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Determination of appropriate proportional in-house flexible radiation shielding material using bismuth powder and natural-silicon rubber compounds

Gunjanaporn Tochaikul, Nutthapong Moonkum, Soontaree Sriwongta, Monchuporn Neamchumnan, Aksarapak Thawornnittayakul and Nuttapong Danthanavat*

Faculty of Radiological Technology, Rangsit University, Patumthani 12000, Thailand
*Corresponding author, E-mail: nuttapong.d@rsu.ac.th

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Abstract

Currently, ionizing radiation is widely utilized in several institutions, especially medical departments. However, the use of radiation can be hazardous. Commonly, lead shielding was approved as commercial radiation protection. The use of lead is also common, but it is an encumbrance to workers due to the weight and potential toxicity. So, the purpose of this study was to determine the appropriate ratio of natural-silicon rubber and bismuth powder for producing in-house radiation shielding and comparing the protection efficiency of the test piece to commercial lead shielding. To begin, pre-vulcanizable natural rubber was blended with silicone rubber in 5 different ratios, injected into a mold and allowed to cure. An exposure technique was set up at 120 kVp, 10 mAs then penetrative radiation was measured through the test pieces. The appropriate ratio of natural:silicon rubber 40:60 was chosen for the later experiments. The bismuth powder 40, 45, and 50 grams was added to the ratios, respectively. We then investigated the radiation protection efficiency of the test pieces. Lead aprons and lead gloves were also examined for the ability of x-ray shielding and were compared to the radiation shielding efficiency of the test pieces. The results showed that the suitable ratio of natural rubber and silicon rubber was 40:60 mixed with 50 grams bismuth powder. The test piece provided the highest protection efficiency with radiation attenuation of 89.63%. Even so, the test piece still cannot provide better performance than lead. However, when the test piece thickness was increased to 1.75 cm, the results showed it provided a higher efficiency than lead materials. So, this study showed that pre-vulcanizable natural rubber and silicone rubber mixed with bismuth powder can be applied to reduce the radiation exposure similar to the commercial lead shielding. In the future, these components might be developed to produce gloves or aprons for radiation shielding.

Keywords: *Bismuth powder; natural rubber; natural-silicon rubber; radiation shielding; Silicon rubber; vulcanizable.*

1. Introduction

In recent years, the ionizing radiation has been increasingly used for several purposes, particularly in radiological applications including diagnostic, nuclear medicine and radiotherapy. On the other hand, the use of radiation can cause adverse biological effects to human health depending on the quantity of radiation. Exposure to the radiation can cause skin burns, hair loss, erythema, severe DNA damage and death (Mu et al., 2018). Hence, organizations like the International Commission on Radiological Protection (ICRP) and the National Council on Radiation Protection and Measurements (NCRP) are responsible to provide standard radiation protection guidelines and recommendations for occupational and public standards to keep the radiation exposure within safe limits (Mu et al., 2018). The basic concept of radiation protection is to use radiation as low as reasonably achievable (ALARA) which consists of time, distance and shielding for minimizing the dose limits. This principle simply refers to minimizing your time spent near radioactive sources, stay as far away from radiation sources as possible and wear proper radiation shielding to reduce the radiation exposure (Awosan et al., 2016; Mu et al., 2018). On occasion, the radiological technologist needs to operate near radiation for prolonged periods. Therefore, the radiation shielding is a crucial device for radiation protection.

