Introducing a novel Polyvinyl chloride/Tungsten composites for shielding against gamma and X-ray radiations

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ABSTRACT

Introduction: This study introduces a novel polyvinyl chloride (PVC)/tungsten composites with characterization of their shielding properties by employing different techniques.

Methods: The PVC/tungsten composites were produced by employing various weight fractions of tungsten micro-particles including 0, 20, and 40 % wt via melt blending method. In the next step, the linear attenuation coefficients of prepared composite samples were experimentally measured at 662 keV γ-ray, and then were compared to the data estimated using MCNP simulation code and XCOM software. Also the shielding properties of samples were evaluated experimentally with an X-ray tube at 40 kVp.

Results: Recorded results showed that by increasing the weight percentage of the tungsten micro-particles, the coefficient of linear attenuation and also the absorbed dose values were increased dramatically. Samples containing 20, and 40% wt of tungsten micro-particles reached to 89.60 and 92.26 %of dose absorption, respectively. Interestingly the proposed composition were approximately 2.3 lighter than the commercial shields.

Conclusion: The linear attenuation coefficient of the composite shields has been calculated to be 0.20 cm^{-1}, which was comparable with commercial Pb-based shields. Tungsten micro-particles addition to PVC matrix can increase the absorbed dose value. Plasticized PVC has suitable flexibility and low stiffness value, therefore it can be a good alternative for commercial aprons and other Pb-based shields in low energy voltages.

Key words: Polyvinyl chloride; Tungsten; Shield; Lead; Composite; X-ray

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INTRODUCTION

Ionizing radiations, such as gamma (γ) and X-rays in medicine and different industrials can cause cancer growth and other defects. The lead as a metal with good shielding characteristics has known as a most popular protective layer in different applications in the last century. However it has some disadvantages including toxicity, sanitation and environmental problems in the reprocessing steps [1-4].

In spite of the suitable ability of lead to harness the carcinogenic radiations, researchers have been reported to replace light materials such as polymer compounds to gradually omit lead radiation protectors. It should be mentioned that polymer-based composites would be considered as a lightweight material which has the capability to replace with lead aprons. For fabrication of these composites, high atomic number elements as an energy reducer agent must be added to polymeric matrix [5-9]. Shielding properties of different polymer-based composites such as polyethylene [10], polypropylene [11], polydimethylsiloxane [12], and polyvinyl chloride as a carrier of high atomic number attenuator components have been studied, already [13-15]. For example, Nambiar et al. fabricated the polydimethylsiloxane (PDMS)-based nanocomposite containing bismuth oxide (BO) as an energy reducer agent. They studied the attenuation properties of the nanocomposites by employing diagnostic X-ray energies from 40 to 150 KeV tube potential. They reports, the PDMS/BO nanocomposite (44.44% of BO and 3.73-mm thick) was capable of attenuating all X-rays generated at 60 KeV [13]. Recently Li et al. fabricated bismuth nanoparticles-loaded cellulose nanofibers by considering the X-ray blocking property of bismuth nanoparticles, and promoted its low cost, lightweight and structure conformability, and claimed that the synthesized composite can be used in a wide range applications especially in personal radiation protections [4]. Yim et al. investigated the shielding properties of nickel-plated MWCNT/high-density polyethylene composites. They reported that the aforementioned composite has capable to be a suitable attenuator due to the shielding nature of the nickel particles [14].

PVC shielding properties against destructive electromagnetic waves has been investigated repeatedly. For instance, Sachdev et al. fabricated pre-localized graphite/PVC with different concentrations of graphite [15]. Using tungsten particles as high atomic number elements has been studied frequently [16-18], but to the best of our knowledge the addition of tungsten particles into the PVC matrix as an attenuator shield has not been investigated yet.

Herein, different weight fractions of PVC/tungsten composites were prepared as a new high performance shielding materials via melt blending technique. Then, the abilities of the synthesized composites toward absorbing and attenuating of gamma and X-ray radiations were evaluated and obtained the results were compared with commercial shields.

METHODS

Materials

Plasticized polyvinyl chloride with molecular weight of 43000 g/mol and hardness value of 70 shore A was purchased from Nippon Gohsei Co., Japan. Tungsten particles with average diameter size of 9.6 µm were provided from Elmet Technologies Co., Lewiston, US. All the other chemicals were analytical reagent grades and were used without further purification.

