Determination of radiation attenuation coefficients of BaSO$_4$/PVC and BaSO$_4$/PS for X-ray shielding

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Abstract. The X-ray radiation shielding properties of PVC and PS containing BaSO$_4$ at different concentrations were investigated using the beam transmission method for X-ray tube with a CdTe detector. The mass attenuation coefficients ($\mu_m$) of these shielding materials were calculated. It was found that the $\mu_m$ increased with the increasing of BaSO$_4$ content up to a value of 60% by weight. The highest value of mass attenuation coefficients at 50 kV tube voltage was 5.985 cm$^2$/g for the BaSO$_4$/PVC sheet and 3.991 cm$^2$/g for the BaSO$_4$/PS sheet. The $\mu_m$ values were compared between BaSO$_4$/PVC and BaSO$_4$/PS. The results showed that BaSO$_4$/PVC had better X-ray shielding performance than that for BaSO$_4$/PS.

1. Introduction

Recently, the development of techniques using X-ray has prompted increasing interest. X-rays with energies in the range of keV are often used in diagnostic radiography and elemental analysis using the X-ray fluorescence (XRF) technique. In order to avoid unwanted radiation, a variety of shielding materials are used to attenuate or absorb the radiation. Lead (Pb, Z = 82) and other high-Z elements are widely used for radiation shielding because of their high density and significant energy of the $K$ absorption edge. On the other hand, the heaviness and toxicity of lead is a major concern. Many studies have been conducted to find alternatives for shielding materials. A lead-free composite, lightweight material with the ability to attenuate radiation has attracted great interest in many areas. Barium sulphate (BaSO$_4$) is one of the alternative materials that have low toxicity and good radiation absorbency. Over the past several decades, researchers have reported on shielding materials containing BaSO$_4$, such as BaSO$_4$/PVA composites [1], rubber containing barite [2], epoxy/barite and polyester/barite composites [3], and cement paste containing barite [4]. The polymer-based composites are especially interesting for radiation shielding materials [5-6]. To develop a lead-free, lightweight and easily workable radiation shielding sheet, polyvinyl chloride (PVC) and polystyrene (PS) containing BaSO$_4$ were prepared. X-ray shielding ability was studied as well. The PVC and PS containing 0% to 60% by weight of BaSO$_4$ were prepared and exposed to X-ray of various tube voltages.
2. Materials and methods

2.1. Sample preparation
In order to prepare the shielding materials, PVC and PS were mixed using different concentrations of BaSO₄ powder. A PVC solution was prepared by mixing 4 ml of tetrahydrofuran solvent with 1 g of PVC. When the PVC was completely dissolved, the BaSO₄ powder was added and the mixed phase was prepared with BaSO₄ at weight percentages of 0 % (control), 10 %, 20 %, 30 %, 40 %, 50 % and 60 %. The BaSO₄/PVC mixture was left to stir with a rotation speed of 300 rpm for 1 h and then placed in an ultrasonic stirrer for 15 min to ensure good dispersion of BaSO₄ powder throughout the host PVC. Further, the BaSO₄/PVC mixture was poured onto a 10 mm circular glass Petri dish and allowed to dry for 24 h. Similarly, the BaSO₄/PS mixture was prepared by the same method as BaSO₄/PVC. The density of the BaSO₄/PVC and BaSO₄/PS sheets was measured by the Archimedes principle using a microbalance with water as the immersion liquid, while the thickness of the sample sheets was measured by a micrometre.

2.2. X-ray spectra measurements
To investigate the X-ray radiation shielding properties, radiation attenuation experiments were performed using the beam transmission method. The X-ray beams were generated by a silver target X-ray tube (Mini-X, Amptek). The X-ray spectra were measured using a CdTe diode X-ray detector (XR-100T, Amptek). The primary X-ray spectra with 30, 40 and 50 kVp tube voltage were measured using the CdTe detector, as shown in figure 1. X-ray attenuation measurements were performed by positioning each sample sheet between the X-ray tube and detector, where the distance between the X-ray tube and detector was 80 cm. Alignment between the focal spot of the X-ray tube and the CdTe detector was performed using a laser device. The energy calibration of the X-ray detector was carried out using the measured spectra of fluorescence X-ray emitted by Cu, Sn and Pb standard materials.

![Figure 1](image-url)  
*Figure 1.* The primary X-ray spectra with 30, 40 and 50 kVp tube voltage measured by CdTe detector.

3. Results and discussion
Table 1 shows the dependence of density for the sample sheets at different concentrations of BaSO₄ powder. Figure 2 shows the relation between the density and concentration of BaSO₄ of BaSO₄/PVC and BaSO₄/PS sheets. It can be observed that the density of the sample sheets increased with increasing BaSO₄ content. However, the density of the BaSO₄/PVC was much higher than that for the BaSO₄/PS at every concentration of BaSO₄.
Table 1. The density of the prepared sample.

| Concentrations of BaSO$_4$ (% by weight) | Density of BaSO$_4$/PVC (g/cm$^3$) | Density of BaSO$_4$/PS (g/cm$^3$) |
|----------------------------------------|------------------------------------|----------------------------------|
| 0                                      | 1.460 ± 0.016                      | 1.038 ± 0.005                    |
| 10                                     | 1.500 ± 0.048                      | 1.121 ± 0.013                    |
| 20                                     | 1.628 ± 0.014                      | 1.213 ± 0.007                    |
| 30                                     | 1.779 ± 0.018                      | 1.294 ± 0.005                    |
| 40                                     | 1.860 ± 0.013                      | 1.458 ± 0.009                    |
| 50                                     | 2.092 ± 0.004                      | 1.629 ± 0.017                    |
| 60                                     | 2.364 ± 0.002                      | 1.681 ± 0.003                    |

Figure 2. Effect of BaSO$_4$ concentration addition by weight to density of the sample sheets.

