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Research Article

Gamma-Ray Attenuation Properties of Flexible Silicone Rubber Materials while using Cs-137 as Radioactive Source

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Abstract

In this study, pure silicone rubber and iron ore concentrate added silicone rubber materials were performed against Cs-137 gamma source. Cs-137 is accepted intermediate energy level gamma source in nuclear technology because of its energy peak at 0.662 MeV. Up to 67 wt. % iron ore concentrate added into silicone rubber materials were used in the experiments. Linear attenuation curves were carried out for the studied samples against Cs-137 gamma energy. Increasing iron ore ratio in the materials caused the higher radiation shielding performance for Cs-137 gamma energy. In addition, increasing iron ore ratio decrease the total volume air bubbles in the samples. Decreasing air bubbles in the samples has contributed to gamma ray shielding. 0.5 mmPbE and 1 mmPbE Lead equivalent (PbE) values were determined for the samples. 0.5mmPbE standard has been provided by using 2.83 mm thick of 67 wt. % iron ore concentrate imbedded silicone rubber at 0.662 MeV gamma energy. In conclusion, iron ore concentrate imbedded silicone rubber materials are among the promising economic radiation shielding materials which could be alternative to lead.

Keywords: Cs-137; Silicone rubber; Gamma attenuation; Lead equivalent thickness; Iron ore concentrate.

1. Introduction

Radiation sources have been used for many years in nuclear technology applications from medicine to nuclear energy. In nuclear technology, protection from the unnecessary radiation is essential and should be provided by some protective materials [1-3]. Lead is the most used material for gamma and x-ray shielding thanks to its properties such as easy and cheap production and high density [4]. Therefore, usually radiation shielding standards were used to provide same attenuation ratio of pure lead and mixed materials [5]. For example, 0.5mmPbE means the equivalent attenuation ratio of pure lead which has thickness of 0.5 mm for a specific radiation energy. However, lead is highly toxic and hazardous materials for environment. Therefore, there were remarkable studies to get lead-free materials for radiation shielding applications. Tungsten, bismuth, antimony, iron and barium was among the candidate materials for radiation shielding instead of lead [4-15]. On the other hand, some of the alternative materials have more expensive production cots whereas some of them have bigger lead equivalent thickness and weight. Although tungsten has bigger linear attenuation coefficients [8] than lead, the price of tungsten prevents to use it widely in commercial applications. In addition, producing the radiation shielding garments with light-weight, easy to use, comfortable and effective cost properties will help using these materials in applications, widely.

Flexible materials with some additives are used to produce radiation protective garments, collars, caps, curtains etc. [8-11, 13]. Usually rubbers, polymers, vinyl are used as matrix materials to get flexible radiation protective materials whereas lead, antimony, tungsten and bismuth powders are used for additives. Silicone rubbers are one of the matrix materials which has good elasticity properties [16, 17]. In addition, iron is one of the good radiation attenuators. It has relatively cheap production cost when the ore form of iron is used [13].

Cs-137 is a gamma source which has been used in many applications [18]. It is accepted as medium energy level gamma source which has unique gamma peak at 0.662 MeV. The Compton scattering effect is dominant when the gamma rays of Cs-137 interact with

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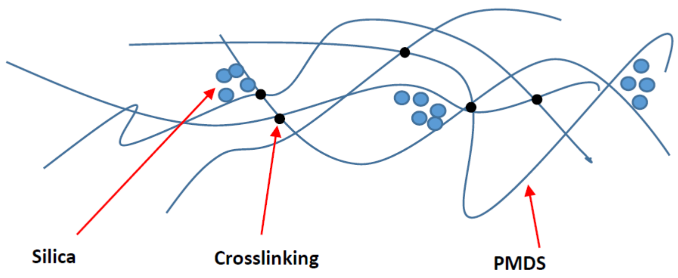
the materials atoms. Also photo electric events are possible in interactions whereas no pair production event takes place because of the gamma energy under 1.02 MeV.

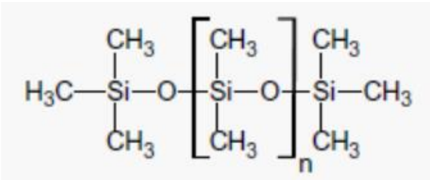
The Cs-137 gamma attenuation properties of pure silicone rubber and iron ore concentrate added silicone rubber materials were carried out. The lead equivalent thicknesses of the samples were determined at 0.662 MeV. The possible uses of the samples were evaluated for nuclear technology applications.

