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Preparation and characterization of iron-ore-imbedded silicone rubber materials for radiation protection

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Abstract Iron-ore-imbedded silicone rubber materials were produced for radiation shielding. Samples were tested against a Co-60 gamma source, which is widely used in nuclear technology and medicine. Decreasing the particle size of iron ore resulted in better gamma radiation protection owing to more homogenous distribution. In addition, the materials had flexible properties up to the addition of 60 wt% iron ore content. Further, 0.5 mmPbE gamma protection was provided by using 2.06-mm-thick SDT-60 as the Co-60 source. Iron ore–silicone rubber composites are candidate materials for lead-free flexible radiation protection systems owing to their relatively inexpensive and easy production.

Keywords Iron ore · Silicone rubber · Radiation shielding · Co-60 · Lead-free flexible materials · Linear attenuation coefficients

1 Introduction

Radiation protection is one of the most important issues to be considered in nuclear technology [1–3]. High-density materials are used for radiation protection. Lead is the most widely used material for gamma- and X-ray shielding as it is inexpensive, is easy to produce, and has high density [4]. In addition, in some cases, lead-imbedded materials are used for gamma- and X-ray shielding applications where elastic material properties are required, especially for radiation shielding garments, curtains, gloves, complementary shielding equipment for human body, radiation-producing equipment, and doors. The radiation shielding standards of mixed materials are prepared with respect to lead (0.25, 0.50, 1 mmPbE) in which the material has equivalent radiation shielding property as lead at a specific radiation energy [4, 5]. However, lead is one of the most hazardous materials for the environment because of its toxicity. The European Union (EU) has released a regulation in 2003 (RoHS) [6] and revised it in 2011(RoHS2) [7] restricting the usage of some hazardous materials in electrical and electronic equipment, which includes lead. However, there were some exemptions in the RoHS directives based on reports indicating that there were no significant alternatives to lead in nuclear technology for radiation shielding [8]. There have been several studies to obtain lead-free materials for radiation shielding applications. Tungsten, bismuth, antimony, iron, zinc, barium, and gadolinium are candidate materials for use in radiation shielding applications in nuclear technology instead of lead [4, 5, 9–11]. Moreover, silicon rubber, vinyl, polymer, glass, and cement are the main matrix elements for radiation protection materials [10–13]. These are the radiation protection materials usually used in garments, gloves, curtains, collars, panels, etc. The materials to be used for producing gloves and collars should have good elasticity. However, garments and curtains do not require such good elasticity. Panels, walls, and door protection items need not possess elastic properties.

Iron ore is one of the primary sources of iron in the industry. Ninety-eight percent of iron ore is used in steel making. It has to be converted into pellets before being

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used in steel making. It mainly consists of iron oxides, which are magnetite (Fe_3O_4) and hematite (Fe_2O_3). Iron ore with more than 60% Fe content is accepted as a commercial material for iron and steel industries [14]. This high Fe content in iron ore has the potential to be used in radiation protection materials.

Silicone rubber is a polysiloxane elastomer material and has the Si–O bond, providing significant benefits. It has a wide area of application because of its excellent properties, such as heat resistance, good elasticity, low toxicity, chemical stability, electrical insulation, abrasion resistance, and transparency [15].

These properties of iron ore and silicone can be combined to produce materials for nuclear shielding. In this study, iron-ore-imbedded silicone rubber materials were produced and tested against a Co-60 gamma source. The characterizations of the materials and shielding performance were carried out for nuclear technology applications.

2 Experimental

Magnetite (Fe_3O_4) iron ore was supplied by Eurasia Mining Company, Turkey. The impurities and Fe content of the ore are given in Table 1. The particle size of the supplied ore was over 1 mm, and the particles were non-homogenously distributed. Initially, the original supplied ore was used to test the sample properties. Subsequently, they were ground and sieved to reduce the average particle size below 500 µm. The sieved iron ore was used in the experiments.

Xiameter RTV-4230-E silicone rubber supplied by Dow Corning Co. was used as the flexible matrix material. The general properties of the matrix material are given in Table 2 [16]. Iron ore–silicone rubber materials were produced at different iron ore ratios (0–67 wt%) and coded according to the iron ore ratio (Table 3).

