various thicknesses of the synthesized composite are examined using a range of X-ray energies, and the experimental data are compared to theoretical values from NIST databases (XCOM and FFAST). The results indicate that either increasing the filler weight percentage or, decreasing the filler particle size, enhanced the attenuation parameters throughout all energies. The composite containing the smallest nanosize of PbO exhibited the maximum radiation shielding efficacy among all combinations and therefore, might be used to develop low-cost and lightweight X-ray shields.

Key words: X-ray shielding, polystyrene, lead oxide, nano-composite, radiation protection

INTRODUCTION

The X-ray spectra are a combination of narrow peaks on a continuous spectrum, formed as a result of characteristics and bremsstrahlung radiation. The majority of diagnostic X-ray energies are in the range of 25 keV to around 200 keV [1]. The energy spectrum of the X-ray beam is critical in both diagnostics and therapeutics for the correction of beam hardening artifacts, the prediction of image quality, and the evaluation of detector performance [2]. Regular calibration of all radiation instruments is maintained, based on international standards set by the International Atomic Energy Agency (IAEA) and the World Health Organization (WHO), for precise and accurate dose measurements [3, 4]. Radiation beams, either in industry or medicine, are calibrated using radiation detectors having directly or indirectly traceable radiation coefficient compared to a primary standard. The primary standards are supported by the primary standards dosimetry laboratories (PSDL) worldwide. In turn, the PSDL calibrates secondary standard dosimeters for the secondary standards dosimetry laboratories (SSDL) which are used to calibrate the user's reference instruments in hospitals (ionization chambers) or radiation processing calorimeters [5, 6].

Around 80 % of X-ray doses received by the overall population are from medical diagnostic X-ray examinations. To overcome the adverse effects of radiation, it is strongly recommended to utilize shielding materials with a high atomic number (Z). Due to its effectiveness in providing high levels of protection against ionizing radiation and its low-cost, lead (82Pb) with a high density (11.35 gcm⁻³) has been widely used, in the form of sheets, foils, plates, and bricks, to block radioactive diffusions [7, 8]. To counter the high weight and toxicity of the heavy metal, efforts have been made to replace it with lead oxide PbO which, when incorporated into polymers, enhances the radiation shielding ability of such composites [9, 10]. Polystyrene (PS) is a brittle thermoplastic polymer, that has a high degree of transparency, rigidity, and viscosity. PS is utilized in a range of applications, including electrical and thermal insulation, due to its ease of manu-

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facture and inexpensive cost, as well as its resistance to alcohols, alkalis, oils, and acids [11]. In their review of radiation shielding polymeric composites, More *et al.* [12] revealed that PS has been widely used since it is a thermoplastic that can be recycled. Polymer composites are new promising materials for radiation shielding due to their lightweight, adaptability, and low cost [13, 14].

Cinan et al. [15] investigated the shielding efficiency of PbO doped cross-linked polystyrene-bpolyethylene glycol (PS-b-PEG) and polystyrene-bpolyethylene glycol-boron nitride (PS-b-PEG-BN) nanocomposites, synthesized by emulsion polymerization methods. The samples were irradiated in various gamma-ray photon energy regions of ¹⁵²Eu (from 121.78 keV to 1408.01 keV). The obtained results showed that the linear attenuation μ decreases when energy increases and the radiation protection capacities of the samples were improved when PbO percentages increased. Azman et al. [16] investigated the X-ray radiation shielding capabilities of epoxy composites filled with PbO and Pb₃O₄. The obtained results demonstrated that such composites exhibit strong attenuation capabilities, suggesting that they are suitable for diagnostic radiology shielding with reduced health risks associated with Pb. Ghaseminejad et al. [17] investigated the X-ray attenuation property of the resin-epoxy composite synthesized by adding 5 and 10 wt.% of graphene oxide (GO), and 5 and 10 wt.% of modified graphene oxide-lead oxide (GO-PbO). The synthesized composites were placed at a distance of 60 cm from diagnostic X-rays, to measure the X-ray mass attenuation coefficients at 20 kV, 40 kV, 60 kV, and 80 kV, at peak. The results showed that among all the samples, the composite with 10 wt.% of GO-modified PbO in epoxy has the best X-ray shielding property. Mahmoud et al. [18] conducted an intriguing investigation on the effect of particle size on the radiation attenuation capabilities of a composite. Lead oxide PbO nanoparticles were prepared by the combustion method. PbO bulk and PbO nanoparticles were incorporated into high-density polyethylene (HDPE) with weight fractions of 10 % and 50 %. The prepared composites (HDPE/PbO Blk and HDPE/PbO NP) were then evaluated for radiation shielding efficiency using four typical radioactive point sources (²⁴¹Am, ¹³³Ba, ¹³⁷Cs, and ⁶⁰Co). The results indicated that, for all energies, the linear and mass attenuation coefficients rose significantly as the weight percentage of PbO in the HDPE matrix increased. Additionally, for the same weight fraction, an increase in the attenuation coefficient values was observed for PbO NP filled composites, compared to PbO Bulk filled composites. Kumar et al. [19] used the MCNP code to evaluate the mass attenuation coefficient, μ_m , half-value layer (HVL), mean-free-path (MFP), tenth-value layer (TVL), and effective atomic number (Z_{eff}) values of a multi-component glass series, and precisely determining the impact of the PbO/GeO₂ addition on the composite properties. The obtained results showed that bismuth borate glass with PbO/GeO₂ of 30 mol % has the lowest MFP and HVL values, hence offering greater radiation protection efficiency than all the other combinations.

This work provided a new economical, cost-effective, and easy processing composite material for shielding against X-rays. Moreover, the particle size effect of PbO as a filler, through the incorporation of various amounts (10 wt.%, 15 wt.%, 25 wt.%, and 35 wt.%) of either bulk, or PbO nanoparticles of size 78 nm and 52 nm, into the PS polymer matrix, were investigated. The X-ray shielding capabilities of the PS/PbO composites were examined using a narrow-spectrum X-ray beam (N-series) in an SSDL at the Lebanese Atomic Energy Commission (LAEC). Narrow-spectrum series is critical for calibrating radiation protection instruments and determining radiation doses [20, 21]. The purpose of this research is to find the optimal particle size of PbO to employ as a filler within the PS polymer to produce lightweight composites with remarkable shielding performance against X-ray radiation.