Normally, the desirable characteristics of ionizing radiation shielding are high density (concrete or steel) or high atomic number materials (lead or tungsten) because of the high ability to attenuate radiation. For several years, lead has exhibited superb properties against radiation and was the primary selected material. On the other hand, this material is potentially toxic and can cause lower-back pain because of the heavy weight (AbuAlRoos, Amin, & Zainon, 2019). As a result, many researchers have focused on finding light, flexible and lead-free radiation shielding materials (Intom et al., 2020; Kalkornsurapranee et al., 2021). Previous research found the advantages of replacing lead with bismuth (Bi) for routine shielding, which is both non-hazardous and provides acceptable protection efficacy. Bismuth is an effective material for lead substitution due to its similar characteristic to lead such as high density (9.80 g/cm^3) and high atomic number (Z=83). In case of low energy photons which provide photoelectric interaction predominantly, bismuth is more effective than lead because it has a higher atomic number (Martinez & Cournoyer, 2001). Also, bismuth is stable in both oxygen and water making it convenient to use (Martinez & Cournoyer, 2001). However, bismuth alone cannot be used to build the shielding (AbuAlRoos et al., 2019). Thus, bismuth was usually formed as a bismuth polymer blend to establish the radiation shielding (AbuAlRoos et al., 2019). Concrete and glass based components which are combined with the bismuth are examples of lead-free radiation shielding (Intom et al., 2020). However, these two methods still present drawbacks of inflexibility and heavy weight (Intom et al., 2020). Natural rubber is one material which will blend with bismuth, and offers the benefits of elasticity, strength and light weight (Intom et al., 2020; Kalkornsurapranee et al., 2021).

So, this study aimed to focus on producing a lead-free radiation protection shielding based on natural and silicon rubber due to the high flexibility and radiation resistance of silicon rubber (El Fiki et al., 2015). According to Nipat and Doonyapong (2013), their results showed that the bismuth powder gave a higher percentage of gamma radiation attenuation than the bismuth solution (48.9% versus 39.4%) (Nipat & Doonyapong, 2013). Therefore, the bismuth powder was chosen for the main component of radiation absorbing material due to its relatively high atomic number and density (AbuAlRoos et al., 2019; Intom et al., 2020). Finding the appropriate proportion between natural-silicon rubber compounded with bismuth powder were performed, with the radiation protection efficiency in the lead commercial shielding sued for comparison. The results could lead to the future development of an in-house radiation protective shielding for personal protective wear such as gloves or aprons.

2. Objectives

The objective of this study was to determine the appropriate proportion between natural-silicon rubber combined with bismuth powder for the construction of in-house radiation shielding. The radiation protection efficiencies were compared between the test piece and the standard lead commercial shielding.

3. Materials and methods

3.1 Natural and silicon rubber sample preparation

The pre-vulcanizable natural rubber latex and silicon rubber (S815M) dipping with its catalyst total volume 100 ml were mixed together for 10 min in 200 ml scale beaker with 5 differential ratios as shown in Table 1 (Nipat & Doonyapong, 2013). The mixture of each ratio was poured into a 10 × 10 × 1 centimeter mold, and the compound was stored for 3-5 days for drying before being removed from the mold.

Table 1 Pre-vulcanizable natural rubber and silicon rubber ratio

Pre-vulcanizable natural rubber : Silicon rubber	Pre-vulcanizable natural rubber volume (ml)	Silicon rubber volume (ml)
70:30	84	36
60:40	72	48
50:50	60	60
40:60	48	72
30:70	36	84

3.2 Radiation absorption test

The Shimadzu x-ray system was set up, with the GAMMEX detector model 330 aligned with the X-ray tube collimator and open the light field size covering the effective area of the detector as shown in Figure 1a. In order to minimize the unwanted scatter radiation, the GAMMEX detector was placed at source to detector distance (SDD) 100 cm and at 74 cm between the detector and the ground. The back-scatter from the sample attenuator was included in this measurement due to the real condition the radiation shielding is place close to the patient. An exposure technique was set with 120 kVp, 10 mAs. The initial radiation quantity was measured with no barrier and record the radiation transmitted to the detector. Figure 1b shows the test piece with 70:30 ratio of pre-vulcanizable natural rubber-silicon rubber placed over the GAMMEX detector and penetrative radiation was measured three times and recorded. The 70:30 test piece was replaced with the 60:40, 50:50, 40:60 and 30:70 ratios, respectively and the radiation measured 3 times per piece.

