Journal of Kerbala University , Vol. 12 No.3 Scientific . 2014

Variation of gamma ray attenuation parameters for Poly vinyl alcohol reinforced by lead acetate

تغير معاملات توهين أشعة كاما لبولي فاينيل الكحول المدعم بخلات الرصاص

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Abstract

Design types of shielding polymers to protect patients and personnel from the effect of scattered radiation during radiotherapy. Some shielding factors were calculated such as mass attenuation coefficient (μ_m), half value layer (HVL), effected atomic number (Z_{eff}) and heaviness for polyvinyl alcohol (PVA) as matrix material mixed with various levels of lead acetate (10 - 50 wt. %) as reinforced materials at photon interactions in the wide gamma ray energy range of 0.001-100 MeV using XCOM program and measured at 0.662 MeV by usage a ^{137}Cs radioactive source. The experimentally obtained values were generally in good agreement with the theoretical ones. The results revealed that the shielding properties of poly vinyl alcohol increased with the addition of lead acetate. Gamma ray shielding properties of our polymer samples have been compared with standard ordinary concrete. It was found that 20wt.% of lead acetate $(CH_3COO)_2Pb$ is the minimum percent mixed with PVA improves the gamma ray shielding properties best than standard ordinary concrete (NIST).

Keywords: Polyvinyl alcohol, Lead acetate, Radiation shielding materials, Gamma ray, Mass attenuation coefficient, Effective atomic number.

ملخص

تم تصميم مواد بوليمرية لحماية المرضى والعاملين في مجال الأشعاع المنتشر اثناء التعرض. حسبت بعض عوامل التوهين مثل معامل التوهين الكتلي، سمك النصف، العدد الذري المؤثر لبولي فاينيل الكحول (كمادة اساس) مدعمة بتراكيز مختلفة من خلات الرصاص بنسب وزنية (10 - 50 wt. %) عند مدى واسع من طاقة أشعة كاما 0.001 -100 MeV باستخدام البرنامج العالمي XCOM . كذلك تم حساب معاملات التوهين عمليا لفوتونات ذات الطاقة 0.662MeV باستخدام المصدر المشع ^{137}Cs . أظهرت النتائج ان توهين الفوتونات يزداد بزيادة تركيز خلات الرصاص في النموذج. القيم العملية لمعاملات التوهين كانت عموما موافقة للقيم النظرية. كذلك قورنت معاملات التوهين للنماذج مع نموذج قياسي للكونكريت العادي. وجد ان خلط 20wt.% من خلات الرصاص مع بولي فاينيل الكحول تمثل الحد الادنى لتحسين معاملات التوهين ليكون افضل من الكونكريت العادي (القياسي).

1. Introduction

Gamma-ray and X-ray attenuation coefficients are very important in both fundamental and applied science. They are invaluable in many applied fields, such as nuclear diagnostics, radiation protection, nuclear medicine, and radiation dosimetry [1, 2]. Protection of the body from unnecessary radiation exposure when working in a radiation area is a priority for every health physicist. Delivery of an accurate and precise dose plays a very important role for achieving these goals [3, 4]. Shielding is designed to combine the most effective shielding components into single homogeneous composite, which satisfy specific shielding requirements for radiation sources. Recently, there is a continuous demand for improved plastics that satisfy stringent requirements such as high mechanical strength and heat resistance for the use as shielding materials. Fillers played the key role to obtain all such requirements. Since polymeric materials are on their own hydrocarbonic substances we would expect good neutron moderation. Judicious choice of heavy mineral or metal fillers, gamma rays and X-rays could be also shielded.Various composite materials have been recently synthesized by starting from different polymers containing heavy metals, inorganic salts, and other particles [5]. The incorporation of the doping into polar organic polymers can induce pronounced changes in various properties of polymers in order to modify and improve its properties [6-8]. In the present work, photon attenuation parameters like mass attenuation coefficient (μ_m), half value layer (HVL), effective atomic number (Z_{eff}) and heaviness for PVA and five different lead acetate concentrations in PVA polymer have been studied at photon energies varying from 1keV to 100MeV.