THEORETICAL VIEWPOINT

The linear attenuation coefficient

The linear attenuation coefficient μ [cm⁻¹], describes the fraction of incident photons attenuated in a monoenergetic beam, per unit thickness of a material. It takes into account all the possible interactions, such as coherent scattering, Compton scatter, and the photoelectric effect. The linear attenuation coefficient increases as the atomic number and physical density of the absorbing material increase. It decreases as photon energy increases, except at K-edge [22]. The intensity of the beam at a distance *x* (cm) within a material is calculated using the Beer-Lambert law.

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

where *I* is the intensity at a depth of *x* (cm), I_0 – the initial intensity, and μ – the linear attenuation coefficient.

The mass attenuation coefficient

The mass attenuation coefficient μ_m is a normalization of the linear attenuation coefficient per unit density ρ of a material, yielding a constant value for any given element or compound. It's expressed as

$$\mu_{\rm m} \quad \frac{\mu}{\rho} \tag{2}$$

Half and tenth value layers

The *HVL* and *TVL* are the thicknesses or layers of a shield or absorber that reduce the intensity of radia-

tion by one-half and one-tenth of the initial intensity, respectively.

$$HVL \quad \frac{Ln2}{\mu} \tag{3}$$

$$TVL \quad \frac{Ln10}{\mu} \tag{4}$$

Relaxation length

The average distance between two successive interactions is called the relaxation length λ ; it is also called a photon mean free path and can be calculated from the value of the linear attenuation coefficient μ [cm⁻¹]

$$\lambda = \frac{1}{\mu}$$
 (5)

Heaviness

The heaviness of the composite was calculated according to pure lead as a standard normalized to 100 %, using the following formula

Heaviness
$$\frac{\text{Density of composite}}{\text{Density of lead}} 100[\%]$$
 (6)

MATERIALS AND METHODS

Materials

Commercial PS purchased from Egyptian Styrene Polystyrene Production Company, with a density of 1.03 gcm^{-3} and melt flow rate of 11.10 g per 10 min, was used as a polymer matrix. Lead (II) oxide (PbO) from Sigma-Aldrich, yellow powder with purity 99.00 %, molecular weight 223.30 gmol⁻¹, and density 9.53 gcm⁻³, was utilized for the synthesis of PbO nanoparticles and used as fillers in the composites.

The PbO nanoparticles synthesis

Retsch PM 100 planetary ball milling machine was used for the preparation of PbO nanoparticles. The milling process was conducted in a 250 ml zirconium oxide jar, the weight ratio of the zirconium ball of powder was 10:1, and the rotation speed was set to 400 rpm. The milling operation was repeated for four different milling times (15, 30, 60, and 120 minutes). Each milling process consisted of a 5-minute grind followed by a 1-minute break to avoid overheating of metal oxide particles. The PbO particles grinded for 30 and 60 minutes achieved nano sizes of 78 nm and 54 nm, respectively, and were denoted PbO NP(A) and PbO NP(B).

The PS/PbO composite synthesis

The preparation of PS/PbO composite was performed using roll mill mixing and compression mold-

ing techniques by adding various amounts (0 wt.%, 10 wt.%, 15 wt.%, 25 wt.%, and 35 wt.%) of either bulk, PbO NP(A), and PbO NP(B) as fillers, as described in tab. 1. In this method, PbO and polystyrene with appropriate proportions were sensitively weighed and mixed thoroughly in a two-roll mill mixer (XK400, Shandong, China) at 200 °C. To ensure proper filler distribution and composite homogeneity, the mixing duration and roll speed were set to 30 minutes and 50 rpm, respectively. The sample was gathered, grinded, and spilled into a mold of stainless steel (25 cm \times 25 cm \times 0.3 cm) then placed between teflon layers to get a smooth surface. The next step consists of hot pressing the sample for 15 minutes at 200 °C and 20 MPa by applying the hydraulic press. After sintering, the shaped composite sample was gradually cooled to ambient temperature under compression for 15 minutes. A template of the specimen's shapes for required tests was prepared and disc specimens of 8.5 cm diameter were cut from the prepared samples for the evaluation of radiation properties, as shown in tab. 1.

EXPERIMENTAL TECHNIQUES

Sample density measurement

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The apparent density ρ of the samples was determined according to the Archimedes principle based on the following expression.

$$\rho = \frac{M}{M_a - M_w} \rho_w \tag{7}$$

where M, M_a , and M_w are the mass of the sample weighed at the balance, the mass weighed when the sample is hanging on the balance arm suspended in the air, and the mass weighed when the sample is hanging on the balance arm immersed in water, respectively,

Table 1. Code and composition of the prepared samples

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Sample code	Description
PS	Polystyrene without reinforcement
PbO bulk	Lead oxide as provided by Sigma Aldrich
PbO NP(A)	Lead oxide nanoparticle size 78 nm
PbO NP(B)	Lead oxide nanoparticles size 52 nm
PS/PbO Bulk10	PS reinforced with 10 wt.% of PbO Bulk
PS/PbO Bulk15	PS reinforced with 15 wt.% of PbO Bulk
PS/PbO Bulk25	PS reinforced with 25 wt.% of PbO Bulk
PS/PbO Bulk35	PS reinforced with 35 wt.% of PbO Bulk
PS/PbO NP(A)10	PS reinforced with 10 wt.% of PbO NP(A)
PS/PbO NP(A)15	PS reinforced with 15 wt.% of PbO NP(A)
PS/PbO NP(A)25	PS reinforced with 25 wt.% of PbO NP(A)
PS/PbO NP(A)35	PS reinforced with 35 wt.% of PbO NP(A)
PS/PbO NP(B)10	PS reinforced with 10 wt.% of PbO NP(B)
PS/PbO NP(B)15	PS reinforced with 15 wt.% of PbO NP(B)
PS/PbO NP(B)25	PS reinforced with 25 wt.% of PbO NP(B)
PS/PbO NP(B)35	PS reinforced with 35 wt.% of PbO NP(B)

where ρ_w is the density of water (1.00 gcm⁻³). A calibrated balance (M-120, Denver Instrument) with a precision of 0.1 mg was used for mass evaluation. Equation (8) was used to calculate the theoretical density values for the composites

$$\rho_T = \frac{100}{M_m / \rho_m - M_f / \rho_f} \tag{8}$$

where $M_{\rm m}$ is the wt.% of PS, $M_{\rm f}$ – the wt.% of PbO, $\rho_{\rm m}$ – the density of PS, and $\rho_{\rm f}$ – the density of PbO.

