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Development of an Epoxy/Carbon Fiber Composite for Radiation Attenuation with a Dispersion of Micro Particles of Bismuth Trioxide (Bi2O3)

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Abstract: The objective of this research was the development of an epoxy/carbon fiber composite with bismuth trioxide (Bi2O3) dispersion in the polymeric matrix for application as a low-energy photon barrier and to determine the mass attenuation coefficient of this composite. Quantitative and experimental methodology was used for this research. The mass ratios of the bismuth oxide in the composite were approximately 0.1, 0.2, 0.3 and 0.4. The Pantak/Seifert irradiator model Isovolt HS 160 was used as an X-radiation source. The photon energies were 48, 65, 82 and 118 keV, with radiation doses of 471, 1912, 92.6 and 74.2x10-3 mGy.min-1 respectively, with energies and radiation doses being typical of X-ray diagnostic radiography. At an energy of 118 keV, the dispersion of Bi2O3 in the polymeric matrix increased the mass attenuation coefficient from 0.15 cm2.g-1 (without dispersion) to 1.28 cm2.g-1 (39.13% by mass of Bi2O3). This is an increase of approximately 753%. At an energy of 82 keV, the percentage increase was approximately 582%. At an energy of 65 keV, there was an increase of 739% and for photons with an energy of 48 keV the percentage increase in the mass attenuation coefficient was 1262%. In conclusion, a composite epoxy/carbon fiber with bismuth oxide dispersion is an excellent option as compared to a lead plate. The composite studied can attenuate photon energy and does not present an acute or chronic danger to the environment or to health. Also, it is non-carcinogenic and does not cause reproductive toxicity, both being clear advantages over lead. Finally, it should be noted that composite applications could be radiological shields for the X-ray, aerospace industries, among others.

Keywords: Composite, bismuth (III) oxide, X – rays, radiation attenuation

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Desenvolvimento de Compósito Epóxi/Fibra de Carbono para Atenuação de Radiação com Dispersão de Micropartículas de Trióxido de Bismuto (Bi2O3)

Resumo: O objetivo desta pesquisa foi o desenvolvimento de um compósito epóxi/fibra de carbono com dispersão de trióxido de bismuto (Bi_2O_3) na matriz polimérica para aplicação como barreira de fótons de baixa energia e determinar o coeficiente de atenuação mássica deste compósito. A metodologia quantitativa e experimental foi utilizada para esta pesquisa. As proporções de massa do óxido de bismuto no compósito foram aproximadamente 0,1; 0,2; 0,3 e 0,4. O irradiador Pantak/Seifert modelo Isovolt HS 160 foi utilizado como fonte de radiação X. As energias dos fótons foram de 48, 65, 82 e 118 keV, com dose de radiação de 471, 1912, 92,6 e $74{,}2\times10^{-3}$ $mGy.min^{-1}$ respectivamente, energias e doses de radiação típicas da radiografia diagnóstica. Portanto, para uma energia de 118 keV, a dispersão do Bi_2O_3 na matriz polimérica aumentou o coeficiente de atenuação mássica de 0,15 $cm^2.g^{-1}$ (sem dispersão) para 1,28 $cm^2.g^{-1}$ (39,13% em massa de Bi_2O_3). Este é um aumento de aproximadamente 753%. Para uma energia de 82 keV, o aumento percentual foi de aproximadamente 582%. Para uma energia de 65 keV também houve um aumento de 739% e para fótons com energia de 48 keV o aumento percentual no coeficiente de atenuação de massa foi de 1262%. Concluindo, um compósito epóxi/fibra de carbono, com dispersão de óxido de bismuto é uma excelente opção em comparação com uma placa de chumbo. O compósito estudado pode atenuar a energia dos fótons não apresenta perigo agudo ou crônico ao meio ambiente ou à saúde. Além disso, não é cancerígeno e não causa toxicidade reprodutiva, ambas vantagens claras em relação ao chumbo. Por fim, deve-se notar que as aplicações de compósitos seriam escudos radiológicos para as indústrias de raios X, aeroespacial, entre outras.

Palavras-chave: Compósito, óxido de bismuto (III), raios X, atenuação de radiação.