Table 1 Fe content and impurities of the studied iron ore

Total Fe content (wt%)	62.73		
Impurities (wt%)			
SiO_2	5.77	As	< 0.01
Mn	1.02	Cr	0.01
Al_2O_3	0.90	Ni	< 0.01
CaO	0.20	Zn	0.02
MgO	0.79	Pb	0.03
Na_2O	0.26	Cu	< 0.01
K_2O	0.01	Sn	< 0.01
TiO_2	0.01	Mo	< 0.01
P	0.02	V	< 0.01
S	0.53		

Silicone rubber and stiffener (10 wt%) were placed in a bowl and stirred for 60 s. Subsequently, iron ore was added and the mixture was further stirred for 180 s to obtain a homogenous mixture. The mixture was poured into cylindrical molds (five molds) of diameter 5 cm and thickness 0.5 cm. After 24 h, the samples became solid and were removed from the molds. X-ray radiograph films (RayzorX Pro portable digital radiography system) of the samples were captured to investigate the uniform distribution of iron ores in the matrix element (Fig. 1).

The iron ores with bigger particle sizes exhibited a non-homogenous distribution. However, when the iron ore particle size was reduced below 500 µm, the samples produced were relatively uniform. In this case, air bubbles were formed in the samples owing to stirring, but it was possible to avoid them by producing the samples under vacuum. The images of the produced homogenous iron-ore-imbedded silicone rubber samples are shown in Fig. 2.

The gamma transmission technique (Fig. 3) was used in the experiments to determine the radiation shielding properties of the produced materials. A Co-60 gamma radiation source with an average energy peak at 1.25 MeV was used in the experiments. Canberra Model (802-2X2) NaI scintillation detector was used to detect gamma radiation. The gamma radiation intensities were counted with/without samples for an accumulation time of 300 s.

Subsequently, the graphs were fitted exponentially by using Origin 8 computer program to obtain the linear attenuation coefficients of the samples according to the Beer–Lambert law as follows:

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

where I and I_0 are the penetrated and incident radiation intensities, respectively, μ is the linear attenuation coefficient at a specific gamma-ray energy, and x is the material thickness. Iron ore (wt%)–linear attenuation coefficient graphs were drawn and evaluated. The linear attenuation coefficients of the samples were compared with the lead (0.5 mmPbE) standard, which is a commonly used radiation shielding parameter in nuclear and medical technology. The thicknesses of the materials corresponding to 0.5 mmPbE were calculated. The potential uses of the materials as radiation protection materials in nuclear technology were discussed.

3 Results and discussion

The relative intensity values of the samples at different thicknesses were measured as shown in Fig. 4.

Table 2 General properties of the studied matrix material (silicone rubber)

	XIAMETER RTV-4230-E
Specific gravity (g/ml)	1.14
Mixing ratio, base to curing agent, by weight	10:1
Elongation (%)	350
Pot life (h)	2
Cure time (h)	24
Tensile strength (MPa)	5.5
Tear strength (kN/m)	19

Table 3 Produced iron ore–silicone rubber samples

	SDT-0	SDT-5	SDT-10	SDT-20	STD-30	SDT-33	SDT-40	SDT-50	SDT-60	SDT-67
Iron ore (wt%)	0	5	10	20	30	33	40	50	60	67
Silicone rubber (wt%)	100	95	90	80	70	67	60	50	40	33