Scanning electron microscope – energy dispersive x-ray spectroscopy (SEM-EDS)

Samples were coated with a 5 nm gold layer using a magnetron sputtering machine (Quorum Q150R ES, Japan) to inhibit charging during the imaging process since the composite is polymer-based. All samples were then analyzed by SEM (JCM-6000 plus, JEOL, Japan). Images were taken at three different magnification orders (100, 900, and 1500) under a low vacuum at 15 kV using PC-High mode. EDS quantitative analysis was also performed at magnification order 100 to study the elemental composition of the samples.

Experimental setup for X-ray attenuation measurements

The X-ray shielding parameters, such as mass attenuation coefficients, half-value layer, tenth-value layer, and heaviness, were evaluated by investigating the radiation attenuation performance of the polymer composite at the Secondary Standard Dosimetry Laboratory (SSDL, LAEC). The set-up of the experiment was mainly divided into four parts:

- The X-ray tube (irradiator).
- The narrow-spectrum filtration (Quality beam).
- The samples and holder.
- The radiation detection system.
 - The detailed system setup is described in fig. 1.

The COMET MXR225/22 X-ray tube was used for irradiation with a beam collimation diameter of 3 cm, as shown in fig. 1. The *N*-type filters, which are placed 4 cm from the tube collimator and have a diameter of 7 cm, are described in tab. 2 [23]. The resulting beam is the *N*-series reference X-ray beam recommended by ISO 4037-1, and used with tube voltage ranging from 40 to 250 kV for radiation protection purposes (narrow-spectrum series: N-40 to N-250). The sample is placed 45 cm away from the X-ray tube on a holder with a 7 cm collimator and a 5 cm horizontal support.

The solid-state detector (Radcal, AGMS-DM+, USA) is placed 50 cm away from the X-ray tube and is connected to the electrometer (Radcal Accu Gold) lo-

Fable 2. C	Characteristics	of the N-type fi	lters of X-ray spectra
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	Thickness [mm]							
	N filter composition Added Al							
X-ray quality	Pb	Sn	Cu	Al				
N-40			0.213	3.8				
N-60			0.616	3.8				
N-80			1.980	3.8				
N-100			5.0	3.8				
N-120		1.016	4.964	3.8				
N-150		2.621		3.8				
N-200	1.065	3.219	1.980	3.8				
N-250	3.099	2.142		3.8				



Figure 1. The experimental set-up for the radiation attenuation measurements

N-series	X-ray tube voltage [kV]	E _{mean} [keV]	Tube current [mA]
N-40	40	33	10
N-60	60	48	15
N-80	80	65	15
N-100	100	83	15
N-120	120	100	10
N-150	150	118	10
N-200	200	164	5

 Table 3. The values of mean energy and COMET recommendation for tube current

cated in the SSDL's control room. The AGMS-DM+ is a solid-state multi-parameter detector with a detection dose threshold of 80 nGy and a 5 % accuracy. It measures dose, dose rate, exposure time, kVp with FFT analysis, Flash HVL, and beam filtration. A laser beam was used to ensure the alignment of the X-Ray source, the studied sample, and the detector. At the time of irradiation, a monitoring camera was set up to observe the experiment. The shielding performance of the composites was assessed for tube voltages ranging from 40 to 200 kV, which is the range commonly used in medical radiology departments. Herrati et al. [20] calculated the mean energy by simulating the X-ray spectra of the quality X-ray Beam. Table 3 summarizes the values of mean energies. The exposure time for each measurement was set to 30 seconds. Table 3 also indicates the tube current determined in line with the tube voltage, as recommended by COMET.

The results were plotted and the linear attenuation coefficient was calculated as the slope of Ln (D_0/D_x) vs. x, as illustrated in fig. 2.

RESULTS AND DISCUSSIONS

Samples densities

Theoretical and Archimedes methods were used to calculate composite densities using eqs. (7) and (8), and the results are displayed in tab. 4. The results showed that the values are similar for both methods, and the density of the composites increased with increasing PbO con-



Figure 2. The plot of Ln (D_0/D_x) vs. thickness x

Table 4. Samples composite densities

Sample		Density [gcm ⁻³]						
		$ ho_{ ext{Theory}}$	$ ho_{ m Archamedes}$					
PS 1.030 1.031								
			PS/PbO bulk	PS/PbO NP(A)	PS/PbO NP(B)			
	10 wt.%	1.131	1.132	1.112	1.136			
PbO	15 wt.%	1.189	1.181	1.155	1.152			
wt.%	25 wt.%	1.326	1.264	1.236	1.267			
	35 wt.%	1.498	1.438	1.4015	1.356			

tent, as a result of the high density of PbO. At high filler concentrations (25 wt.% and 35 wt.%), the results were not entirely in agreement with theoretical values due to a shortage of PS to completely cover the surfaces of the filler powder, resulting in an increase in the number of pores and hence, a reduction in the composite's density [24].

Scanning electron microscope – energy dispersive X-ray spectroscopy

Figure 3(a)-3(f) shows the SEM micrographs with the corresponding EDS spectra for pure PS and PS/PbO composites with 10 wt.% and 35 wt.% of the various sizes of PbO filler. Pure polystyrene appeared to have a rough and compact surface, whereas the texture morphology of the PS/PbO composite revealed a significant variation, with PbO particles appearing brighter due to their high atomic number. The SEM micrographs indicated that the grain size of PbO was related to PbO type, where PS/PbO Bulk showed a larger PbO particle size than PS/PbO NP(A) which, in turn, displayed a larger size than PS/PbO NP(B). Additionally, the number of PbO particles in the micrographs increased by increasing the PbO load in the composite. Images of PS/PbO with 35 wt.% captured more PbO particles than the images of PS/PbO with 10.wt %. As shown in the micrographs in figs. 4(a), 4(c), and 4(e) the amount of PbO particles in the composite increased with decreasing PbO particle size.