1. INTRODUCTION

Ionizing radiation, such as X-ray and gamma radiation, is utilized daily in the healthcare and aerospace industries. Professionals who operate ionizing radiation emission equipment have to protect themselves due to the potentially damaging effects of daily exposure to radiation. Operators protect themselves through the use of various radiological protection systems including: CEP's – collective protection equipment (radiological visors, lead sheets, radiological barriers and lead screens) and PPE's – personal protective equipment (apron of lead, lead glasses, gonad protectors and thyroid protectors). In other words, lead-based equipment has routinely been used for protection from various types of ionizing radiation. However, due to its high specific mass (11,300 kg.m-3), its carcinogenicity and its environmental impacts, such as soil contamination, the demand has increased [1] for alternative materials for radiological protection that can be used as replacements for lead.

Several materials have been researched as alternatives to lead in radiological protection from low-energy photons (below 500 keV) [2], including barium titanium (BaTiO3); bismuth trioxide (Bi2O3); bromine gas (Br2); bromine iodide (BrI); and calcium tungstate (CaWO4) [3-5]. Among these substances, bismuth oxide is an attractive alternative to lead [5-7]. A composite whose polymer matrix consists of an epoxy resin reinforced with carbon fiber fabric containing a dispersion of micro particles of bismuth trioxide (Bi2O3), with a specific mass lower than lead, was shown to be more durable, less toxic, and can serve as a barrier to ionizing radiation in protective equipment.

Therefore, the objective of this research was the development of an epoxy/carbon fiber composite with bismuth trioxide (Bi2O3) dispersion in the polymeric matrix for application as a low-energy photon barrier and to determine its mass attenuation coefficient.

This composite was demonstrated to be an excellent alternative to lead shielding for protection from lower energy photon exposure.

2. MATERIALS AND METHODS

To reinforce the composites, 200 – 3k carbon fiber fabric (grammage of 0.20 $kg.m^{-2}$, bidirectional weave; with a thickness of 0.40 mm, with the same number of threads in the weft and warp) were used. The polymeric matrix was composed of RUV 4230 epoxy resin (bisphenol A, for high thicknesses, viscosity of 80 to 150 cP), gel time of 25°C of 90 to 100 minutes and RUV 6820 hardener (isophorone diamine) with the dispersion of bismuth trioxide microparticles in the proportions [5, 8, 9] shown in Table 1.

Table 1: Concentrations in the polymeric matrix

Resin (%)	Hardener (%)	Si_2O (%)	Bi_2O_3 (%)
82.5	14.8	2.7	00.0
74.3	13.4	2.3	10.0
66.7	12.0	2.0	19.3
57.9	10.4	1.7	30.0
49.3	09.1	1.5	40.0

The resins presented in Table 1 were used as the polymeric matrix for the epoxy/carbon fiber composite with bismuth trioxide (Bi2O3) dispersion. Table 2 presents the concentrations present in the polymer composite, taking reinforcement into account.