2. Theoretical background

The theoretical relations used in the present work are summarized in this part. A collimated beam of mono-energetic gamma ray is attenuated in matters according to the Lambert-Beer law [9,10]:

$$I = I_0 \ e^{-\mu x} \qquad (1)$$

Where I_0 is the initial intensity of gamma ray, I is the intensity of gamma ray after attenuation through a material of thickness x and μ is the linear attenuation coefficient (cm^{-1}) of the material. Mass attenuation coefficient (μ_m) of the material is obtained by dividing μ by the material density (ρ). The mass attenuation coefficient, for a compound or mixture is given by [9,10]:

$$\mu_m = \sum_i w_i (\mu_m)_i \qquad (2)$$

Where w_i and $(\mu_m)_i$ are the weight fraction and mass attenuation coefficient of the ith constituent element, respectively. For any compound, the total atomic cross section (σ_a) can be calculated from the knowledge of mass attenuation coefficient by the following formula [7,11]:

$$\sigma_a = \frac{\mu_m}{N_A \sum_i \frac{w_i}{A_i}} \qquad (3)$$

Where N_A is Avogadro's number and A_i is the atomic weight of ith element. Similarly, the total electronic cross section (σ_{el}) is given by [7,11]:

$$\sigma_{el} = \frac{1}{N_A} \sum f_i \frac{A_i}{Z_i} (\mu_m)_i \qquad (4)$$

Where $f_i = (n_i / \sum_j n_j)$ is the fractional abundance of ith element with respect to number of atoms and Z_i is the atomic number of the ith element. Finally, using Eqs. (3) and (4), the effective atomic number (Z_{eff}) can be defined as:[7,11]:

$$Z_{eff} = \frac{\sigma_a}{\sigma_{el}} \qquad (5)$$

The thickness of the material that reduces the photon beam intensity to half of its original value (I_0), i.e. (½) I_0, is called the half value layer (HVL) and is given by [9]:

$$HVL = \frac{\ln 2}{\mu} = \frac{0.693}{\mu} \qquad (6)$$

3. Experimental details

3.1 Sample preparation and density measurements

Polyvinyl alcohol (PVOH or PVA) is a water-soluble synthetic polymer. It has the idealized formula $[CH_2CH(OH)]_n$. Lead acetate powder $(CH_3COO)_2Pb$ and Polyvinyl alcohol (PVA) were of commercial grade and used without any modifications. All the chemicals were weighed accurately using an electrical balance with an accuracy of 0.001g and mixed thoroughly. Composites of lead acetate were 10, 20, 30, 40 and 50 weight %. Preparation of lead acetate -PVA samples in the form of solid crystal was first taken in a beaker and then stirred with 300ml of water at temperature of 60 ^{0}C for one hour. After overcoming the first stage of gel stage formation, a true solution is formed. These solutions are prepared using open mould casting technique at room temperature and left to dry for 7 day to remove any residual solvent. The density values are shown in Tablel1. It can be seen that the density values increase of both polymer systems with increase the concentration of lead acetate which may be contributed to higher atomic weight of lead.

Table 1: Density of lead acetate - PVA samples.

Ratio of lead acetate in the composite (wt %)	Density (g/cm^3)
100% PVA	1.09 ± 0.02
10% lead acetate +90% PVA	1.21± 0.02
20 % lead acetate +80% PVA	1.37± 0.02
30 % lead acetate +70% PVA	1.53± 0.04
40 % lead acetate +60% PVA	1.72± 0.04
50 % lead acetate +50% PVA	1.91± 0.05

3.2 Calculation of the total mass attenuation coefficients

The mass attenuation coefficients (μ_m) were calculated for the five lead acetate – PVA polymer samples using a computer program XCOM (version 3.1). The XCOM program used to calculate the total mass attenuation coefficient for elements, compounds and mixtures at photon energies varying from from1 keV to 100 GeV [7], and provides total cross section as well as partial cross sections for various interaction processes. By using the values of mass attenuation coefficient, the values of HVL have been calculated. Authenticity of XCOM program for evaluating the gamma ray shielding parameters has been checked by several authors [12-14] and it has been established that XCOM program can be used as a tool to evaluate the gamma-ray shielding parameters.