Although minor agglomerations are visible as blurry white patches in the SEM elemental mapping of Pb, shown in the insets of fig. 3(b), 3(d), and 3(f), PbO was found to be fairly uniformly dispersed over the composite's surface. The PbO dispersion appeared to improve with decreasing particle size, indicating good interfacial adhesion between the polymer chains and PbO nanoparticles due to their high surface-to-volume ratio. Despite the high PbO concentration of 35 wt.%, the PbO particles were well dispersed in PS/PbO NP(B) compared to PS/PbO NP(A) which, in turn, exhibited better particle dispersion than PS/PbO Bulk, as shown in fig. 3(b), 3(d), and 3(f).

The EDS was used to determine the surface elemental composition of pure PS and PS/PbO composite. An examination of the EDS spectra in fig. 3 dem-



Figure 3. The SEM photos and the corresponding EDS spectra for the Polystyrene and PS/PbO composites



Figure 4. Mass attenuation coefficient for (a) PS/PbO bulk, (b) PS/PbO NP(A), and (c) PS/PbO NP(B)

Table 5. Elemental composition and mass percent of PS/PbO composites evaluated by EDS

Element Peak energy [keV]	Mass [%]							
	Peak energy	PS/PbO (bulk)		PS/PbO (A)		PS/PbO (B)		
		10 %	35 %	10 %	35 %	10 %	35 %	
С	0.277	88.06 0.04	78.49 0.04	84.18 0.11	75.10 0.10	83.21 0.10	75.23 0.11	
Pb	2.342	3.19 0.03	11.89 0.04	4.81 0.09	16.47 0.12	7.77 0.09	17.45 0.13	

onstrated that carbon is the predominant element at roughly 80 wt.%, and emphasized the presence of Pb elements in the composite's spectra. The Au-peak, which appeared in the PS EDS spectrum, is attributed to the gold coating of the samples [25]. The EDS was performed in a low vacuum, which explains the appearance of oxygen and nitrogen peaks in the spectra as a result of gas ionization caused by the generated electron beam. Furthermore, a very weak Na-peak was detected, which could be a result of sample contamination or water adsorption [26-28]. Table 5 illustrated the mass percent distribution of carbon and lead. The Pb peak at 2.342 keV was raised by increasing PbO weight percent in the composite, implying an equitable distribution of particles. Additionally, the relatively high Pb mass percent was exclusively assigned to the PS/PbO composite with the smallest particle size PbO NP(B), showing widespread Pb diffusion on the composite's surface as a result of particle size reduction. The disparity between the weight fraction of filler and the mass percent measured by EDS was due to purity issues.

The X-ray attenuation measurements

Mass attenuation coefficient

To define the attenuation behavior of a sample, it is more advantageous and accurate to use the mass attenuation coefficient μ_m [cm²g⁻¹]. The experimental values for PS, PS/PbO Bulk, PS/PbO NP(A), and PS/PbO NP(B) are listed in tab. 6 for the energies of the narrow-spectrum X-ray beam utilized. The observed results of μ_m for the PS/PbO bulk were compared to theoretical values calculated from Hubbell's database (XCOM NIST Standard Reference Database 8) and Chantler's database (FFAST NIST Standard Reference Database 66) [29]. This experiment used a N-series X-ray beam rather than the monoenergetic photon beam used in Xcom or the continuous spectrum X-ray beam used in FFAST, which accounts for some substantial discrepancies in tab. 6. Furthermore, because NIST does not consider the filler size and structure, the values of the mass attenuation coefficient from NIST databases could be utilized as guidance levels. However, the high quality of the experimental data, as well as the observed trend concerning energy, are strong indicators of the validity of the current approach.

Figure 4 depicts the variation of the mass attenuation as a function of energy. The mass attenuation of PS/PbO Bulk, PS/PbO NP(A), and PS/PbO NP(B) decreased with increasing X-ray energy from 33 keV to 80 keV and from 100 keV to 164 keV. A sharp increase from 80 keV to 100 keV corresponds to the K-edge of Pb at 88 keV, where photoelectric absorption of X-ray photons at energies just beyond the binding energy of the k-shell electrons dominates [30]. In general, photons interact with materials primarily through the photoelectric effect in the low energy range, whereas Compton scattering dominates in the high energy range. The attenuation decreases with increasing photon energy due to the energy dependence of the photoelectric effect [31, 32]. Additionally, fig. 4 shows clearly that the mass attenuation of PS/PbO composites increases as PbO concentration increases across all energy ranges. The cross-section of the photoelec-

ISO 4037 code	N40	N60	N80	N100	N120	N150	N200
Tube voltage [kV]	40	60	80	100	120	150	200
Energy _{mean} [keV]	33	48	65	80	100	118	164
$\mu_{ m m}$			Mass attenua	tion coefficien	$t [cm^2g^{-1}]$		
PS	0.142	0.152	0.139	0.133	0.121	0.115	0.102
NIST XCOM	0.219	0.188	0.175	0.166	0.159	0.153	0.140
% (Xcom)	34.85	19.36	20.39	19.62	23.68	24.61	26.84
FFAST	0.246	0.215	0.192	0.175	0.163	0.153	0.134
% (FFAST)	42.16	29.42	27.47	23.83	25.50	24.64	24.02
PS/PbO bulk 10	2.426	0.968	0.512	0.440	0.497	0.410	0.236
NIST XCOM	2.282	0.935	0.498	0.328	0.640	0.463	0.268
% (Xcom)	2.43	0.97	0.51	0.44	0.50	0.41	0.24
FFAST	2.366	1.006	0.544	0.355	0.634	0.469	0.275
% (FFAST)	2.51	3.75	5.90	23.95	21.56	12.55	14.09
PS/PbO NP(A)10	2.641	0.861	0.466	0.391	0.439	0.359	0.211
PS/PbO NP(B)10	2.635	0.921	0.481	0.417	0.458	0.379	0.226
PS/PbO bulk 15	3.880	1.293	0.666	0.542	0.645	0.531	0.296
NIST XCOM	3.313	1.309	0.660	0.410	0.880	0.619	0.333
% (Xcom)	17.10	1.21	1.08	32.35	26.75	14.17	11.16
FFAST	3.426	1.402	0.720	0.445	0.869	0.626	0.345
% (FFAST)	13.24	7.76	7.41	21.84	25.81	15.25	14.36
PS/PbO NP(A)15	4.147	1.401	0.727	0.581	0.701	0.580	0.326
PS/PbO NP(B)15	5.439	1.270	0.662	0.565	0.638	0.525	0.292
PS/PbO bulk 25	4.718	1.822	0.933	0.709	0.885	0.741	0.402
NIST XCOM	5.376	2.057	0.983	0.572	1.360	0.929	0.461
% (Xcom)	12.23	11.43	5.02	23.91	34.95	20.21	12.96
FFAST	5.546	2.193	1.072	0.625	1.339	0.942	0.485
% (FFAST)	14.92	16.94	12.93	13.43	33.94	21.32	17.29
PS/PbO NP(A)25	5.234	1.943	0.978	0.692	0.903	0.771	0.418
PS/PbO NP(B)25	6.419	2.031	1.014	0.784	0.980	0.814	0.436
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PS/PbO bulk 35	5.105	1.851	0.963	0.694	0.875	0.74	0.413
NIST XCOM	7.440	2.804	1.306	0.735	1.841	1.239	0.590
% (Xcom)	31.39	33.99	26.26	5.57	52.49	39.57	30.05
FFAST	7.666	2.985	1.424	0.805	1.810	1.258	0.626
% (FFAST)	33.41	37.99	32.37	13.82	51.67	40.48	34.06
PS/PbO NP(A)35	6.896	2.019	1.024	0.758	1.024	0.826	0.454
PS/PbO NP(B)35	7.247	2.904	1.382	1.062	1.344	1.222	0.646