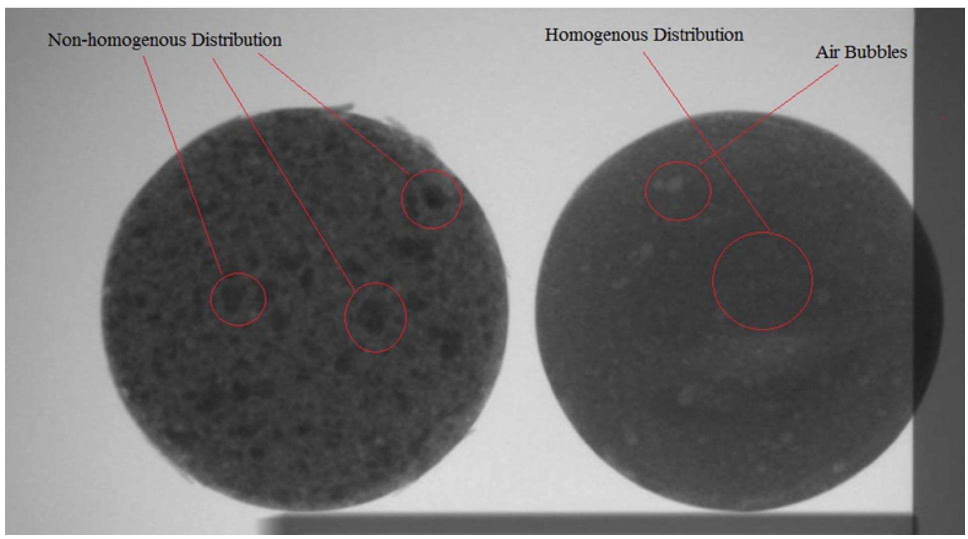

Fig. 1 Non-homogenous (left) and homogenous (right) distribution of iron ores in silicone rubber

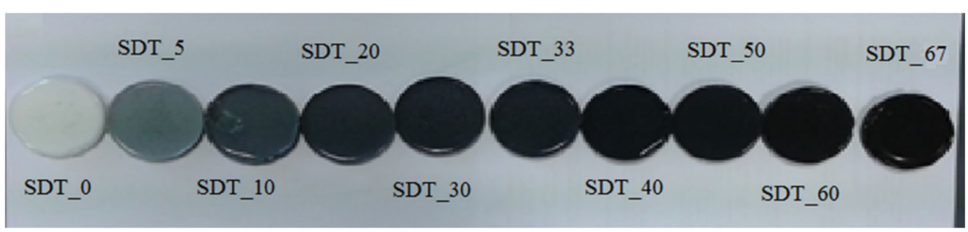

Fig. 2 Iron-ore-imbedded silicone rubber materials at different iron ore percentages

Increasing the iron ore percentage yielded lower relative intensity values, which indicates that higher iron ore percentages result in greater radiation shielding capabilities.

The half-value layer (HVL), tenth-value layer (TVL), mean free path (MFP), and effective atomic number (Z_{eff}) values of the samples were determined as listed in Table 4. The same values for pure lead are given in Table 4 [17]. Furthermore, the HVL, TVL, and MFP values were calculated for a standard 0.5 mmPbE lead apron (2 mm thick) at the energy of 1.25 MeV by using XCOM computer code [18], and they are given in Table 4.

The HVL, TVL, and MFP values of the studied samples were significantly different from those of pure lead, but close to those of 0.5 mmPbE lead apron (2 mm thick). Increasing the iron ore ratio in the materials yielded closer values to those of the lead apron.