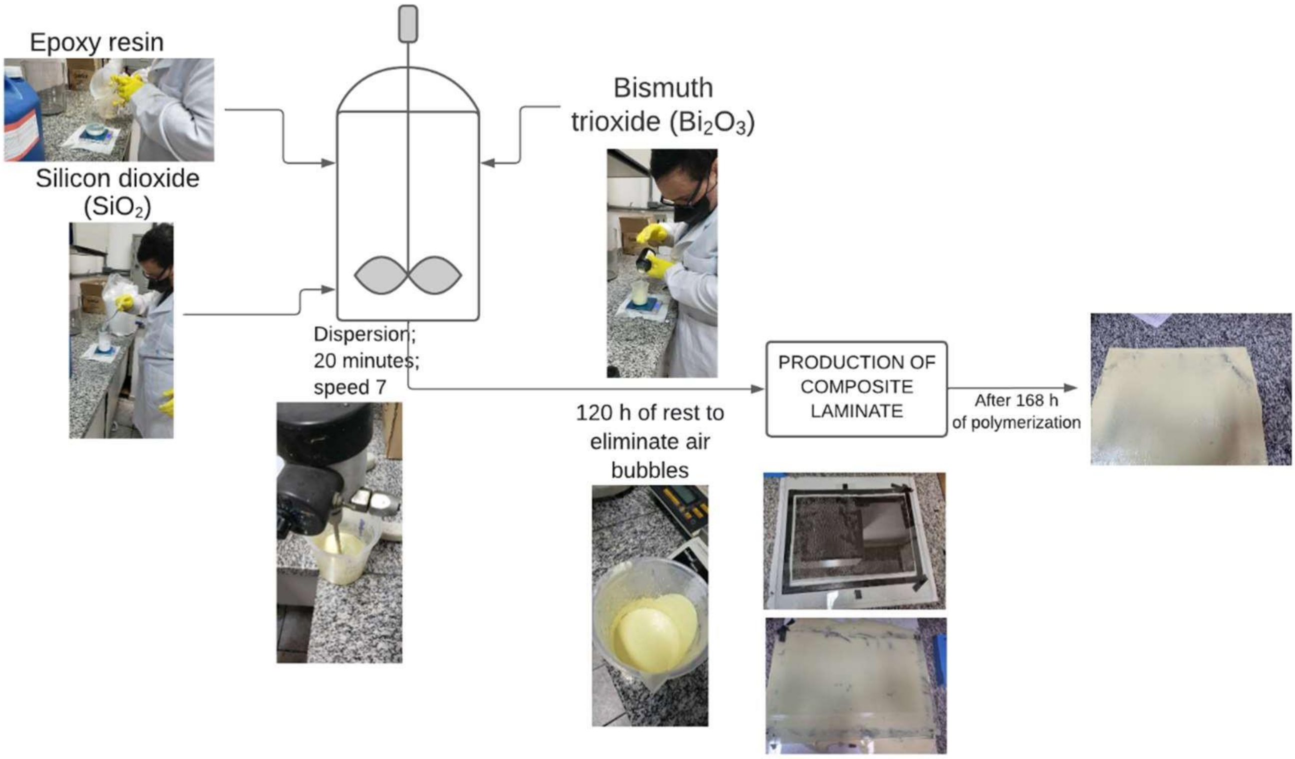
Table 2: Concentrations in the polymeric composite

Bi_2O_3 (%)	Polymeric Matrix (%)	Fiber (%)
00.00	96.88	3.12
09.69	87.32	2.99
18.77	78.58	2.65
29.30	68.41	2.29
39.13	58.45	2.42

It can be seen in Table 2 that the reinforcement concentration used was low in comparison to that which is routinely used (60 to 70%). Because the focus of the research is radiation attenuation, bismuth trioxide was dispersed in the matrix at a higher concentration of matrix in relation to that which is typically utilized. Due to the low concentration of reinforcement, carbon fiber was used as this provided mechanical resistance and tensile strength to the composite that was comparable to lead.

The flowchart of the composite production process is shown in Figure 1. Images of the laminate production process are also shown.

Figure 1: Production processes for Ep/FC composites; Ep/FC micro Bi2O3



Composite plates with an average thickness of 2.5 mm were produced for mechanical tests [10]. The composite was compared with and without the dispersion of Bi2O3 micro particles, and such formulations were cross-linked at room temperature.

Agitation was started using a laboratory mechanical stirrer, with a centrifugal propeller rod, at a speed between 1400 and 2000 rpm, and for a period between 20 and 25 min.

After stirring, the suspension was kept at rest for a period between 100 and 140 h to eliminate air bubbles.

To produce the laminate, the mold was prepared by applying the release agent (RDI 40 rare crystal epoxy resin), then the hardener was added and part of the suspension was transferred onto the mold. After applying bubble-breaking spray, the reinforcing element (carbon fiber fabric) was then placed on part of the suspension with a sliding roller, breaking bubbles over the reinforcement. Subsequently, the rest of the suspension was poured out and the suspension was covered with the finishing mold [11].

The radiation attenuation coefficients were determined according to the IEC 61331 – 1:2018 – for protective devices against X-radiation for medical diagnostic purposes – Part 1: Determination of attenuation properties of materials, for short beam [12].

The quality of the X-ray beam is presented in Table 3, the photon energy used was 48, 65, 82 and 118 keV, with dose rate of the 471, 191, 92.6 and 74.2 μGy.min-1, respectively [13].

Table 3: X-Ray beam quality [12]

Photon energy (keV)	Voltage (kV)	Beam Filters	Air kerma rate (μGy.min^{-1})
48	60	4.25 mm de Al+ 0.60 mm de Cu	471
65	80	4.61 mm de Al+ 2.00 mm de Cu	191
82	100	5.14 mm de Al+ 5.00 mm de Cu	92.6
118	150	7.40 mm de Al+ 2.00 mm de Sn	74.2

The Pantak/Seifert irradiator model Isovolt HS 160 was used as an X-radiation source, shown in Figure 2.