Figure 3. X-ray spectra obtained from 50 kVp tube voltage attenuated by (a) PVC and (b) PS containing BaSO$_4$ at different concentrations.
The measured X-ray spectra obtained from the attenuation of PVC and PS at different concentrations of BaSO₄ are shown in figure 3 (a) and figure 3 (b), respectively. The results show that an increase in BaSO₄ concentration leads to a decrease in X-ray intensity. For the BaSO₄/PS sheets, the intensity slightly decreases for the low energy range of X-ray spectra. On the other hand, the intensity greatly decreases when increasing the BaSO₄ content of the BaSO₄/PVC sheets. Moreover, the X-ray intensities of the PVC and PS containing BaSO₄ with a concentration of 60 % by weight were roughly ten times smaller than that for the PVC and PS without BaSO₄ content. These results indicate that BaSO₄/PVC attenuates X-ray better than BaSO₄/PS at low X-ray energy levels. The X-ray shielding properties of BaSO₄/PVC and BaSO₄/PS sheets were presented in terms of the $\mu_n$ (cm²/g). The radiation interaction process removes X-ray radiation from the X-ray tube by absorption in the sample sheets. The X-ray was attenuated to an intensity from I₀ in passing through the sample sheets with thickness x (cm) and $\rho$ is the density of sample sheets (g/cm³). The mass attenuation coefficient is written as follows.

$$\mu_n = \frac{\ln(I_0/I)}{\rho x} \quad (1)$$

Table 2 shows the dependence of the mass attenuation coefficient of the PVC and PS with different concentrations of BaSO₄ content. For the 50 keV X-ray energy, the PVC sheet without BaSO₄ content has $\mu_n = 2.433$ cm²/g, while the PVC with BaSO₄ concentration of 60 % by weight has $\mu_n = 5.986$ cm²/g. This result shows that $\mu_n$ of the BaSO₄/PVC sheet with BaSO₄ concentration of 60 % by weight was roughly two times higher than that PVC sheet without BaSO₄. On the other hand, the $\mu_n$ of BaSO₄/PS sheet with BaSO₄ concentration of 60 % by weight was roughly six times higher than that of the PS sheet without BaSO₄. These results indicate that the BaSO₄ contributed to the X-ray transmission of PS more than PVC.

| Concentrations of BaSO₄ (% by weight) | Mass attenuation coefficient of BaSO₄/PVC (cm²/g) | Mass attenuation coefficient of BaSO₄/PS (cm²/g) |
|--------------------------------------|-----------------------------------------------|-----------------------------------------------|
|                                      | 30 keV | 40 keV | 50 keV | 30 keV | 40 keV | 50 keV | 30 keV | 40 keV | 50 keV |
| 0                                    | 4.516  | 3.130  | 2.433  | 0.686  | 0.660  | 0.636  |        |        |        |
| 10                                   | 5.053  | 3.455  | 3.038  | 2.846  | 1.943  | 1.764  |        |        |        |
| 20                                   | 7.453  | 5.141  | 4.599  | 3.757  | 2.462  | 2.362  |        |        |        |
| 30                                   | 7.823  | 5.380  | 4.990  | 4.923  | 3.418  | 3.288  |        |        |        |
| 40                                   | 7.871  | 6.312  | 5.012  | 5.706  | 3.967  | 3.705  |        |        |        |
| 50                                   | 9.202  | 6.470  | 5.886  | 5.883  | 4.113  | 3.979  |        |        |        |
| 60                                   | 9.727  | 7.318  | 5.986  | 6.601  | 4.317  | 3.992  |        |        |        |

In figure 4, the ratio between the mass attenuation coefficient of (a) BaSO₄/PVC and (b) BaSO₄/PS is displayed as a function of the concentration of BaSO₄ and X-ray tube voltage. The data shows that the $\mu_n$ of the sample sheets increases with increasing BaSO₄ concentration in every voltage of the X-ray tube. The $\mu_n$ of BaSO₄/PVC and BaSO₄/PS were compared using the same method mentioned above. This is related to the shielding ability of the sample sheets. The BaSO₄/PVC showed better shielding ability than BaSO₄/PS over all the BaSO₄ concentrations studied in this work. The difference between the $\mu_n$ value of BaSO₄/PVC and BaSO₄/PS may be attributed to the absorption effect of each of the element compositions present in the sample sheets. In addition, the $\mu_n$ is sensitive to the effective atomic number of the composites as well as to the density.
Figure 4. Effect of BaSO$_4$ concentration addition by weight to mass attenuation coefficient of the (a) BaSO$_4$/PVC and (b) BaSO$_4$/PS sheets.

4. Conclusion
In this study, a radiation shielding sheet was fabricated using polymer (PVC and PS) and BaSO$_4$, which was more economical than existing lead shielding. The mass attenuation coefficients of BaSO$_4$/PVC and BaSO$_4$/PS sheets increased with increasing BaSO$_4$ content. The best shielding ability of the sample sheets reached 60% by weight of the BaSO$_4$ content. The transmission X-ray spectra were measured at X-ray tube voltages of 30, 40 and 50 kVp. A BaSO$_4$/PVC sheet showed better shielding ability than a BaSO$_4$/PS sheet at every tube voltage. Density and BaSO$_4$ concentration play an important role in shielding ability. The results suggest that the shielding materials fabricated in this work could be effectively used for protection in the low X-ray energy range.

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