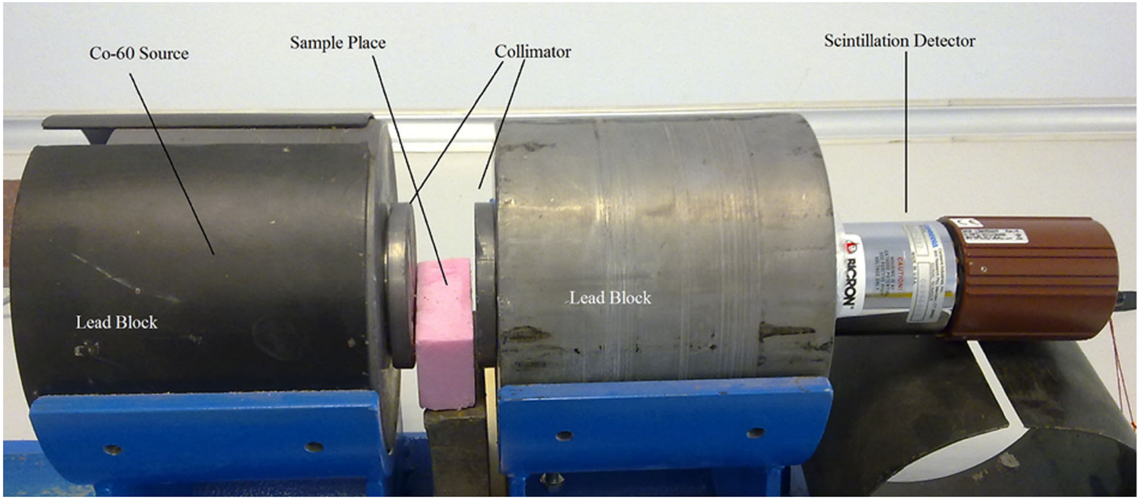

Fig. 3 (Color online) View of the gamma transmission system

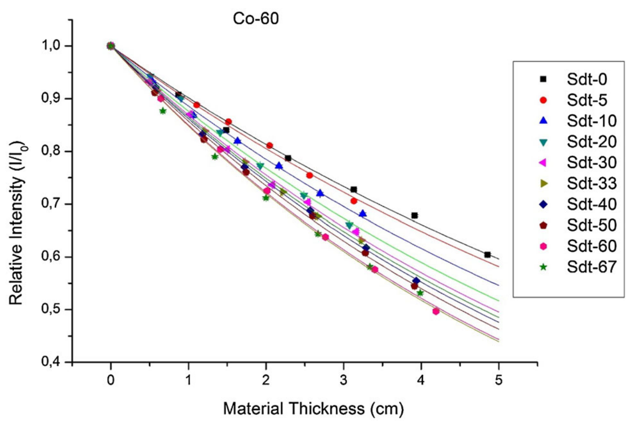

Fig. 4 (Color online) Relative intensity values of the samples for Co-60 gamma source

The obtained linear attenuation coefficients were used to determine the radiation shielding characteristics of the iron-ore-imbedded silicone rubber materials for radiation protection against the Co-60 gamma source (Fig. 5).

It can be concluded that imbedding iron ore into silicone rubber material increased the linear attenuation coefficients. Figure 5 is divided into three main parts in the graph. The first region shows the iron ore content of 0–33 wt% (Circle A) where silicone rubber was dominant in the materials. In this region, the iron ore content affects the linear attenuation coefficient significantly and the material has good elastic properties owing to higher silicone rubber content. Therefore, adding iron ore up to 33 wt% to silicone rubber provides significant radiation shielding capability, and these mixed materials can be used

Table 4 HVL, TVL, MFP, and Z_{eff} values of iron ore–silicone rubber materials

Material code	HVL (cm)	Error (±)	TVL (cm)	Error (±)	MFP (cm)	Error (±)	Z_{eff}
SDT-0	6.702	0.782	22.269	8.630	9.671	1.628	12.440
SDT-5	6.393	0.792	21.242	8.739	9.225	1.649	13.470
SDT-10	5.723	0.406	19.014	4.477	8.258	0.845	14.367
SDT-20	5.246	0.437	17.431	4.829	7.570	0.911	15.892
SDT-30	4.932	0.312	16.389	3.440	7.117	0.649	17.176
SDT-33	4.793	0.127	15.924	1.403	6.916	0.265	17.527
SDT-40	4.682	0.148	15.558	1.635	6.757	0.308	18.297
SDT-50	4.497	0.197	14.942	2.173	6.489	0.410	19.298
SDT-60	4.259	0.156	14.152	1.723	6.146	0.325	20.207
SDT-67	4.200	0.310	13.955	3.422	6.061	0.646	20.800
Lead apron (2 mm thick) (0.5 mmPbE)	4.076	–	13.545	–	5.882	–	N/A
Pure lead (Pb)	1.109	0.017	3.683	0.022	1.599	0.004	82.000

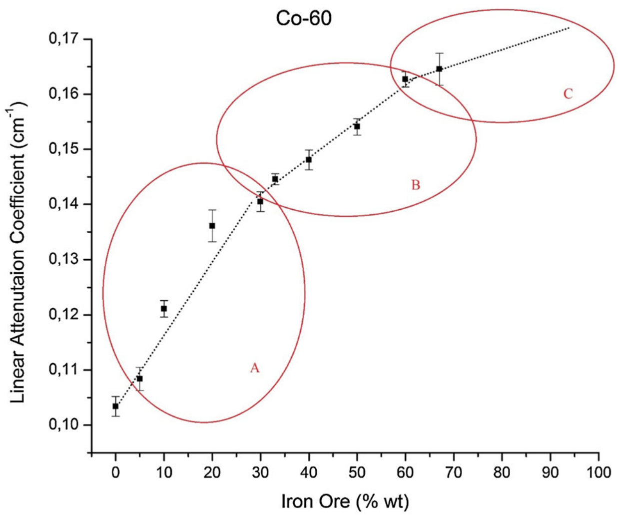

Fig. 5 (Color online) Linear attenuation coefficients of the iron-ore-imbedded silicone rubber materials for radiation protection against the Co-60 gamma source