Table 6. Experimental values of mass attenuation coefficient μ_m for the PS, PS/PbO bulk, PS/PbO NP (A), and PS/PbO NP (B) at energies of narrow-spectrum X-ray beam

tric effect ($Z^4/E^{3.5}$) increased since it depends on the higher loading of Pb with high atomic number Z, and hence, increased the photon absorption capability of the composite. For the X-ray beam N60 with energy 48 keV, the values of mass attenuation coefficients for PS/PbO bulk composite increased from 0.9684 cm²g⁻¹ to 1.8510 cm²g⁻¹ as the weight percent of PbO bulk increases from 10 to 35 wt.%, reflecting an increment of 91 % of $\mu_{\rm m}$.

Figure 5 illustrates the comparison of the mass attenuation coefficient for the composites with various PbO sizes (PS/PbO Bulk, PS/PbO NP(A), and PS/PbO NP(B)) concerning X-ray energy and PbO concentration. Along with the previously discussed dependence of $\mu_{\rm m}$ on X-ray energy and PbO weight percent, the effect of PbO particle size is readily apparent.

For X-ray beam N40 with energy 33 keV, the mass attenuation values for PS/PbO NP(B) are greater than that for PS/PbO NP(A), which in turn are greater than that for PS/PbO Bulk, indicating that particle size has a significant effect at this energy level. The increasing rate of μ_m is approximately 35 % with PS/PbO NP(A) 35 wt.% over PS/PbO (Bulk) 35 wt.%, while PS/PbO NP(B) 35 wt.% exhibited a 42 % increase. For X-ray beams N60 to N200 with an energy range of 48 to 164 keV, the mass attenuation coefficients for PS/PbO composites are close at low filler concentrations (10 wt.% and 15 wt.%), with no change



Figure 5. Mass attenuation coefficient vs. energy and wt.% for PS/PbO bulk, PS/PbO NP (A), and PS/PbO NP (B) composites

in behavior due to particle size, indicating a slight increase in mass attenuation coefficient values, for PS/PbO composites with PbO NP(A). At high filler concentrations (25 wt.% and 35 wt.%), mass attenuation coefficients increase as particle size decreases, reaching a maximum with PS/PbO NP(B), compared to PS/PbO NP(A) and PS/PbO Bulk. For N100 and N120 beams with an energy range surrounding the Pb K-edge, the mass attenuation values of PS/PbO NP(B) and PS/PbO (Bulk) were 1.062 and 0.694 cm²g⁻¹ for N100, and 0.875 and 1.344 cm²g⁻¹ for N120, respectively, indicating an increment level of 53 % caused solely by the effect of particle size.

Comparing mass attenuation coefficient values demonstrates that as particle size decreases, the composite absorbs more photons, particularly at low energies and at Pb K-edge. When particle size decreases, the density and number of particles per unit weight increase, the distance between the nanoparticles decreases, and the particles are uniformly distributed over a larger surface area within the polymer matrix due to the high surface-to-volume ratio, and therefore increasing the probability of the incident X-ray to interact with more dense material and more Pb particles [33]. Several authors have addressed the effect of filler grain size on transmitted radiation intensity. The investigation was conducted between micro-sized and nanosized particles and revealed that nanosized particles exhibit high dispersion forces and perform better in radiation attenuation [34-37]. This research demonstrates that this conclusion holds at the nano-scale as well.

Half value layer, tenth value layer, and the relaxation length

Tables 7-9 list the experimental values of HVL, TVL, and λ for all PS/PbO composites, at all X-ray en-

ergies, respectively. The HVL, TVL, and λ are all regarded as critical parameters in radiation shielding. These practical values indicate the required shield thickness to reduce the incident beam to half or a tenth of its initial intensity and are inversely proportional to the mass attenuation coefficient. These parameters increase with increasing photon energy from 33 keV (N40) to 80 keV (N100), then decrease at 100 keV (N120) and keep increasing for higher energies (N150, N200). This behavior is ascribed to the presence of the Pb K-edge at 88 keV. According to the obtained results, increasing PbO content would pave the way for a more compact shield [38]. The nano-size effect of PbO particles is observed in fig. 6, the smallest nano-size filler provides better shielding performance with remarkable parameters. For X-ray beam N120 at 100 keV, the HVL, TVL, and λ of PS/PbO NP(B) 35 wt.% are 0.3804 cm, 1.26 cm, and 0.55 cm, respectively, while for PS/PbO Bulk 35 wt.% are 0.551 cm, 1.83 cm, and 0.79 cm, which are 31 % less due to the particle size effect in the nanoscale. This comparison can also be made at the nanometric level, where PS/PbO NP(B) 35 wt.% shielding parameters showed a reduction of 21 % compared to PS/PbO NP(A) 35 wt.%.