Samples preparation

40 g of plasticized PVC with different weights of tungsten micro-particles including 0, 20, and 40 g were mixed in an internal mixer at 170 ℃ and 60 rpm for 10 min. PVC/tungsten composites prepared by melt blending method were labeled as PVC/0, PVC/20, and PVC-40, respectively (Table 1). The prepared composite samples were transferred into the mold, and then were inserted into the hot press machine (Toyo seiki co, Japan) at the temperature of 185 ℃ and the pressure of 3920 kPa. After 10 minutes, the samples were extracted and cooled for 5 minutes at room temperature, and have been prepared for further characterization.

Table 1: Composition and physical properties of the prepared PVC/tungsten composite samples.

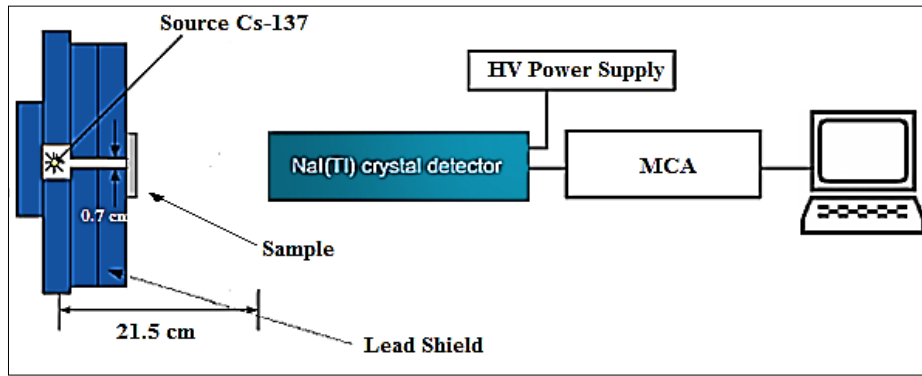| Sample	PVC (wt. %)	Tungsten micro-particle (wt. %)	Thickness (mm)	Density (g/cm³)
PVC/0	100	0	2.78	1.30
PVC/20	80	20	2.22	1.78
PVC/40	60	40	2.10	2.00

Fig. 1. Schematic view of the experimental setup.

Measurements

The linear attenuation coefficients of the prepared composite samples have been measured using the gamma spectrometer which contains a 3″ by 3″NaI(Tl) detector [19]. The amplified signal from the detector is recorded by a 16 k channel Multi-Channel-Analyzer (MCA) which communicates with the PC by Genie 2000(3.0) software. The schematic view of the experimental setup is shown in Figure 1. The spectrometer has been calibrated using γ-ray energies of 662 keV (from ^{137}Cs source) and 1173, 1332 keV (from [60]Cosource). The γ-ray energy spectrum obtained from those sources is displayed in the upper part of Figure 2, and the related energy-to-channel fit is displayed in the lower part of Figure 2. The linear attenuation coefficients μ (cm^{-1}) is obtained by:

$$\mu = \frac{1}{x} Ln \frac{I_0}{I} \qquad (1)$$

where x is the material thickness and I and I_0 are the background subtracted number of counts recorded in detector with and without material between detector and source, respectively. The measured linear attenuation coefficients were compared with the calculation obtained via the mass attenuation coefficients (μ/p) which were obtained using XCOM computer code. The XCOM is a data base and can run on a PC and it uses pre-existing data bases for coherent and incoherent scattering, photoelectric absorption, and pair production cross-sections to calculate mass attenuation coefficients at photon energies of 1 keV–1 GeV [20]. In this study, in order to calculate radiation mass attenuation coefficients we also employed MCNPX (version 2.4.0). All calculations were performed by using Intel® Core™i5 CPU 2.71 GHz computer hardware. MCNPX is a general purpose Monte Carlo code used for modeling radiation interactions between different radiation types and materials. MCNPX input file has definitions of cell card, surface card, material card, features of energy sources, and positions of each component which form the simulation geometry.
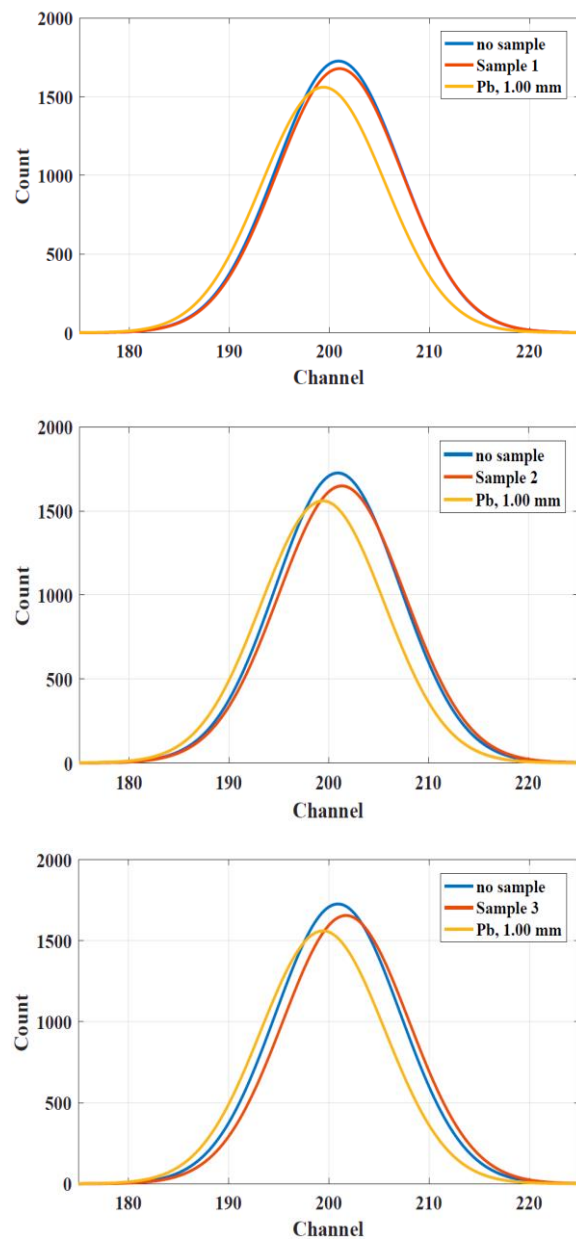

Fig 2. Smoothened graphs for the photon counting and the calculation of the samples' ability for γ- ray attenuation; pure PVC/0 (above), PVC/20 (middle), and PVC/40 (below).

The effectiveness of γ-ray shielding is described in terms of the half value layer (HVL) of a material. The HVL is the thicknesses of an absorber that will reduce the γ-radiation to half.

$$x_{1/2} = \frac{Ln2}{\mu} \qquad (2)$$

To measure the absorbed dose value, an X-ray tube radiometer was used, which can produce up to 80 keV photons. Figure 3 displays the apparatus for calculating the absorbed dose values of the prepared composite samples.
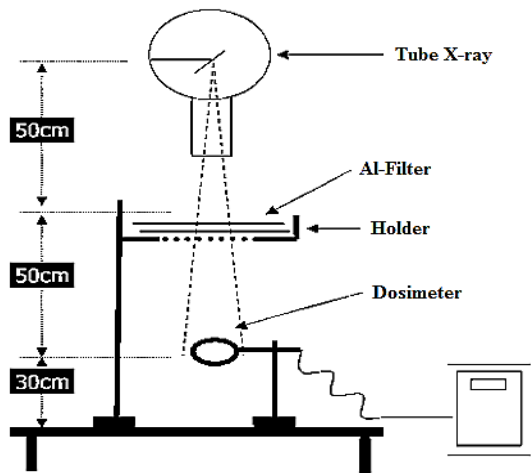

Fig 3. Arrangement of samples for measuring absorbed dose according to ISO/IEC 17025.

The sample arrangement procedure was according to the ISO/IEC 17025.Aforementioned machine is able to count radiated and also passed rays through the sample, so the number of absorbed rays could be obtained from equation 3.

$$Absorbtion\ (\%) = \frac{I_0 - I}{I_0} \times 100 \qquad (3)$$

where, I_0 is the number of primary rays, I is the number of passed ones, and the irradiation time is 0.06 s.