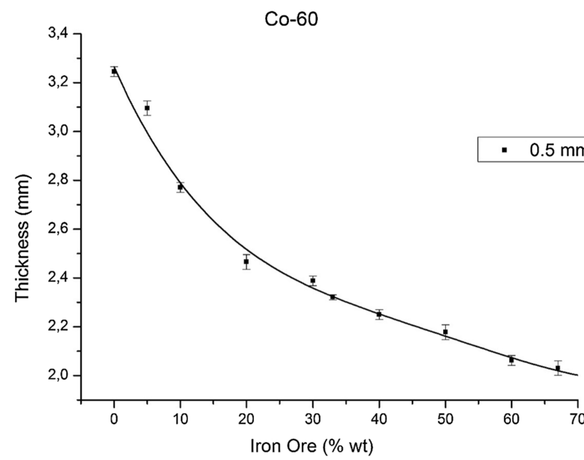

Fig. 6 0.5 mmPbE material thicknesses of iron-ore-imbedded silicone rubber materials

as elastic radiation shielding materials. These materials can also be used for hand, neck, and gonad radiation protection applications. The second region shows the iron ore content of 33–60 wt% (Circle B). In this region, imbedding iron ore into silicone rubber still results in higher radiation shielding capability, but it is lower than that in the first region. The materials have semi-elastic properties in this region and are compatible for body and equipment protection against radiation. These materials can be used to produce radiation protection garments, curtains, and clothes.

The final region shows the iron ore content of 60 wt% and above (Circle C). In this region, increasing the iron ore percentage relatively reduces the increase in radiation shielding capability of silicone rubber materials. In addition, the mixed materials lose their elastic property and become solid. However, owing to the high content of iron ore, they can be used in radiation protection tables, panels, and wall plating and nuclear equipment.

Iron-ore-imbedded silicone rubber materials were compared with the 0.5 mmPbE lead standard for radiation protection against the Co-60 gamma source (Fig. 6).

The material thicknesses for 0.5 mmPbE show that iron-ore-imbedded silicone rubber materials are good alternatives to lead as radiation shielding materials. For example, lead aprons commonly used for radiation protection have thicknesses 1.5–2.0 mm for 0.5 mmPbE, whereas 60% iron-ore-imbedded silicone rubber materials have thickness 2.06 mm for 0.5 mmPbE. Additionally, when the particle size of iron ore is decreased, the total surface area of the particles increases. Therefore, liquid silicone rubber molecules have relatively more penetration in iron ore particles. After solidification, the iron ore particles have more uniform distribution as shown in Fig. 1. Decreasing the size of the iron ore particles results in a more homogenous particle distribution in the material, resulting in uniform radiation shielding capacity throughout the material. In addition, producing the materials under vacuum has the potential to lower the thickness below 2.0 mm. When the materials were stirred and cured in air atmosphere, some air bubbles were formed in the materials. Producing materials under vacuum prevents this occurrence. Furthermore, iron-ore-imbedded silicone rubber materials are environmentally friendlier materials than lead. Moreover, the production cost of iron-ore-imbedded silicone rubber materials is lower than that of lead-containing materials. The price of lead is approximately \$2.000 per metric ton, whereas that of iron ore powder is approximately \$60 per metric ton. Therefore, iron-ore-imbedded silicone rubber materials are promising candidates for radiation shielding applications instead of lead.

4 Conclusion

Iron-ore-imbedded silicone rubber materials were produced for radiation shielding applications. The gamma protection capabilities of the samples were tested against a Co-60 gamma source. Iron ore is the cheapest form of iron and steel. The results obtained were as follows:

- Decreasing the size of the iron ore particles resulted in a more homogenous distribution in silicone rubber.
- Increasing the stirring time caused air bubbles to form in silicone rubber.
- Producing samples under vacuum can prevent the formation of air bubbles in the materials.
- The addition of iron ore up to 60% to silicone rubber sufficiently preserves the elastic property of materials,

which can be used for producing radiation-protective garments and curtains.

- The addition of iron ore up to 30% to silicone rubber well preserves the elastic property of materials, which can be used for producing radiation-protective gloves.
- 0.5 mmPbE radiation protection was provided by using 2.06 mm thick of 60% iron-ore-imbedded silicon rubber material, against Co-60 gamma source.

In conclusion, iron-ore-imbedded silicone rubber materials have the potential to be used as alternatives to lead for radiation protection because their production costs are lower than those of lead and they are non-toxic, green materials.

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