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Gamma radiation shielding efficiency of a new lead-free composite material

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Abstract The aim of the study is to produce a new metal-polymer composite in the form of disc and investigate shielding efficiencies against gamma radiation (^{137}Cs and ^{131}I and ^{241}Am). The composite discs were produced from mixing polymer and different percentage tungsten carbide (50, 60, and 70 %). Compared with lead in same conditions the new material is more lightweight and flexible. Moreover the material's shielding efficiency is higher than lead also.

Keywords Gamma radiation · Shielding · Tungsten carbide · Polymer · Lead-free

Introduction

Up to the present, lead and lead compounds have been used for protection from ionizing radiation's hazardous efficiency. Ionizing radiations are absorbed best by high density materials and heavy atoms such as lead and barium [1]. Because of the cost and potential of radiation shielding, lead has usually been used in medical settings for technician and patient protection in the field of X-ray, nuclear medicine, and equipment containers. Unfortunately, although its benefits, lead is toxic and mechanical properties are weak [2, 3]. For this reason, began the research for new lead-free materials. Shielding efficiency of several materials and composites were tested and their linear attenuation coefficients (LAC) were calculated. When the new material was compared to lead, it was non-toxic, flexible and durable. The new material represents an ecologically and economically sound alternative to traditional materials that are toxic and undesirable from environmental standpoint [4, 5].

Nowadays in most of the researches, new materials were obtained from composites that were produced various polymers and high density metals. Polymers are used here because of their important role in primary and secondary protection against gamma radiation [6, 7]. Shielding efficiencies of the materials against X rays and gamma rays were tested. In Eder's study tin, bismuth and tungsten were mixed with different percentages of polymer and it was tested for X-ray attenuation properties [8]. In another study Mc Alister has produced a composite material that was made mixing polymer was named T-Flex with tungsten and iron powder. Then shielding efficiency of the materials was measured against gamma rays using with different energy rates gamma sources [9]. In this study linear attenuation coefficient was determined by using X-COM computer code.

In this study, a new composite material was produced that contained different rate of tungsten carbide (WC) and ethylene vinyl acetate (EVA) polymer composite. Shielding efficiency of the material against gamma radiation was evaluated by Geiger–Muller counter. ^{137}Cs, ^{131}I and ^{241}Am were chosen as gamma source and these sources were counted when their distances from detector 2, 6 and 10.

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Materials and methods

Materials

The composite discs used in experiments were manufactured using EVA polymer and WC micro powder (≤10 μm). EVA (density: 0.94 g/cm^3) used contents 19 % by weight vinyl acetate and it was supplied from DuPont. Another content of WC has 15.63 g/cm^3 density and it was supplied from Sigma-Aldrich.

Preparing the composite discs

In the experiment, the composite discs were produced using the micro-compounder. The micro-compounder is used for preparation of polymer blends and can be operated in co-rotation as well as counter-rotation. At first composite discs were prepared molding in 15 cc DSM Xplore Micro-compounder in 120 °C and 100 rpm for 2 min. After molding process, molten mixture was cut as pellets. Then the pellets were hot pressed in 120 °C to produce discs that have 1 and 2 mm thickness and 5 cm diameter. The diameter of detector is also 5 cm. Ratio of WC in composite was preferred considering Yue et al.'s study. On the other hand preferred polymer EVA is flexible, soft and hydrogen-rich. Moreover the polymer is cheaper than other rubbers for use. The WC–EVA composites list which contents on different WC rates are shown in Table 1 with their codes. The discs with C1, C2 and C3 codes are including 50, 60 and 70 % WC respectively. On the other hand lead and pure EVA with same shape were used for compared with each other.

Gamma detection

The experiments were designed according to gamma transmission technique in which radiation source and detector on the both sides of the disc on the same axis were set up (Fig. 1). Geiger Muller detector was used in the experiments. The shielding efficiency of the discs was calculated as percentage. The attenuation of gamma radiation could be calculated from the formula of Lambert–Beer [9].