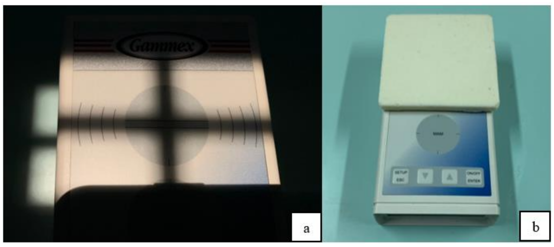

Figure 1 GAMMEX and x-ray system set up (a) the test piece placed over GAMMEX for measured the radiation (b)

3.3 Preparation of composites

The combination of rubber with 40:60 ratio and bismuth 40 grams were added to the beaker for preparation of the composites. Mixtures were injected into the mold size 10 × 10 × 1 centimeter, left to dry 5 to 7 days before being removed from the mold. Other composites were prepared by replicating these techniques with 45 and 50 grams of bismuth, respectively.

3.4 Radiation shielding efficiency and homogeneity test

The Shimadzu x-ray system and GAMMEX detector were set up as previously described in section 3.2 (Radiation absorption test). Evaluation of the radiation shielding efficacy of the bismuth composites (bismuth load 40, 45 and 50 grams), a lead apron and lead glove were performed as shown in Figure 2. The transmitted radiation was recorded and the measurements were repeated with rotation of the bismuth test pieces at 90, 180 and 270 degrees, respectively for a homogeneity test.

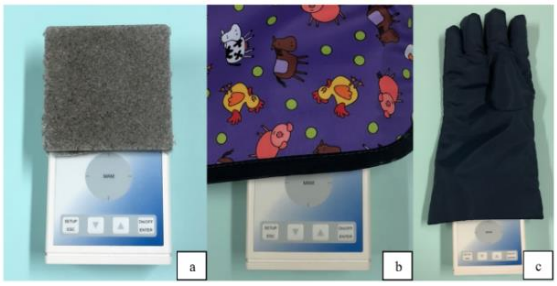

Figure 2 Set up for radiation quantity measurement of the Bismuth composites (a) lead apron (b) and lead glove (c)

3.5 Calculate of the test piece's x-ray properties

The linear attenuation coefficient (μ) of the bismuth test piece material was calculated by using the Lambert-Beer law as express in Equation 1 and estimate the half value layer (HVL) (El-Khatib et al., 2020). In additional, the photons attenuation with the any mixture compound should also present the mass attenuation coefficient (μ/ρ) given by Equation 2 (Akça & Erzeneoğlu, 2014).

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

$$\left(\frac{\mu}{\rho}\right) = \sum_i w_i \left(\frac{\mu}{\rho}\right)_i \quad (2)$$

where, I is a transmitted radiation intensity, I_0 is an incident radiation intensity, ρ is a density of material (g/cm^3), x is a thickness of the matter traversed (cm), w_i and $(\mu/\rho)_i$ are the weight fraction and mass attenuation coefficient of the i_{th} element, respectively.

3.6 Sample and lead commercial shielding efficiency comparison

The percentage difference of radiation quantity between the bismuth test piece and commercial lead apron and glove can be calculated using Equation 3 as follows (Onjun et al., 2019).

$$\% \text{ Difference} = \frac{\text{transmission of bismuth instance-transmission of lead}}{\text{transmission of lead}} \times 100 \qquad (3)$$

4. Results

4.1 The appropriate proportional of pre-vulcanizable natural rubber and silicon rubber

The four ratios of pre-vulcanizable natural rubber and silicon rubber (70:30, 60:40, 50:50 and 40:60), were presented as a stabilized sheet, without chapping, quite smoothly, and flexible (Figure 3a). On the other hand, the sample with 30:70 ratio was very sticky and adhered to the mold as shown in the Figure 3b. Table 2 and Figure 4 show the radiation absorption of the five test pieces with the pre-vulcanizable natural rubber- silicon rubber at the ratio 30:70 had the best radiation absorption efficiency. This efficiency was decreased as the proportion of silicon rubber was decreased. The researchers chose the pre-vulcanizable natural rubber and silicon rubber at the 40:60 ratio as the suitable proportion for the bismuth test piece shielding based-construct.