Heaviness

Heaviness is also an important factor in the application of any shielding material. The lightness of polymer composites is what makes them so appealing. Figure 7 depicts the percent heaviness of the polystyrene reinforced by high-density lead oxide, as well as some conventional shielding materials, and was calculated using eq. (6). According to the chart, with lead at 100 % heavy, concrete, barite, and steel are 20.28 %,

X-ray beam	N40	N60	N80	N100	N120	N150	N200
Energy _{mean} [keV]	33	48	65	80	100	118	164
				HVL [cm]			
PS	4.726	4.442	4.836	5.048	5.546	5.845	6.590
Pb	0.003	0.007	0.017	0.032	0.011	0.017	0.003
PS/PbO bulk 10	0.257	0.632	1.196	1.391	1.232	1.495	2.593
PS/PbO bulk 15	0.155	0.454	0.881	1.083	0.911	1.106	1.987
PS/PbO bulk 25	0.119	0.301	0.587	0.774	0.620	0.740	1.366
PS/PbO bulk 35	0.097	0.260	0.501	0.695	0.551	0.644	1.168
PS/PbO NP(A)10	0.232	0.724	1.339	1.595	1.419	1.736	2.953
PS/PbO NP(A)15	0.142	0.428	0.826	1.033	0.856	1.036	1.839
PS/PbO NP(A)25	0.105	0.289	0.574	0.810	0.622	0.728	1.343
PS/PbO NP(A)35	0.070	0.245	0.483	0.653	0.483	0.599	1.091
PS/PbO NP(B)10	0.232	0.662	1.268	1.462	1.332	1.612	2.702
PS/PbO NP(B)15	0.111	0.474	0.909	1.066	0.943	1.146	2.060
PS/PbO NP(B)25	0.085	0.269	0.539	0.698	0.558	0.672	1.254
PS/PbO NP(B)35	0.071	0.176	0.370	0.481	0.380	0.418	0.791

Table 7. The HVL of PS/PbO bulk, PS/PbO NP(A), and PS/PbO NP(B)

Table 8. The TVL of PS/PbO bulk, PS/PbO NP(A), and PS/PbO NP(B)

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X-ray beam	N40	N60	N80	N100	N120	N150	N200
Energy _{mean} [keV]	33	48	65	80	100	118	164
				TVL [cm]			
PS	15.699	14.754	16.065	16.771	18.422	19.418	21.890
PS/PbO bulk 10	0.854	2.100	3.974	4.622	4.093	4.965	8.614
PS/PbO bulk 15	0.514	1.508	2.925	3.596	3.026	3.674	6.600
PS/PbO bulk 25	0.395	1.000	1.951	2.570	2.059	2.457	4.536
PS/PbO bulk 35	0.322	0.865	1.663	2.307	1.830	2.139	3.880
PS/PbO NP(A)10	0.770	2.406	4.446	5.299	4.712	5.768	9.808
PS/PbO NP(A)15	0.470	1.423	2.743	3.432	2.844	3.440	6.108
PS/PbO NP(A)25	0.348	0.959	1.906	2.692	2.064	2.417	4.460
PS/PbO NP(A)35	0.232	0.814	1.604	2.168	1.605	1.989	3.623
PS/PbO NP(B)10	0.770	2.200	4.214	4.857	4.424	5.356	8.976
PS/PbO NP(B)15	0.368	1.575	3.021	3.542	3.134	3.808	6.842
PS/PbO NP(B)25	0.283	0.895	1.791	2.318	1.854	2.232	4.164
PS/PbO NP(B)35	0.234	0.585	1.228	1.599	1.264	1.390	2.629

39.5 %, and 69.22 % heavy, respectively. In the case of PS/PbO composites, the heaviness of PS/PbO NP(B) 35 wt.% is 12.7 % of lead, whereas for polystyrene is 9.1 % of lead. As a result, when compared to traditional shielding materials such as lead, barite, and steel, the polymer nanocomposites are lightweight shields [39-41].

CONCLUSION

In this study, the effect of particle size and concentration of PbO on X-ray shielding properties of PS/PbO composites was investigated by measuring the mass attenuation coefficients, HVL, TVL, and λ , using the narrow-spectrum X-ray, used for radiological purposes. As demonstrated by SEM, good particle dispersion in the polymer was obtained, when the filler particle size was reduced. The experimental results proved that increasing PbO concentration, or reducing PbO particle size, improved the X-ray shielding capability of PS/PbO composites for all examined energies. The effect of particle size on the mass attenuation coefficient resulted in a 53 % enhancement at energy 80 keV (N100) and a 42 % increase at energy 33 keV (N40), for PS/PbO with NP (B) over PS/PbO with bulk PbO. Moreover, the HVL and TVL get thinner as the particle size decreases. In terms of percents heaviness, PS/PbO NP (B) 35 wt.% is 12.75 %

X-ray beam	N40	N60	N80	N100	N120	N150	N200			
Energy _{mean} [keV]	33	48	65	80	100	118	164			
		Relaxation length [cm]								
PS	6.818	6.408	6.977	7.283	8.001	8.433	9.507			
PS/PbO bulk 10	0.371	0.912	1.726	2.007	1.778	2.156	3.741			
PS/PbO bulk 15	0.223	0.655	1.271	1.562	1.314	1.595	2.866			
PS/PbO bulk 25	0.172	0.434	0.848	1.116	0.894	1.067	1.970			
PS/PbO bulk 35	0.140	0.376	0.722	1.002	0.795	0.929	1.685			
PS/PbO NP(A)10	0.335	1.045	1.931	2.301	2.047	2.505	4.260			
PS/PbO NP(A)15	0.204	0.618	1.191	1.490	1.235	1.494	2.653			
PS/PbO NP(A)25	0.151	0.416	0.828	1.169	0.897	1.050	1.937			
PS/PbO NP(A)35	0.101	0.353	0.697	0.942	0.697	0.864	1.573			
PS/PbO NP(B)10	0.334	0.956	1.830	2.109	1.921	2.326	3.898			
PS/PbO NP(B)15	0.160	0.684	1.312	1.538	1.361	1.654	2.972			
PS/PbO NP(B)25	0.123	0.389	0.778	1.007	0.805	0.969	1.808			
PS/PbO NP(B)35	0.102	0.254	0.533	0.694	0.549	0.604	1.142			

Table 9. The relaxation length of PS/PbO bulk, PS/PbO NP (A), and PS/PbO NP (B)



Figure 6. The HVL and TVL vs. X-ray energy and PbO concentration for PS/PbO composites with different PbO particle sizes



Figure 7. Heaviness of PS/PbO composites and conventional shielding materials

when compared to lead. These findings imply that the novel PS/PbO nanocomposite which is composed of PbO nanoparticles produced by high-speed ball milling, and incorporated with polystyrene by compressing molding technique, is low cost, lightweight, and nontoxic, and can be effectively used for radiological protection purposes as an efficient lightweight shield with a massive impact on X-ray attenuation.