Table 1 Codes of EVA–WC composites by percent contained

Composites	EVA (%)	WC (%)
EVA	100	0
C1	50	50
C2	40	60
C3	30	70
Lead	0	0

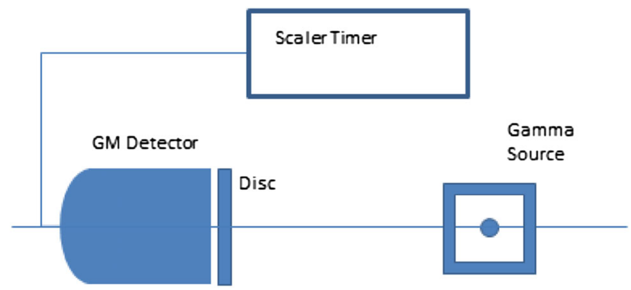

Fig. 1 Schematic view of the Geiger Muller detector and studied geometry

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

where, I is the intensity of the beam after passing through the absorbing material, I_0 is the initial intensity of the beam, μ is the mass attenuation coefficient in cm^2/g and x is the mass thickness in g/cm^2.

In the experiments, radioisotopes with three different gamma (^{137}Cs, ^{131}I and ^{241}Am as high, medium and low energy, respectively) energies were preferred. ^{137}Cs ($E\gamma$: 662 keV), ^{131}I ($E\gamma$: 364 keV) and ^{241}Am ($E\gamma$: 60 keV) radioisotopes were used as gamma source where their half lives are 30.1 years, 8.04 days and 10 years, respectively. The distances between the source and detector was 2, 6, 10 cm.

Results and discussion

Homogeneous dispersion of the metal powders into the polymer is important for the accuracy of measurements. For this reason this case was confirmed by scanning electron microscope (SEM). The SEM micrographs of WC–EVA composites (50, 60, and 70 %) are shown in Fig. 2.

When the composite discs were exposed to ^{137}Cs gamma source, obtained shielding efficiency due to thick of the discs was seen in Fig. 3. The shielding efficiencies of 1 mm thick discs C1, C2 and C3 were observed as 84.9 ± 0.1, 86.4 ± 0.7 and 86.9 ± 0.1 %, respectively. As seen in the results the efficiency of the discs increases with increasing the amount of WC. Hence compared the composites C3 with C2 their shielding efficiencies are not observed remarkable different and both have high shielding efficiency than C1. Therefore, disc C2 can be preference economically according to C3. In the results presented it is clearly shown that the shielding efficiency of discs is higher than pure EVA and almost same with lead (Fig. 3).

On the other hand, effect of disc thickness was seen on shielding. While the shielding efficiency of 1 mm thick disc C3 with is 86.9 ± 0.1 %, the efficiency of 2 mm thick disc C3 is 93.3 ± 0.2 % like C2. As seen in Fig. 3 when