3.3 Gamma ray measurements by NaI (Tl) detector

The schematic arrangement of the experimental setup in the present work is shown in Fig.1. The gamma ray spectrometer will be energy calibrated using standard multi energy gamma sources (^{137}Cs, ^{22}Na and ^{60}Co). All samples were used in the form of a tablets plate with 2 cm diameter. Samples with different thicknesses 0.3-1.2 cm were arranged in front of a collimated beam emerged from ^{137}Cs radioactive point source. Standard radioactive gamma source ^{137}Cs of energy 0.662MeV with 69.74μCi (2.58 MBq) strength manufactured by LD.G.mbh-Germany was used. The intensities of gamma photons were measured by using 2"x2" NaI (Tl) scintillation detector (Saint- Gobain Crystals Bicron). The detector was coupled to pre-amplifier, amplifier, power supply and multi-channel analyzer with LD Didactic GmbH sensor-cassy for data acquisition and analysis the obtain areas. The detector was also housed in a thick lead jacket to reduce the radiation background as low possible. The distance between detector and source was 10 cm. While taking the readings a sufficient number of counts were collected under photo peak to limit the static error to less than 1%. For each sample, I_0 and I intensities which are without and after investigated sample were measured.

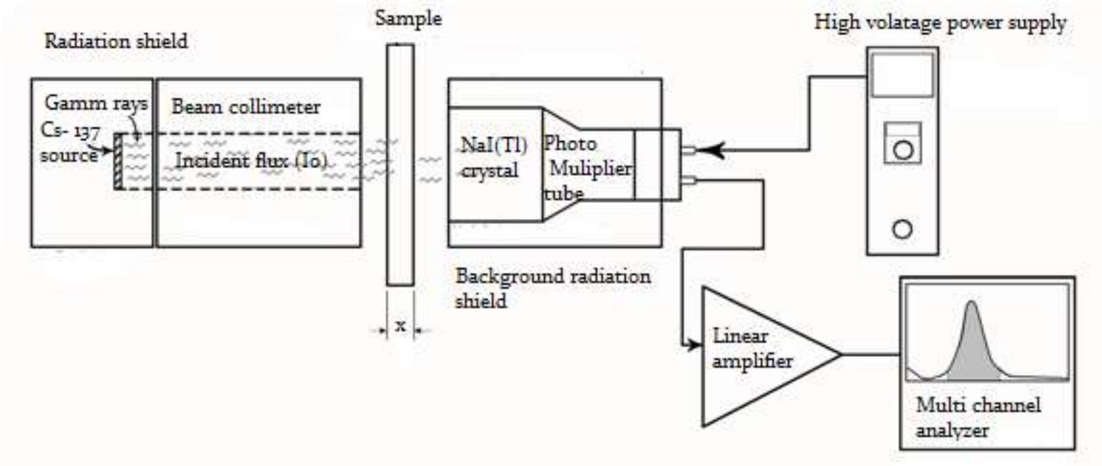

Fig.1. Experimental setup.

4. Results and discussion

4.1 Mass attenuation coefficient

The variation of the mass attenuation coefficients (μ_m) with the incident photon energy of gamma rays is shown in Fig.2 and it is observed that the μ_m values for all the selected lead acetate-PVA samples decrease very rapidly with increase in the incident photon energy up to 0.1 MeV with a peak due to photoelectric effect around the K, L and M-absorption edges (88, 15.86 and 3.58keV) of the lead, then μ_m values decrease slowly and are almost the same for all the lead acetate-PVA. Beyond 10 MeV, the μ_m values start increasing very slowly this may be due to the dominance of different partial interaction processes. The rapid decrease in μ_m values below 0.1MeV can be explained on the basis of the dominance of the photoelectric effect, whose cross section depends on atomic number as Z^4 (for low photon energy)[10]. Beyond 0.1 MeV, the Compton scattering process becomes dominant, whose cross section varies linearly with Z and is inversely proportional to the incident photon energy; thus the μ_m values for all the lead acetate-PVA samples become almost the same and decrease slowly up to 10MeV.With the further increase in incident photon energy, the pair production process starts dominating whose cross section depends on atomic number as Z^2 and is proportional to the incident photon energy as *log*E, and hence the μ_m values increase slowly. Fig.2 also seen that μ_m values increases with the increase in weight fraction of lead acetate. This can be attributed to increasing values of Pb which has higher atomic number as compared to other elements. It is estimated that 20 % lead acetate +80% PVA sample better than standard ordinary concrete NIST (National Institute of Standards and Technology) taken from literature[15] in terms of mass attenuation coefficient for gamma-ray shielding applications. Fig.3 shows plot of *ln* (I_0/I) Vs. thickness of the attenuators at 0.662 MeV. The slope of the graph gives the linear attenuation coefficient (μ) of lead acetate-PVA samples at that particular energy. Table 2 gives the experimental and theoretical values of mass attenuation coefficients (μ/ρ) for selected samples. The comparison of their measurements with the theoretical values is done by calculating the relative deviation (RD). We found the deviation mostly below 3%, the difference between the two results is due to the purity of the elements in the samples. In general, the experimental values agreed with the theoretical values.