ACKNOWLEDGMENTS

This work was done in the frame of the scientific collaboration between the Physics Department, Faculty of Science, Beirut Arab University (BAU), and the National Council for Scientific Research-Lebanon (CNRSL), Lebanese Atomic Energy Commission (LAEC).

AUTHORS CONTRIBUTIONS

A. F. Osman performed the experimental part with the valuable supervision of M. S. Badawi and H. El Balaa. M. S. Badawi, R. Awad, O. El Samad, and Z. Alsayed carried out the theoretical analysis and numerical testing performance. M. S. Badawi, Z. Alsayed, and A. F. Osman arranged all the figures. All authors reviewed and discussed the manuscript.

REFERENCES

- Elbary, A., Tammam, M. T., Physical and Mechanical Properties of Polyamide 6/Polystyrene (PA6/PS) Reinforced by PbO2 Composites for X-Ray Shielding, *Journal of Thermoplastic Composite Materials* (2019), Sept., pp. 1-19
- [2] Mahesh, M., The Essential Physics of Medical Imaging, Third Edition, *Med Phys*, 40 (2013), 7, 077301
- [3] Elbakri, I. A., Fessler, J. A., Statistical Image Reconstruction for Polyenergetic X-Ray Computed Tomography, *IEEE Transactions on Medical Imaging 21* (2002), 2, pp. 89-99
- [4] El-khatib, A. M., *et al.*, Study on the Effect of the Self-Attenuation Coefficient on γ-ray Detector Efficiency Calculated at Low and High Energy Regions, *Nuclear Engineering and Technology*, 46 (2014), 2, pp. 217-224
- [5] Melhem, N., et al., Characteristics of the Narrow Spectrum Beams Used in the Secondary Standard Dosimetry Laboratory at the Lebanese atomic Energy Commission, Radiation Protection Dosimetry (2016), pp. 1-8
- [6] Badawi, M. S., A Numerical Simulation Method for Calculation of Linear Attenuation Coefficients of Unidentified Sample Materials in Routine Gamma Ray Spectrometry, *Nucl Technol Radiat*, 30 (2015), 4, pp. 249-259
- [7] Hosseini, S., Askari, M., Ezzati, S., X-Ray Attenuating Nanocomposite Based on Polyaniline Using Pb Nanoparticles, *Synthetic Metals*, 196 (2014), pp. 68-75
- [8] Abbas, Y. M., et al., Gamma Attenuation Through Nano Lead – Nano Copper PVC Composites, Nucl Technol Radiat, 36 (2021), 1, pp. 50-59
- [9] Noor Azman, N. Z., Abunahel, B. M., Electrospun Polymer Nanocomposites for X-Ray Shielding Application, *Electrospun Polymers and Composites*, 110 (2021), Chapter 17, pp. 513-565
- [10] Alharshan, G. A., et al., A Comparative Study Between Nano-Cadmium Oxide and Lead Oxide Reinforced in High Density Polyethylene as Gamma Rays Shielding Composites, Nucl Technol Radiat, 35 (2020), 1, pp. 42-49
- [11] Craver, C. D., Carraher, C. E., Applied polymer Science: 21st Century ELSEVIER, 2000, Chapter 7
- [12] More, C. V., et al., Polymeric Composite Materials for Radiation Shielding: A Review, Environmental Chemistry Letters 19 (2021), pp. 2057-2090
- [13] Alsayed, Z., *et al.*, Investigation of -Ray Attenuation Coefficients, Effective Atomic Number and Electron