Heaviness values of the prepared samples was calculated by employing equation 4, in which the lead was assumed as a standard and synthesized composite samples were normalized related to the lead [21].

$$\%Heaviness = \frac{density\ of\ the\ given\ material}{density\ of\ lead} \times 100 \qquad (4)$$

RESULTS AND DISCUSSION

Study of attenuation properties of samples in the exposure of γ-rays

The measured and simulated attenuation properties prepared PVC composites reported in Table 2. γ-ray energies of 662 keV (from ^{137}Cs source) and 1173, 1332 keV (from ^{60}Co source) were used for this analysis. Based on reported results, by increasing of tungsten micro-particles weight fractions, the linear attenuation coefficient values (μ) of produced shields and Pb as a reference tend to close to each other, which is an indication that employed operation conditions for the measurement and calculation of linear attenuation coefficient were precise and desirable. Table 2 results shows that linear attenuation coefficient values increases by increasing of tungsten micro-particles weight fractions. Linear attenuation coefficient values of 0.092, 0.136, and 0.165 cm^{-1} were obtained for PVC/0, PVC/20, and PVC/40 samples, respectively, where linear attenuation coefficient value for Pb as reference was calculated to be 1.120 cm^{-1}.

Table 2: Attenuation results of PVC/tungsten composite samples. γ-ray energies of 662 keV (from ^{137}Cs source) and 1173, 1332 keV (from ^{60}Co source) were used for this analysis.

Sample	Thickness (mm)	Density (g/cm³)	HVL (cm)[a]	Attenuation (%) $\frac{I_0 - I}{I_0} \times 100$	μ(cm^{-1})[b]		
					Experiment	MCNPX	XCOM
PVC/0	2.78	1.30	7.5	2.5	0.092	0.090	0.111
PVC/20	2.22	1.78	5.1	3.0	0.136	0.105	0.129
PVC/40	2.10	2.00	4.2	3.4	0.165	0.152	0.169
Pb	2.02	11.0	0.6	20.0	1.120	1.130	1.140

[a]half value layer, [b]linear attenuation coefficients

Figure 2 shows the prepared shield samples' performances for the attenuation of γ-ray in comparison to two different conditions including when there is no sample in front of the energetic photons and when a sheet of lead with the thickness of 1mm inserted in the exposure of γ-ray emissions. As it is clear from the represented curves, the sample of PVC/0was not a suitable attenuator of γ-ray energetic photons but addition of tungsten micro-particles into the polymeric matrix induced attenuating properties that caused shifting the graph towards the pure lead graph (Pb 1mm, mentioned in Figure 2 by yellow curve). Also, by increasing the weight fractions of tungsten particles the attenuating characteristics of composites were improved.

Absorbed dose results of produced shields

Tungsten based composites due to the absorption abilities have enormous uses as shields. In order to explore absorption capability of prepared composites, the absorbed dose analysis was performed (Figure 4). The results of Figure 4 were obtained based on the optimized conditions: the voltage of 40 kV tube, the current of 200 mA and, the irradiation time of 0.06 s. Absorbed values of 20.10, 89.60, and 92.27 % were obtained for PVC/0, PVC/20, and PVC/40 samples, respectively. Deep analyzing of Figure 4 results shows that our produced PVC/tungsten composite samples have absorbed values in the close range with the commercial shields in which Thyroid, Gonad, and Apron commercial samples represented absorbed values of 91.20, 97.47, and 99.49 %, respectively.
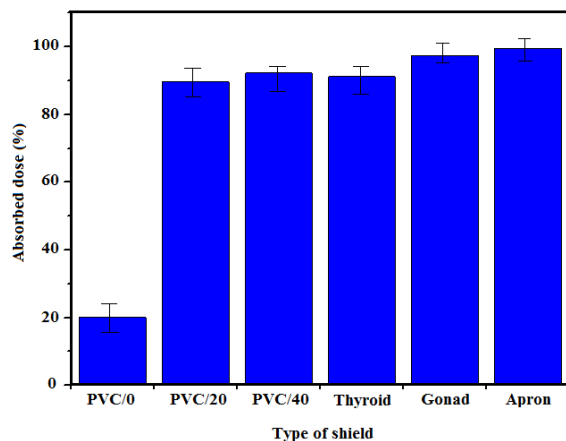

Fig 4. Absorbed values of the synthesized PVC/tungsten composite samples in comparison to the commercial ones (thickness values of the PVC/0, PVC/20, PVC/40, Thyroid, Gonad, and Apron samples were 2.78, 2.22, 2.10, 3.00, 400, and 5.50 mm, respectively).
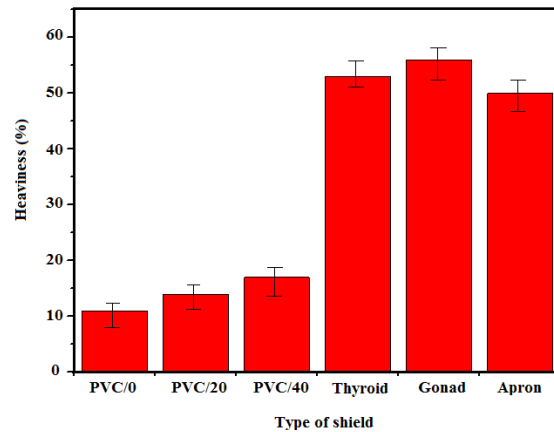

Fig 5. Heaviness% as a function of shield type.