Table 2: Comparison between mass attenuation coefficients μ_m (cm^2/g) for lead acetate - PVA samples with relative deviation (RD) at photon energy 0.662 MeV

Ratio of lead acetate in the composite (wt %)	$\mu_m \times 10^{-2}$ (cm^2/g) (theoretical)	$\mu_m \times 10^{-2}$ (cm^2/g) (experiment)	RD (%)
100% PVA	8.414	8.258 ± 0.022	1.85
10% lead acetate +90% PVA	8.569	8.501 ± 0.027	0.80
20 % lead acetate +80% PVA	8.723	8.613 ± 0.031	1.26
30 % lead acetate +70% PVA	8.878	8.785 ± 0.028	1.03
40 % lead acetate +60% PVA	9.032	8.803 ± 0.049	2.54
50 % lead acetate +50% PVA	9.187	8.968 ± 0.065	2.38

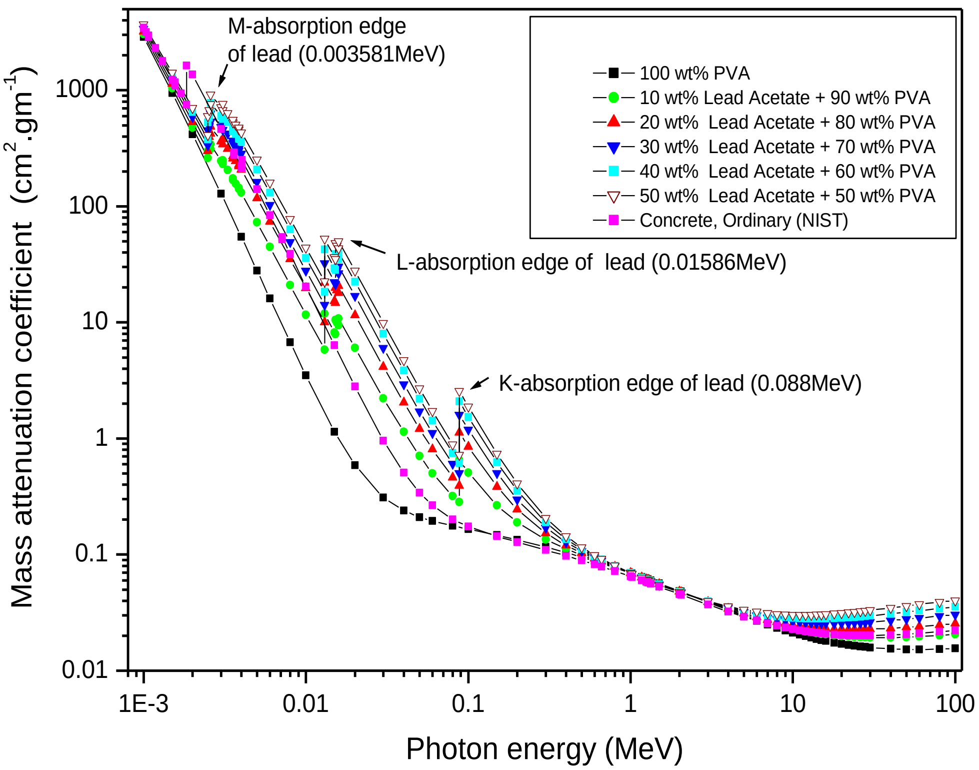

Figure 2. Variation of mass attenuation coefficient as a function of photon energy (1keV to 100 MeV) in the lead acetate-PVA Polymer