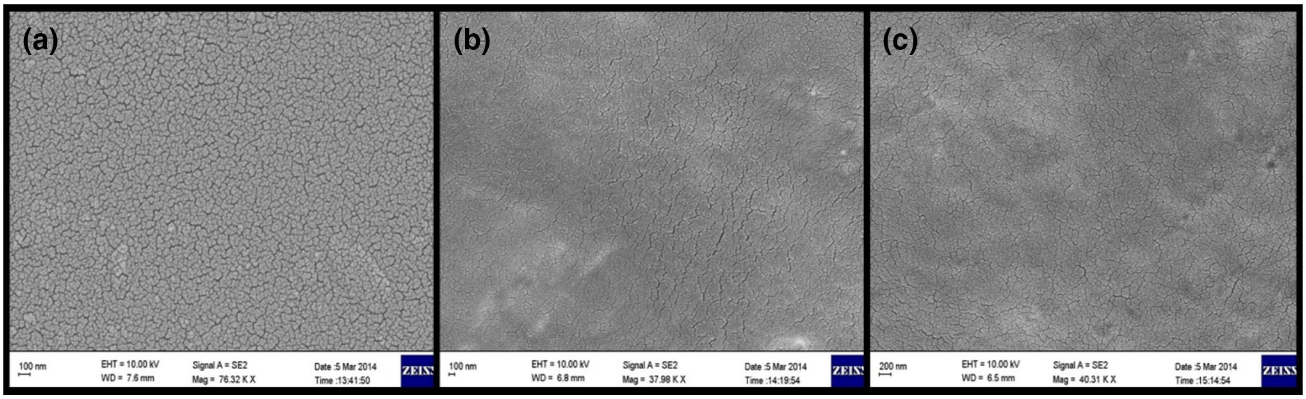

Fig. 2 SEM micrographs of composites **a** C1, **b** C2 and **c** C3

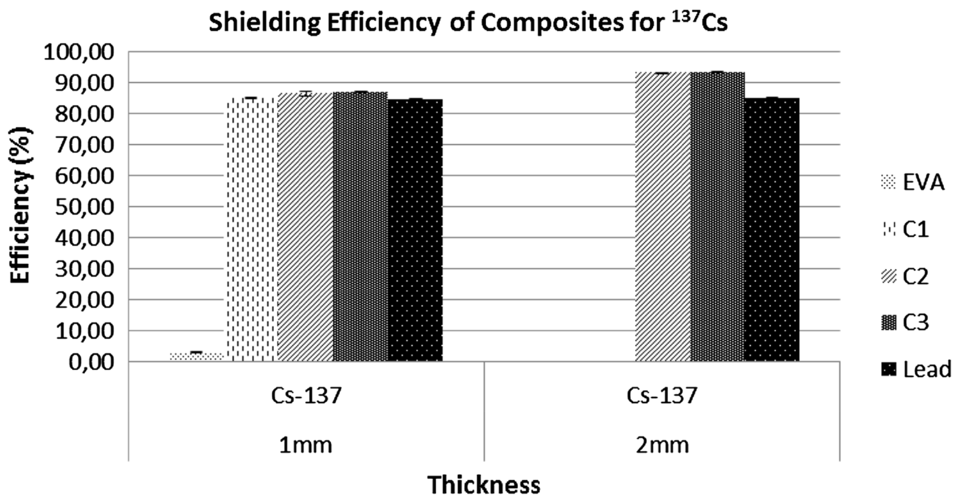

Fig. 3 Shielding efficiency of composites against ^{137}Cs

compared the shielding efficiency of 2 mm thick discs with lead discs the shielding efficiency of composite disc is higher than lead. The best shielding efficiency obtained with the C3 composite disc when the source was 2 cm away from detector (Fig. 3).

When the composite discs were exposed to ^{131}I gamma source, obtained shielding efficiency due to thick of the discs was seen in Fig. 4. The shielding efficiency of 1 mm thick disc C1, C2 and C3 were determined as 80.2 ± 0.3, 81.5 ± 0.3 and 81.0 ± 0.3 %, respectively. Thus, compared the disc C3 with C2, their shielding efficiencies were not observed remarkable different and both discs have high shielding efficiency than C1. Therefore disc C2 can be first choice economically according to C3. It is clearly shown that the shielding efficiency of discs is higher than shielding efficiency of pure EVA and shielding efficiency of lead (Fig. 4).

Shielding efficiency of 1 and 2 mm composite discs and lead discs against ^{131}I gamma source were given in Fig. 4, respectively. As seen on bar chard, when compared composite discs with lead discs for both thicknesses, it is observed all discs have highly effective shielding for ^{131}I source. It could be said that disc C2 and disc C3 have nearly same shielding efficiency. Therefore when considered economically, preference of C2 disc would be more accurate as a shielding material.

Effect of disc thickness was shown significantly difference on shielding. While the shielding efficiency of 1 mm thick disc C3 with is 81.0 ± 0.3 %, the efficiency of 2 mm thick disc C3 is 87.3 ± 0.9 % like C2. As seen in Fig. 4 when compared the shielding efficiency of 2 mm thick discs with lead discs the shielding efficiency of composite disc is higher than shielding efficiency of lead. The best shielding efficiency obtained with the C2 composite disc when the source was 2 cm away from detector (Fig. 4).