Density for ZnO/HDPE Composite, *Physica Scripta*, 95 (2020), 8, 085301

- [14] Alsayed, Z., et al., Study of Some -Ray Attenuation Parameters for New Shielding Materials Composed of Nano ZnO Blended with High Density Polyethylene, *Nucl Technol Radiat*, 34 (2019), 4, pp. 342-352
- [15] Cinan, Z. M., et al., Gamma Irradiation and the Radiation Shielding Characteristics: For the Lead Oxide Doped the Crosslinked Polystyrene-b-Polyethyleneglycol Block Copolymers and the Polystyrene-b-Polyethyleneglycol-Boron Nitride Nanocomposites, Int J Energy Res. (2021), pp. 1-34
- [16] Azman, N., et al., Microstructural Design of Lead Oxide-Epoxy Composites for Radiation Shielding Purposes, J. Appl. Polym. Sci. (2012), pp. 1-75
- [17] Ghaseminejad, M., Gholamzadeh, L., Ostovari, F., Investigation of X-Ray Attenuation Property of Modification PbO with Graphene in Epoxy Polymer, *Mater: Res. Express*, 8 (2021), 035008
- [18] Mahmoud, M. E., *et al.*, Fabrication, Characterization and Gamma Rays Shielding Properties of Nano and Micro Lead Oxide-Dispersed-High Density Polyethylene Composites, *Radiation Physics and Chemistry* 145 (2018), pp. 160-173
- [19] Kumar, A., et al., Tailoring Bismuth Borate Glasses By Incorporating PbO/GeO2 for Protection Against Nuclear Radiation, Scientific Reports, 11 (2021), 7784
- [20] Herrati, A., et al., Establishment of ISO 4037-1 X-ray Narrow-Spectrum Series at SSDL of Algiers, Radiation Protection Dosimetry (2016), pp. 1-18
- [21] Zhang, D., et al., Establishment of ISO 4037-1 X-Ray Narrow-Spectrum Series, *The Journal of Engineering* (2019), eISSN 2051-3305
- [22] Priamo, F., Murphy, A., Linear Attenuation Coefficient Radiopaedia, 2021
- [23] Ankerhold, Ulrike, Catalogue of X-Ray Spectra and Their Characteristic Data: ISO and DIN Radiation Qualities, Therapy and Diagnostic Radiation Qualities, Unfiltered X-Ray Spectra, Physikalisch- Technische Bundesanstalt (PTB), 2000
- [24] Azman, N. Z. N., et al., Synthesis and Characterization of Epoxy Composites Filled with Pb, Bi or W Compound for Shielding of Diagnostic X-Rays, Appl Phys A, 110 (2013), pp. 137-144
- [25] Neves, J. S., et al., In situ Production of Polystyrene Magnetic Nanocomposites Through a Batch Suspension Polymerization Process, Macromolecular Materials and Engineering, 296 (2011), pp. 1107-1118
- [26] Zhang, G., et al., CuO/PbO Nanocomposite: Preparation and Catalysis for Ammonium Perchlorate Thermal Decomposition, ACS Omega, 5 (2020), pp. 32667-32676
- [27] Newbury, D. E., Ritchie, N. W. M., Performing elemental Microanalysis with High Accuracy and High Precision by Scanning Electron Microscopy/Silicon Drift Detector Energy-Dispersive X-ray Spectrometry (SEM/SDD-EDS), *J Mater Sci.*, 50 (2015), pp. 493-518
- [28] Bappah, AU: Haruna, Adamu, Fractionation of Pb in Soil of Abandoned Pb Mine by SEM-EDX and XRD, J. Appl. Sci. Environ. Manage. 19 (2015), 3, pp. 403-409
- [29] Chantler, C. T., et al., X-Ray Form Factor, Attenuation, and Scattering Tables, NIST Standard Reference Database, 66 (2005)
- [30] Bagheria, R., Adeli, R., Gamma-Ray Shielding Properties of Phosphate Glasses Containing Bi₂O₃, PbO, and BaO in Different Rates, *Radiation Physics and Chemistry*, 174 (2020), 108918
- [31] Hassan, H. E., et al., Studying the Effect of Nano Lead Compounds Additives on the Concrete Shielding Properties for -Rays, Nuclear Instruments and Methods in Physics Research B, 360 (2015), pp. 81-89

- [32] Al-Buriahi, M. S., *et al.*, Effects of Reducing PbO Content on the Elastic and Radiation Attenuation Properties of Germanate Glasses: A New Non-toxic Candidate for Shielding Applications, Research Square, 2021
- [33] Kunzel, R., Okuno, E., Effects of the Particle Sizes and Concentrations on the X-Ray Absorption by CuO Compounds, *Applied Radiation and Isotopes*, 70 (2012), pp. 781-784
- [34] Kim, S. C., CuO/PbO Nanocomposite: Preparation and Catalysis for Ammonium Perchlorate Thermal Decomposition Analysis of Shielding Performance of Radiation-Shielding Materials According to Particle Size and Clustering Effects, *Appl. Sci. 11* (2021), 4010
- [35] Sarshough, S., Hadad, K., Faghihi, R., Particle Size and Concentration Effects on Low Energy X-Ray Attenuation in Nanostructure and Microstructure Materials, *Nucl Technol Radiat*, 33 (2018), 1, pp. 75-80
- [36] Botelho, M. Z., et al., X-Ray Transmission Through Nanostructured and Microstructured CuO Materials, *Applied Radiation and Isotopes*, 69 (2011), pp. 527-530
- [37] El-Khatib, A. M., *et al.*, Gamma Attenuation Coefficients of Nano Cadmium Oxide/High density Poly-

ethylene Composites, Scientific Reports, 9 (2019), 16012

- [38] Kiani, M. A., et al., Study on Physico-Mechanical and Gamma-Ray Shielding Characteristics of New Ternary Nanocomposites, Applied Radiation and Isotopes, 143 (2019), pp. 141-148
- [39] El-Toony, M. M., *et al.*, Synthesis and Characterisation of Smart Poly Vinyl Ester / Pb2O3 Nanocomposite for Gamma Radiation Shielding, *Radiation Physics and Chemistry*, 168 (2020), 108536
- [40] Ambika, M. R., et al., Role of Bismuth Oxide as a Reinforcer on Gamma Shielding Ability of Unsaturated Polyester Based Polymer Composites, J. Appl. Polym. Sci.134 (2016), 44657
- [41] Obeid, et al., Effects of Different Nano Size and Bulk WO₃ Enriched by HDPE Composites on Attenuation of X-Ray Narrow Spectrum, *Nucl Technol Radiat*, 36 (2021), 4, pp. 315-328

Received on March 30, 2022 Accepted on May 16, 2022

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ЕФЕКТ УГРАДЊЕ ОЛОВООКСИДА СА РАЗЛИЧИТИМ ВЕЛИЧИНАМА ЧЕСТИЦА НА СЛАБЉЕЊЕ РЕНДГЕНСКОГ ЗРАЧЕЊА У ПОЛИСТИРЕНУ

Коришћењем техника мешања у ролну и пресовања у калуп, маса оловооксида и наночестице две различите величине (A = 78 nm и B = 54 nm) уграђују се одвојено у полистиренску матрицу у различитим концентрацијама (0, 10, 15, 25, и 35%). Затим се серија рендгенских зрака уског спектра (H-серија / ИСО 4037-1) користи за истраживање способности слабљења зрачења новог полимерног композита PS/PbO, као и утицаја различитих величина честица PbO на перформансе заштите. Испитиване су дисперзија испуне и хемијска анализа елемената синтетизованог композита коришћењем скенирајуће електронске микроскопије и енергетски дисперзивне рендгенске спектроскопије. За одређивање масеног коефицијената слабљења, μ_m , узорци различитих дебљина синтетизованог композита испитују се коришћењем рендгенских енергија у опсегу и експериментални подаци се упоређују са теоријским вредностима из НИСТ база података (ХСОМ и FFAST). Резултати показују да је или повећање процента тежине испуне, или смањење величине честица испуне, побољшало параметре слабљења у свим енергијама. Композит који садржи PbO најмањих нанодимензија показао је максималну ефикасност заштите од зрачења међу свим комбинацијама и стога би се могао користити за развој јевтиних и лаких штитова од рендгенских зрака.

Кључне речи: зашиши од рендгенских зрака, йолиси ирен, оловни оксид, нанокомиозии, зашиши од зрачења