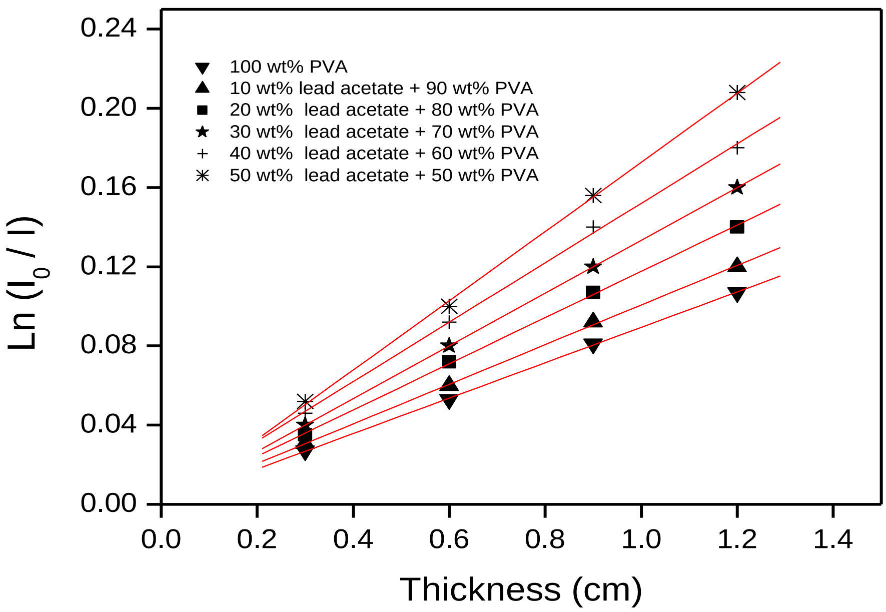

Figure 3. ln (I_0/I) versus thickness for lead acetate-PVA polymer samples at 0.662 MeV.

4.2 Half value layer

Half value layer (HVL) of prepared lead acetate-PVA samples based on the present work with standard ordinary concrete (NIST) at photon energies varying from 1keV to 100MeV were shown in Fig.4. HVL decreases with the increase in weight fraction of lead acetate. HVL result showed that the better shielding properties are achieved at higher lead acetate concentrations. This can be attributed to increasing values of Pb which has higher atomic number as compared to other elements. It was found that 20wt.% of lead acetate $(CH_3COO)_2Pb$ is the minimum percent mixed with PVA improves the gamma ray shielding properties best than standard ordinary concrete (NIST).

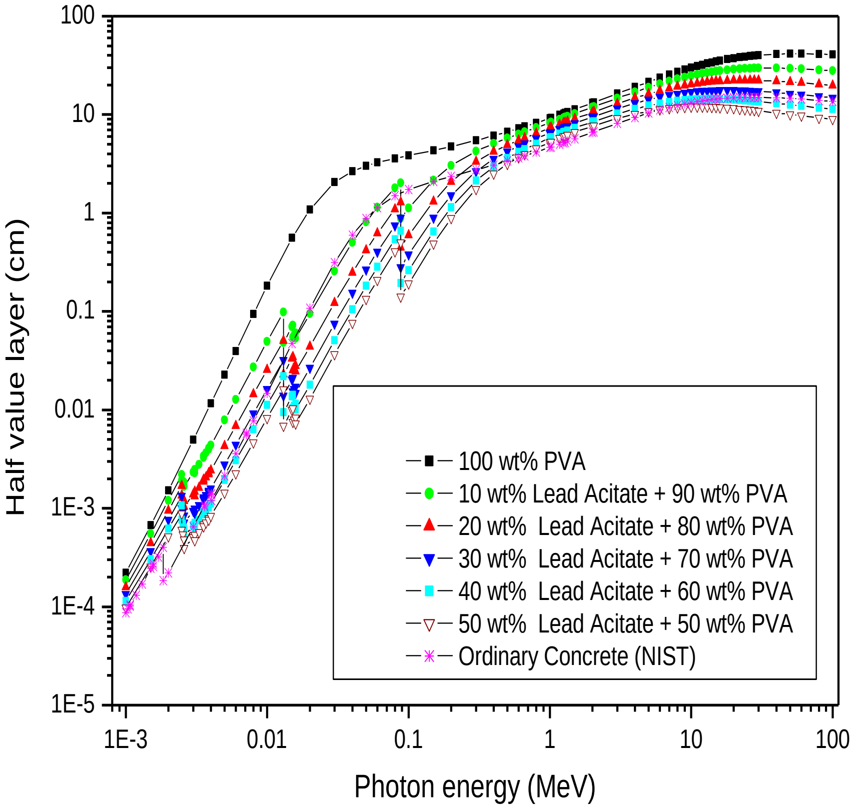

Figure 4. Variation of half value layer as a function of photon energy (1keV to 100 MeV) in the Lead Acitate-PVA Polymer and ordinary concrete