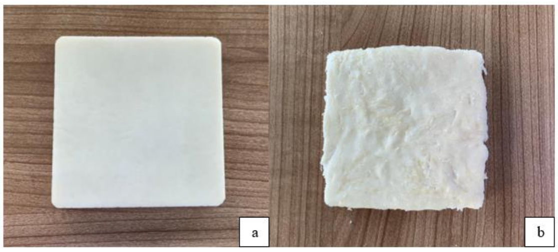

Figure 3 Pre-vulcanizable natural rubber and silicon rubber at the 40:60 ratio (a) and 30:70 ratio (b)

Table 2 The radiation quantities results of pre-vulcanizable natural rubber and silicon rubber in each ratios

Pre-vulcanizable natural rubber : Silicon rubber	Transmitted radiation (µGy)	Radiation absorbed (%)
No barrier	1,040.00	0
70:30	808.08	22.30
60:40	768.87	26.07
50:50	741.94	28.66
40:60	734.97	29.33
30:70	696.49	33.03

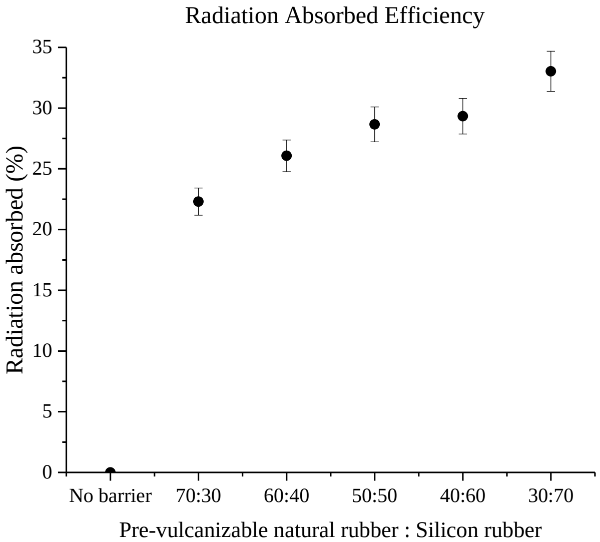

Figure 4 Radiation absorbed efficiency of the five pre-vulcanizable natural rubber and silicon rubber ratios

4.2 Radiation shielding efficacy and homogeneity

The pre-vulcanizable natural rubber and silicon rubber at 40:60 ratio was used as the based-compound for 3 bismuth weights (40, 45, and 50 grams). The results found these three bismuth test pieces were stabilize, light weight, bendable, flexible and quite smooth as shown in Figure 5. The radiation shielding efficiency of the bismuth test piece was improved when the quantity of bismuth was increased as shown in Table 3 and Figure 6. Additionally, the radiation shielding evaluation resulted from the commercial lead apron and lead glove were 95.66% (45.1 µGy transmitted) and 97.97% (21.1 µGy transmitted), respectively. The homogeneity test showed that the radiation shielding efficiency at 0, 90, 180 and 270 degrees were 89.63%, 89.71%, 90.50% and 89.47%, respectively.