The composite discs shielding efficiency due to thick of the discs against ^{241}Am gamma source was presented in Fig. 5. The shielding efficiency of disc C1, C2 and C3 (thickness 1 mm) was determined as 55.0 ± 0.6, 56.2 ± 0.6 and 64.7 ± 1.5 %, respectively. As the data is shown that the efficiency increases with increasing the amount of WC. Therefore disc C3 in comparison with C1

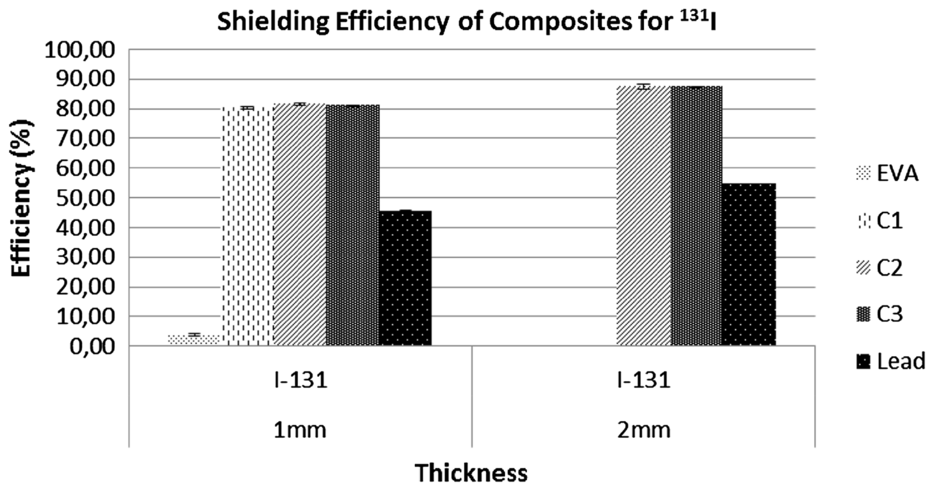

Fig. 4 Shielding efficiency of composites against ^{131}I

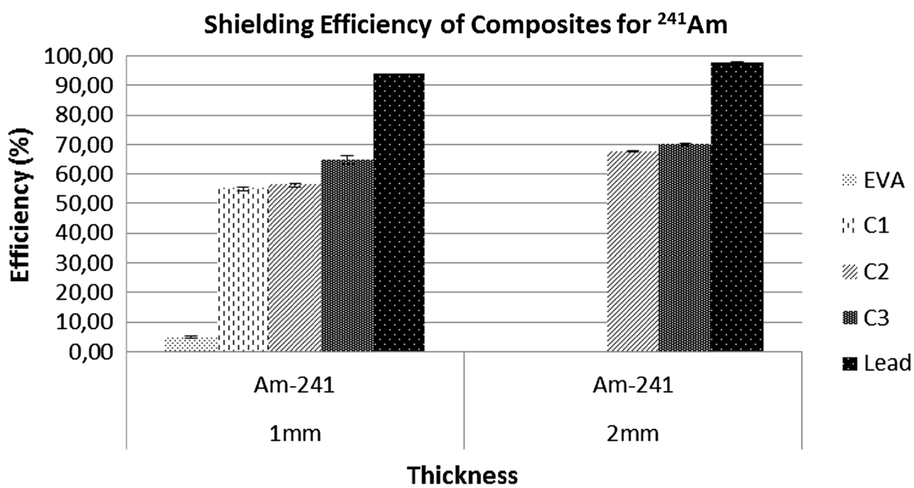

Fig. 5 Shielding efficiency of composites against ^{241}Am

and C2, has high shielding efficiency and their shielding efficiencies are determined nearly same. As seen in Fig. 5 the results were showed that the shielding efficiencies of the discs are higher than shielding efficiencies of pure EVA's.

The composite discs and lead discs have 1 and 2 mm thicknesses their shielding efficiency against ^{241}Am gamma source was given in Fig. 5 respectively. As seen in the figure, it could be assumed that C3 disc has higher shielding efficiency than C1 and C2 discs. The values of WC composite discs were compared lead discs for both thicknesses WC composite discs efficiency was shown decreasing according to lead. On the other hand, when compared WC composite disc's shielding efficiency against ^{241}Am point source with the other gamma source we can see decreasing surprisingly. As the reason of that it is thought that the tungsten element has more secondary scattering in low energies [10]. It could be said that WC discs more effective in gamma photon with high energy.