4.3 Effective Atomic Number

The variation of the effective atomic number (Z_{eff}) with the incident photon energy is shown in Fig.5. The Z_{eff} values show a broad peak and a maximum value at 0.02 MeV and minima at 1 MeV for all lead acetate - PVA samples. The variation of Z_{eff} with photon energy may be attributed to the relative domination of the partial processes, viz. photoelectric effect, Compton scattering and pair production [10]. At low energies the photoelectric effect is dominant and hence Z_{eff} for the photon absorption is mainly described by Z_{eff} for this partial process. Hence at low energies, where photoelectric effect dominates, Z_{eff} value is more and at higher energies, where the scattering and pair production process dominate, the Z_{eff} value is less. Therefore, Z_{eff} for photon energy absorption varies from a higher value at lower energies to a lower value at higher energies with peaks due to photoelectric effect around the K, L and M-absorption edges of the lead. Z_{eff} versus weight fraction of lead acetate at photon energy 0.662MeV has been shown in Fig. 6. It is observed that effective atomic number increases with the increase in weight fraction of lead acetate.

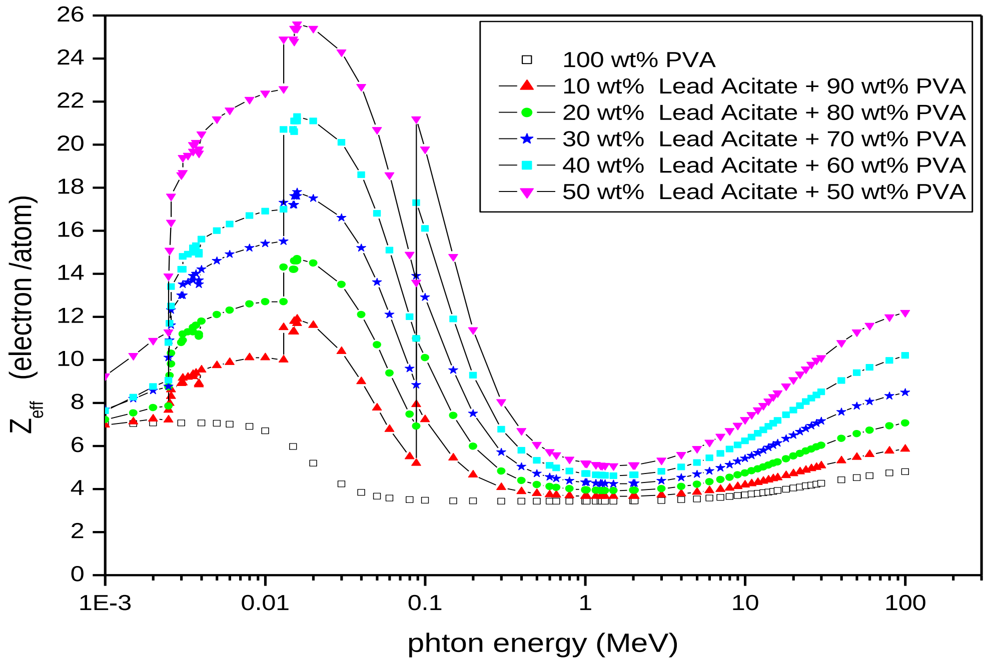

Figure 5. Energy dependence of effective atomic number Z_{eff} for Lead Acitate-PVA Polymer.