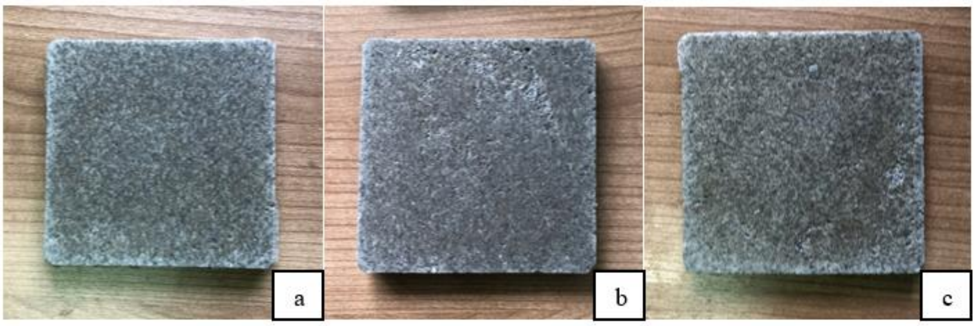

Figure 5 The composites with bismuth 40 grams (a) 45 grams (b) and 50 grams (c)

Table 3 The radiation shielding results of bismuth test piece in each quantities

Bismuth quantity added to the 40:60 rubber ratio	Transmitted radiation (µGy)	Radiation shielding efficiency (%)
No barrier	1,040.00	0
40	138.20	86.71
45	124.20	88.06
50	107.80	89.63

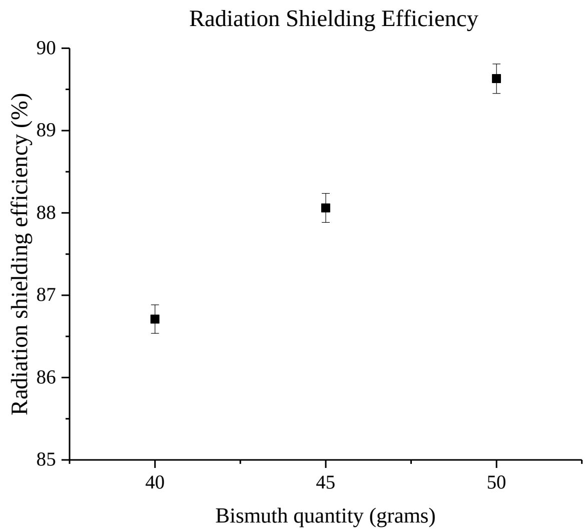

Figure 6 Radiation shielding efficiency of the rubber 40:60 ratio with 3 bismuth quantities

4.3 X-ray shielding properties

Figure 7 illustrates the half value layer of the three bismuth test pieces and indicates that the sample with bismuth 50 g provided the maximum radiation protection from this study. So, the transmitted radiation intensity of the test piece was used to calculate the linear attenuation coefficient (μ). The calculated result with Equation 1 and Equation 2 showed the μ value for the test piece was 2.267 cm^{-1} and μ/ρ was 2.351 cm^2/g.

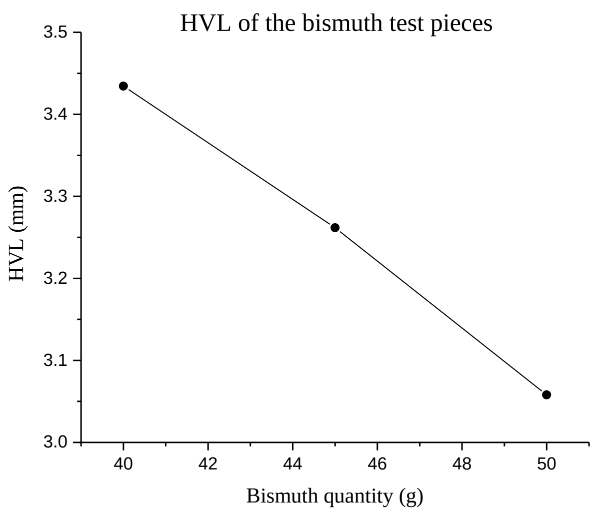

Figure 7 Half value layer of the bismuth-rubber test piece with 3 various quantities

4.4 Efficiency comparison between the bismuth test piece and lead commercial materials

The transmitted radiation quantity of the bismuth 50 g test piece was used to compare the protective efficacy with commercial lead shielding for both lead aprons and lead gloves. The results showed the bismuth test piece provided lower radiation shielding efficiency than lead materials with, 139.02% and 410.09% for lead apron and lead glove, respectively.