2. Experimental Methods

Room temperature vulcanized (RTV-2) silicone rubber was used as flexible matrix material. Polydimethylsiloxane (PMDS) is the most common form of silicone and it is originally liquid. PDMS polymers are transformed elastomeric solid structure by means of catalyzed cross-linking reactions [16]. About 5 wt. % stiffener was added to silicone rubber liquid to get catalyzed cross-linking reactions. These reactions create chemical bonds between neighboring chains. The homogenous mixtures (liquid silicone rubber + stiffener) poured to cylinder molds which have 5 cm diameter and 0.5 cm thickness. After waiting 24 hours the materials become elastomeric solid structure. The main properties of the silicone rubber were given on Fig 1 and Table 1.



(a)



(b)

Figure 1. Schematic view of crosslinking process (a) and chain structure(b) for silicone rubber [16].

Table 1. General properties of the matrix material [17]

RTV-2 Silicone Rubber	
Specific Gravity (g/ml)	1.14
Mixing Ratio, by weight	10:1
Elongation (%)	350
Pot Life (h)	2
Cure Time (h)	24

In addition, Magnetite (Fe_3O_4) iron ore concentrate (~63 wt.% Fe content) powders were added to silicone rubbers for radiation attenuation tests. Iron ore powders which have about 500 µm average particle size were put into the silicone rubbers after adding stiffener in solidification process. Different iron ore concentrate ratios from 5 wt. % to 67 wt. % were imbedded to silicone rubbers successfully without losing significant elasticity. The samples were coded according to iron ore ratio in the sample. For example, 10 wt. % iron ore concentrate imbedded silicone rubber sample coded as SDT-10. Figure 2 and Table 2 shows the produced samples.

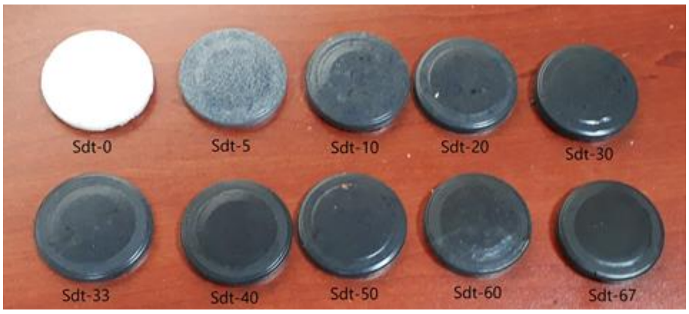


Figure 2. Produced pure silicone rubber and iron ore concentrate added silicone rubber samples.

Table 2. Produced pure silicone rubber and iron ore concentrate-silicone rubber materials.

Code	Iron Ore (wt%)	Silicone Rubber (wt%)
Sdt-0	0	100
Sdt-5	5	95
Sdt-10	10	90
Sdt-20	20	80
Sdt-30	30	70
Sdt-33	33	67
Sdt-40	40	60
Sdt-50	50	50
Sdt-60	60	40
Sdt-67	67	33

The homogeneity of the samples was figured out by X-ray radiograph films (Portable digital radiography system). The view of the x-ray radiograph system was shown in Figure 3. The x-ray radiography films were taken by 10 pulses of the machine at 250 kV operating voltage.

Figure 3. View of X-ray radiography system

In addition, radiation shielding properties of the samples were investigated by gamma transmission technique (Figure 4). Cs-137 gamma radiation source was used in the experiments which has unique energy peak at 0.662 MeV. This energy level was accepted in intermediate energy region which Compton scattering interaction is dominant. NaI Scintillation detector has been used to detect gamma radiation. Two lead blocks with 0.7 mm holes were used to get narrow beam conditions as well as biological shielding. The distance between the source and detector is 35 cm.

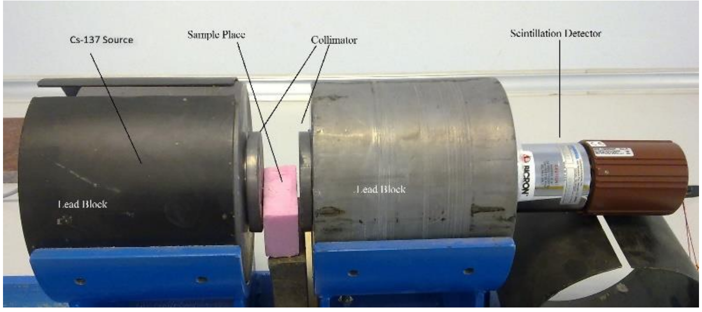


Figure 4. View of Gamma transmission technique for Cs-137 gamma source.