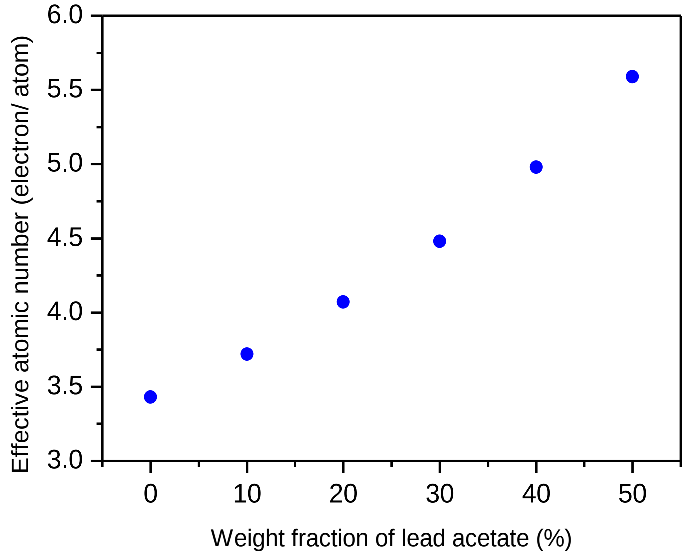

Figure 6.Variation of Z_{eff} versus weight fraction of lead acetate in the lead acetate -PVA polymer system at incedent photon energy 0.662MeV .

4.4 Heaviness

The beauty of lead acetate- PVA lies with their lightness to verify the heaviness of the lead acetate -PVA samples, lead was assumed standard and normalized 100%. With reference to lead, the % of heaviness of the other conventional shielding materials along with lead acetate-PVA samples was evaluated using the following relation as shown in Fig.7.

$$\%\,of\ \ heaviness = \frac{Density\ of\ given\ material}{Density\ of\ lead} \times 100\%$$

With lead at 100% heavier than other shielding materials under consideration, copper at 78.76%, iron at 69.43% and ordinary concrete at 20.28% heavier of lead. In case of lead acetate –PVA samples, the 50% lead acetate + 50% PVA is only 16.8% of lead. These results prove that the polymer composites considered exhibit lightness when compared to conventional radiation shielding materials such as lead, copper, iron and concrete.

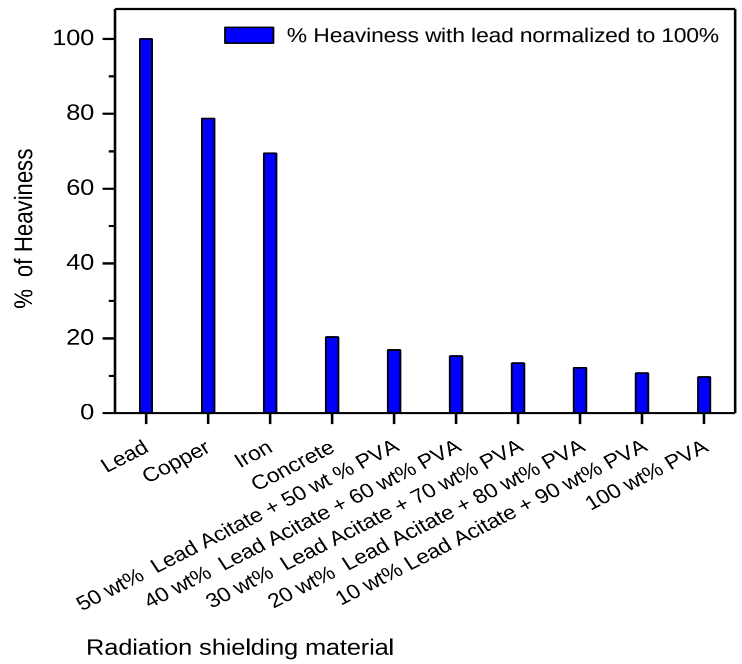

Figure 7. Heaviness of lead acetate-PVA composites along with the other conventional shielding materials

5. Conclusions

From measured and calculated results gamma ray attenuation parameters in Poly vinyl alcohol - Lead acetate composite with different concentrations of lead acetate, it can be concluded: Lead acetate - PVA composite can act as shields against gamma radiation sources. These may be molded into different shapes thus making them useful fillers in empty spaces like ducts, trenches and penetrations. The reasonable agreement between calculated and measured values of the produced results and may be useful for shielding calculations. We expected that these new data are useful in the field of radiation shielding. Also, to the best of the knowledge of the authors, these data are the first of these kind estimated for a wide gamma ray energy range.

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