5. Discussion

From the results we showed extreme proportions of silicon rubber lead to a very sticky mixture and attachment to the mold. So, it cannot be removed due to the excessive cohesive properties of silicon rubber (Gan, Shang, & Jiang, 2016). However, the increased percentage of silicon rubber imparted more radiation absorption efficiency due to the higher density than natural rubber (Gan et al., 2016). Therefore, the pre-vulcanizable natural rubber and silicon rubber at the ratio 40:60 was considered as a suitable proportion for the bismuth test piece shielding based-construct due to its stabilized, non-chapped, smooth, bendability, flexibility and providing the second best radiation absorbing efficiency. For the part of bismuth test piece, the radiation shielding efficiency was improved when the bismuth quantity was increased because of the high atomic number and high density (Z=83, ρ=9.80 g/cm^3), similar to lead (Z=82, ρ=11.30 g/cm^3) (Lim-aroon, Wimolmala, Sombatsompop, & Saenboonruang, 2019; Lopresti et al., 2020; Martinez & Cournoyer, 2001). The half value layer of the test pieces were decreased while linear and mass attenuation coefficient were increased by adding more bismuth. Hence, the added bismuth provided better x-ray shielding properties. The homogeneity of the test piece was good according to the minimal differences between the 4 various ratios of bismuth. Therefore, the test piece can provide similar radiation protection efficiency with no leakage. Regarding the comparison results, the bismuth 50 g composites with 1cm thickness have inferior performance as compared to lead material that might be caused by the insufficient thickness of the test piece. Figure 8 illustrates the transmitted radiation was decreased when increasing the bismuth test piece thickness as the exponential function, $y=107.8e^{-2.267x}$ with R^2=0.9989. Therefore, the increased thickness of the test piece to 1.40 cm and 1.75 cm provided better radiation shielding efficiency than the lead apron and lead glove, respectively as shown in Figure 9-10. Also, the weight testing of the bismuth rubber material was only 227 g which is 3.9 times less than the lead shielding. However, the limitation of this study is the fixed maximum bismuth with 50 g. So, the test piece thickness that provided the similar protection efficiency to the lead shielding was not suitable for clinical situation. In the future, adding more bismuth will provide more radiation shielding efficiency while decreasing the thickness of the test piece as seen by El fiki et al. (El Fiki et al., 2015) and Intom et al. (El Fiki et al., 2015; Intom et al., 2020). Moreover, using bismuth is also non-toxic and environmentally friendly (Sayyed, Akman, Kaçal, & Kumar, 2019; Yao et al., 2016). So, disposal, decontamination procedures, hygiene support and hazard waste storage can be eliminated (Kalkornsuranee et al., 2020; Martinez & Cournoyer, 2001; Yao et al., 2016). Hence, the average total construction cost for bismuth radiation shielding is approximately 2 times less than lead shielding because it has minor additional associated costs (Martinez & Cournoyer, 2001).

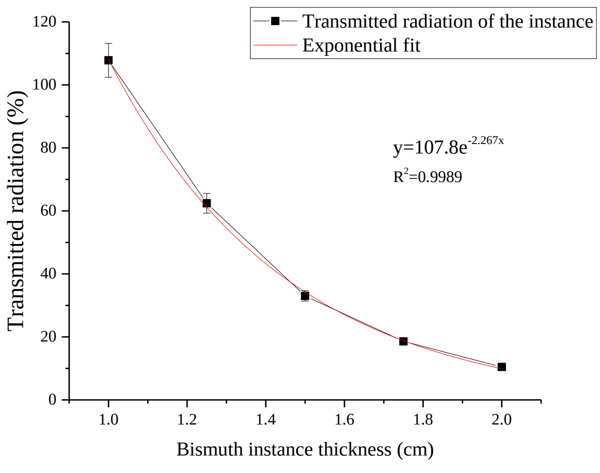

Figure 8 Percent of transmitted radiation with the 5 various test piece thickness