Moreover, here it is seen that shielding efficiency shows difference with disc thickness. While the shielding efficiency of 1 mm thick disc C3 with is 64.7 ± 1.5 %, the efficiency of 2 mm thick disc C3 is 68.9 ± 0.3 %. As seen in Fig. 5 when compared the shielding efficiency of 2 mm thick discs with lead discs of same thickness the shielding efficiency of lead is higher than composite disc when the source was 2 cm away from detector (Fig. 5).

It was observed when studied with 1 mm thick discs, the shielding efficiencies of C2 and C3 discs are higher than C1 and pure EVA disc. For this reason, the shielding efficiencies were only determined for 2 mm thick discs; C2 and C3.

Yue et al. had been produced new material including SEBS co-polymer with Tungsten instead of lead. They had used the Monte Carlo method. In this study, efficiency of shielding determined using 0.3 between 2.7 cm thick materials against 9–12 MeV energy range. They had determined according to lead new shielding material is more effective against electron shielding also more effective

Table 2 Linear attenuation coefficients of 1 and 2 mm tungsten carbide discs against ^{137}Cs gamma source

^{137}Cs (662 keV) μ(cm^{-1})	Distances		
	2 cm	6 cm	10 cm
EVA	0.25	0.19	0.23
%50—1 mm	18.90	18.84	19.53
%60—1 mm	19.99	19.09	20.14
%70—1 mm	20.29	19.24	20.06
%60—2 mm	26.69	25.56	23.38
%70—2 mm	26.97	25.87	23.82

Table 3 Linear attenuation coefficients of 1 and 2 mm tungsten carbide discs against ^{131}I gamma source

^{131}I (364 keV) μ(cm^{-1})	Distances		
	2 cm	6 cm	10 cm
EVA	0.40	0.30	0.22
%50—1 mm	16.87	13.94	11.87
%60—1 mm	16.19	15.05	11.87
%70—1 mm	16.61	14.92	10.88
%60—2 mm	40.97	37.65	34.00
%70—2 mm	40.91	37.89	35.19

Table 4 Linear attenuation coefficients of 1 and 2 mm tungsten carbide discs against ^{241}Am gamma source

^{241}Am (60 keV) μ(cm^{-1})	Distances		
	2 cm	6 cm	10 cm
EVA	0.49	0.27	0.66
%50—1 mm	6.58	5.57	6.99
%60—1 mm	8.26	7.07	6.97
%70—1 mm	10.41	8.72	8.30
%60—2 mm	29.89	28.11	22.43
%70—2 mm	33.90	31.11	27.29

against Bremsstrahlung [3]. Guetersloh et al. simulated efficiency shielding of polyethylene in cosmic rays environment by Monte Carlo method. They had determined polyethylene show effective shielding effect against cosmic radiation but polyethylene is not longevity material [11]. Kim et al. had been investigated efficiency of barium compounds on medical radiation shielding. In this study, six type of shielding material had been produced by combination of tungsten, molybdenum, rubber and silicone with barium sulfate. These materials were exposed to X-rays. According to the results the materials have been determined as 0.3 mm lead equivalent. Thus they suggested barium compounds could be use instead of lead [12].

LAC of 1 and 2 mm WC and lead discs against ^{137}Cs, ^{131}I and ^{241}Am gamma sources were given in Tables 2, 3 and 4, respectively. Linear absorption coefficient does not change according to the distance between the source and the detector. As seen in Table 2, 3, and 4 for the same materials linear absorption coefficients are close to each other for different distance between the source and the detector. However, when the gamma source was changed LAC showed differences. Moreover, the experiment results on these tables indicated that LAC's value is changed according to thickness of materials and energy of the gamma source.

Conclusion

Metal-polymer (WC–EVA) composite could be the potential candidate for gamma ray shielding applications. The composite improves its gamma-ray shielding with increase in the content of WC. The best shielding efficiency against gamma source is obtained using 70 % WC contained composite. In addition, it has been found that the composite has good shield property against gamma ray with high energy instead of with low energy. In concluding as shown D-Shore test results the composite has elastic, soft and easy shapeable at the same time it's lightweight and non-toxic properties as well as better gamma-ray shielding might be choice for commercial utilization.

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