Heaviness results of produced shields

The heaviness values were calculated and the obtained results were plotted as a function of the type of shield. It is clear from Figure 5 that the manufactured shields from polymeric composite material is so light in comparison to the conventional shields such as lead and concrete as well as their performance as a radiation protection shields more receptive when adding high concentrations to it and when it is used with low energy and this agrees with the study [21]. Based on equation 1, at 40 keV, if we normalize the thickness of polymeric composite shield to the apron, it can be obtained that polymer composite sample PVC/40 (with thickness= 4.1 mm) has the same attenuation as apron in thickness 5.5 mm. This is another advantage of polymer composite PVC/40 sample. Prepared PVC/40 samples in terms of heaviness, thickness, and shielding (in low energy X-ray) is so better than the commercial apron one. The functionality of polymer composite (in 20-60 keV) would be a good alternative for the commercial apron. On the other hand, the plasticized PVC matrix used in this research, shown great flexibility in these polymer composite, in comparison with the Pb-based shield. In terms of heaviness, prepared polymeric composite with 20% or 40% tungsten are approximately 2.3 lighter than the commercial shields. The most competitive advantage of polymeric composite is the lightness which made the sample as a suitable alternative to the other available commercial shields.

Morphological studies of produced shields

SEM analysis, is considered as a relatively inexpensive, rapid, and basically non-destructive technique for surface study. Surface SEM images for prepared composite samples (Figure 6) supported good connectivity between the employed nanoparticles and the PVC matrix.
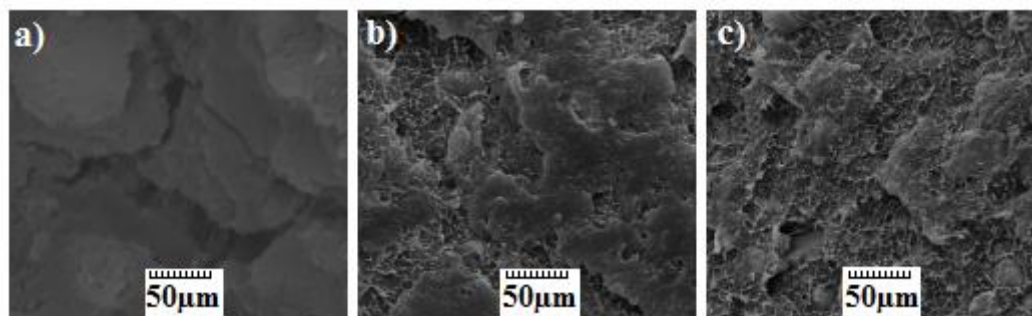
Fig 6. SEM images of the prepared PVC/tungsten composite samples; a) PVC/0, b) PVC/0, and c) PVC/40.

It could be seen that there was complete nanoparticles/matrix wetting or impregnation. This phenomenon resulted from highly dispersion of employed nanoparticles, so that PVC chains intertwined in to nanoparticles through tungsten structure and this issue leads to miscibility between the used nanoparticles and PVC matrix.

CONCLUSION

Herein PVC/tungsten composites were produced by using different weight fractions of tungsten micro-particles including 0, 20, and 40 % wt via melt blending method, and subsequently shielding properties of the produced composites were evaluated and were compared with commercial ones. The linear attenuation coefficient of the composite shields in the choose optimum conditions has been calculated to be 0.20 cm^{-1}, which was comparable with commercial Pb-based shields. According to obtained results, the X-ray absorbed dose in the emission tube had more significant results and showed that tungsten micro-particles addition to PVC matrix can increase the absorbed dose value. Heaviness results showed that, PVC-based composites were lighter than studied commercial shields in this research. Plasticized PVC has suitable flexibility and low stiffness value, therefore it can be a good alternative for commercial aprons and other Pb-based shields in low energy voltages.

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