At first initial radiation intensity was measured without material in the sample place. Then samples were put in the place with different thickness and counted to get transmitted radiation intensity. Each experiment was applied by 300 s. The Relative intensity values of the samples at different thicknesses were carried out and graphed. The graphs were fitted exponentially to get linear attenuation coefficients of the samples according to Beer Lambert's Equation:

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

Where I and I_0 were transmitted and incident radiation intensity, respectively. μ is the linear attenuation coefficient at 0.662 MeV gamma ray energy and x is the material thickness in cm. The linear attenuation coefficient could be derived from Beer Lambert's equation as;

$$\boldsymbol{\mu} = [-(1/x)] \ \ln [I/I_0] \quad (2)$$

The linear attenuation coefficient is sum of three main interaction mechanisms between gamma rays and materials atoms. These are photoelectric event (pe), Compton scattering (cs) and pair production (pp) events.

$$\mu = \mu_{pe} + \mu_{cs} + \mu_{pp} \quad (3)$$

On the other hand, pair production event doesn't occur for gamma energies under 1.02 MeV. Therefore, there is no pair production event for Cs-137 gamma source which has gamma energy 0.662 MeV. The linear attenuation coefficients of the samples were evaluated by the view of radiation shielding capability and compared to each other. In addition, the results were carried out according to iron ore concentrate ratio and discussed.

Radiation shielding properties were figured out for each sample and compared with the 0.5 mm and 1 mm lead equivalent (PbE) radiation shielding for Cs-137 gamma source. The attenuation ratios of 0.5 mmPbE and 1 mmPbE were determined by using XCOM computer code which is widely used in the literature [19].

3. Results and Discussion

3.1. Homogeneity of produced silicone rubbers

The radiographic film of the pure silicone (Sdt-0) sample was given on Figure 5. Pure silicon has uniform distribution whereas just some air bubbles occurred at edge (red circles in Figure 5). The air bubbles could be reasoned of pouring liquid silicone mix to mold with non-uniformly. The pure silicone has also good elasticity and doesn't wear when folded on its own.

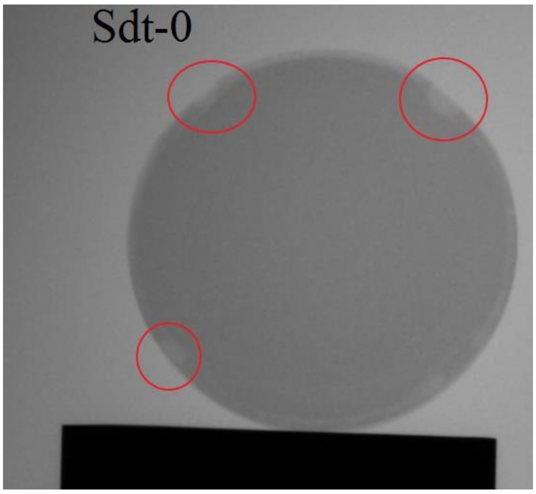


Figure 5. Radiographic film of pure silicone (Sdt-0) sample.

The radiography films of Sdt-50 and Sdt-60 were given in Figure 6. Sdt-50 and Sdt-60 have uniform distribution. The darkness of the samples almost same in every part of the samples. It shows that the iron ore powders were spread uniformly and the sample has homogenous structure. On the other hand, the air bubbles in the samples were spread all over the materials unlike Sdt-0. The air bubbles in Sdt-60 were less and smaller than in Sdt-50 (red circles in Figure 6). Iron ore particles much more take place in the silicone rubber than air bubbles as increasing iron ore percentage. The iron ore added silicone rubbers have also enough elasticity and don't wear when folded on their own.

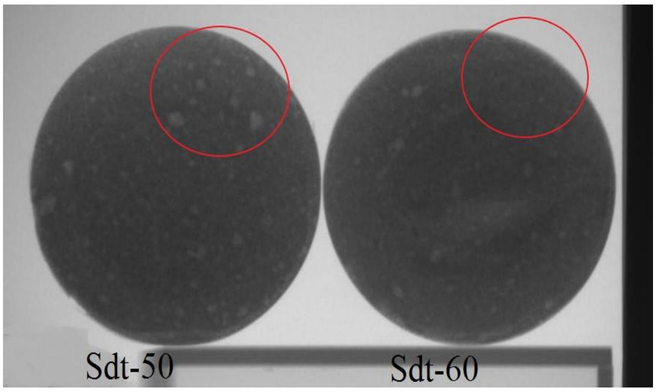


Figure 6. The radiography films of Sdt-50 and Sdt-60 samples.

3.2. Gamma attenuation properties of produced silicone rubbers

Relative intensity values were carried out for pure silicone rubber and iron ore concentrate added silicone rubber samples at different thicknesses. Relative Intensity- thickness curves were drawn and given in Figure 7.