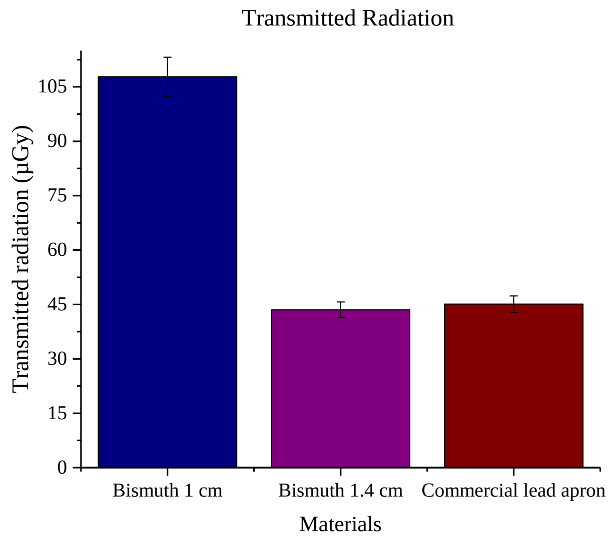

Figure 9 Comparison of the radiation transmitted through the test piece shielding with different thickness and commercial lead apron

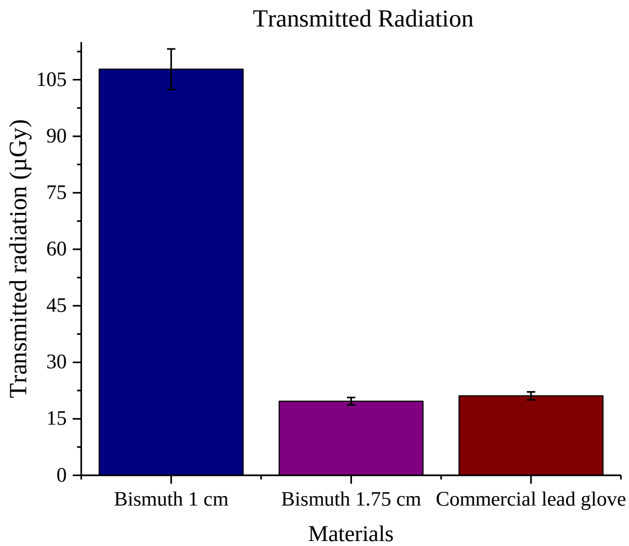

Figure 10 Comparison of the radiation transmitted through the test piece shielding with different thickness and commercial lead glove

6. Conclusion

This research has studied the lead–free radiation shielding materials by applying pre-vulcanizable natural rubber and silicon rubber combined with the bismuth powder that have the comparable properties to the lead material with less weight and toxicity. The results of this study showed the appropriate proportions of the pre-vulcanizable natural rubber and silicon rubber was 40:60 due to several advantageous characteristics such as being stabilized, bendable, flexible, lightweight and homogenous. Subsequently the ratio was mixed with bismuth powder, it was found that 50 grams of bismuth provided the best reduction of radiation, around 90 percent of the radiation shielding efficiency. When the thickness of the test piece was increased to 1.40 cm and 1.75 cm, the efficiency was also increased to 95.82% and

98.11%, respectively which provided better performance than commercial lead materials. Therefore, the bismuth–rubber compound was considered to be a suitable material for radiation protection shielding. The main factors contributed to the radiation shielding effectiveness of the bismuth–rubber test piece, are the proportion of natural rubber and silicon rubber, amount of bismuth powder and the test piece thickness. As mentioned earlier, this study constructed the bismuth-rubber sample for radiation shielding efficiency testing. For future directions, these composites could be produced as gloves or aprons for practical radiation protection.

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