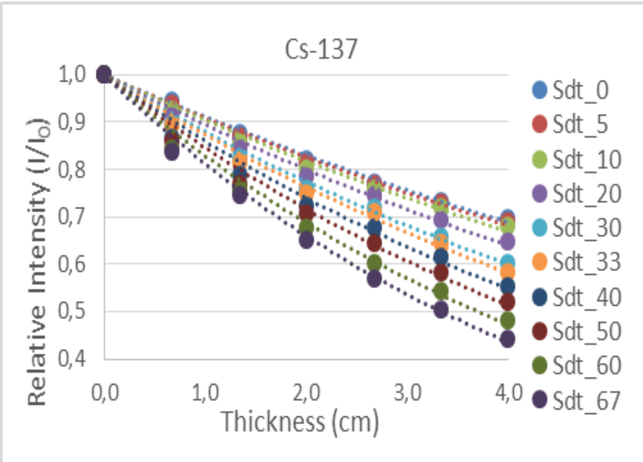


Figure 7. Relative Intensity values of pure silicone and iron ore concentrate added silicone rubber materials at different thicknesses for Cs-137 gamma source.

Pure silicone rubber has the biggest relative intensity values. Iron ore concentrate added silicone rubbers have smaller relative intensities. Increasing iron ore percentage caused to lower relative intensity values which mean having greater radiation shielding capabilities. The graphs on Figure 7 were fitted to exponential distribution in compliance with Beer Lambert's formula. The linear attenuation coefficients were carried out for Cs-137 gamma energy and given in Table 3. In addition, the linear attenuation coefficient changes due to iron ore percentages in the samples were given in Figure 8.

Table 3. Linear attenuation coefficients of the samples for Cs-137 Gamma source.

Sample (Code)	Linear Attenuation Coefficient, μ (cm^{-1})
Sdt-0	0,093
Sdt-5	0,096
Sdt-10	0,101
Sdt-20	0,112
Sdt-30	0,128
Sdt-33	0,135
Sdt-40	0,150
Sdt-50	0,166
Sdt-60	0,187
Sdt-67	0,207

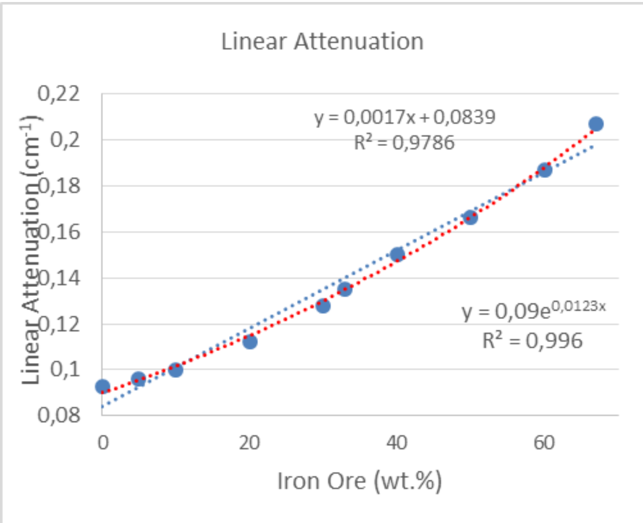


Figure 8. Linear attenuation coefficients of pure silicone and iron ore concentrate added silicone rubber samples for Cs-137 gamma energy.

Pure silicone has the smallest linear attenuation coefficient as shown on Figure 8. Iron ore concentrate added silicone rubber materials have higher linear attenuation coefficients than pure silicone. Linear attenuation coefficients were increased with higher iron ore concentrate ratios. The distribution of the linear attenuation values has two possible fitting which are the linear and exponential. Both linear (blue) and exponential (red) trend lines were given in Figure 8. When the R-square values of the lines investigated they were closed to each other just exponential one is much closer to 1. The air bubbles in Sdt-60 were less and smaller than in Sdt-50. Iron ore particles much more take place in the silicone rubber than air bubbles as increasing iron ore percentage. Therefore, the linear attenuation values increased with not only increasing ratio but also decreasing air bubbles. So this was the reason of exponential increasing of linear attenuation coefficients.

Lead equivalent thicknesses (0.5 mmPbE and 1 mmPbE) of pure silicone rubber and Iron ore concentrate added silicone rubber materials were determined by using XCOM computer code and given in Figure 9. Pure silicone sample has the biggest lead equivalent thickness values. Iron ore concentrate added silicone rubbers have smaller led equivalent thickness values than pure silicone rubber. In addition, lead equivalent thickness values were decreased by increasing iron ore ratio. For Sdt-67, 0.5 mmPbE is provided by 2.83 mm which means 0.5 mm pure lead and 2.83 mm Sdt-67 have same radiation attenuation ratios for Cs-137 gamma source. Common used commercial radiation protective garments have 1.5-2.0 mm in thickness (for 0.5 mmPbE). Although, Sdt-67 has greater thickness than commercial products, it has still could be an alternative radiation protection material because of its cheap cost [13]. Also its possible to decrease the lead equivalent thickness of Sdt-67 by increasing iron ore ratio and/or adding extra economic additives such as antimony concentrate. Moreover, iron ore concentrate imbedded silicone rubber materials could be accepted as green materials according to lead.

Furthermore, these materials have lower cost than lead and non-lead ones. Therefore, iron ore concentrate imbedded silicone rubber materials are among the candidate materials for using radiation shielding applications instead of lead.

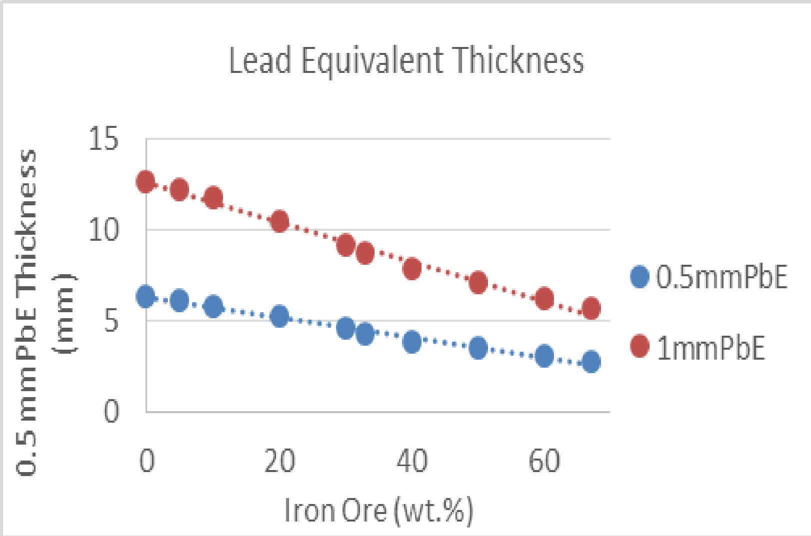


Figure 9. 0.5mmPbE and 1 mmPbE lead equivalent thicknesses of pure silicone rubber and iron ore concentrate added silicone rubber materials for Cs-137 gamma source.

4. Conclusions and recommendations

Pure silicone rubber and iron ore concentrate imbedded silicone rubber materials were produced in order to observe the linear attenuation coefficient and radiation shielding while gamma-ray source is selected as Cs-137. Pure silicone rubber has uniform distribution and there were some air bubbles on the edges. Pure silicone rubber material has the smallest linear attenuation coefficient which means the lowest radiation shielding capability. On the other hand, iron ore concentrate added silicone rubbers have also uniform distribution with some air bubbles all over the samples. Iron ore concentrate added silicone rubbers have greater linear attenuation coefficients than pure silicone rubber. In addition, increasing iron ore ratio causes the higher radiation attenuation capability. Moreover, increasing iron ore ratio provides the lower air bubbles ratio which makes contribution to radiation shielding effect. Lead equivalent values of the samples were determined for common commercial used standards of 0.5 mmPbE and 1 mm PbE. 0.5 mm PbE standard has been achieved by 2.83 mm Sdt-67 sample for Cs-137 gamma source. The energy of radiation and contents of the materials affect the lead equivalent thickness values.

0.5 mmPbE value of Sdt-60 was determined as 2.06 mm for Co-60 gamma source in the previous study [13]. Sdt-67 has 2.83 mm thickness for 0.5 mmPbE in this study which is higher than previous study. It is known that Co-60 has two gamma peaks at 1.17 MeV and 1.33 MeV which average energy of 1.25 MeV. As, the gamma energies of Co-60 are over 1.02 MeV, the pair production event takes place in radiation-materials atoms interactions whereas Cs-137 doesn't have. Therefore, pair production event could help the decreasing value of lead equivalent thickness for iron ore added silicone rubbers. In addition, it shows that the lead equivalent thickness values of the samples depend on the material content and energy of radiation.

The produced samples could be accepted as green materials due to their being lead-free. Also the production cost of the samples were lower than commercial lead and lead-free products. Even though, lead equivalent thickness values are bigger than commercial ones, they have still potential to be used in applications with some improving materials such as antimony. In conclusion, an experimental study was realized to produce flexible radiation protective materials and to investigate using potentials in applications.

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