Figure 2: Pantak/Seifert Isovolt HS 160 model irradiator

Figure 3 (a) shows the radiation detector, a Radcal Corporation model 9010 radiation meter, that was used along with a 1.8 L Radcal model 10x5 – 1800 ionization chamber, shown in Figure 3 (b).

Figure 3: Radiation meter (a) and ionization chamber (b)

(a)

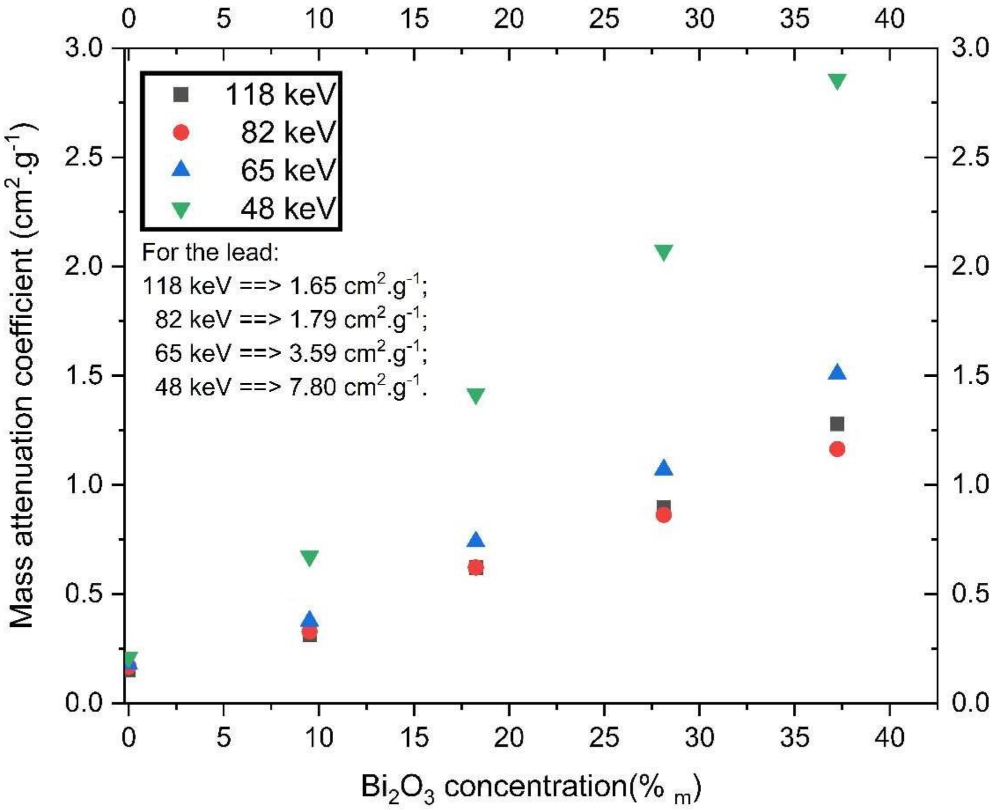
(b)

The ionization chamber was placed at a distance of 2500 mm from the beam exit.

3. RESULTS AND DISCUSSIONS

In Figure 4, the horizontal axis represents the concentration, in mass percentage, of bismuth trioxide in the polymer composite and the vertical axis represents the mass attenuation coefficient.

Figure 4: Mass attenuation coefficient as a function of photon energy and Bi2O3 concentration



From Figure 4, it was determined that for an energy of 118 keV, the dispersion of Bi2O3 in the polymeric matrix increased the mass attenuation coefficient from 0.15 cm2.g-1 (without dispersion) to 1.28 cm2.g-1 (39.13% by mass of Bi2O3). This is an increase of approximately 753%. For an energy of 82 keV, the percentage increase was approximately 582%. For an energy of 65 keV, there was an increase of 739% and for photons with an energy of 48 keV, the percentage increase in the mass attenuation coefficient was 1262%.

4. CONCLUSIONS

It can be verified that for a concentration of 30% bismuth trioxide in the composite, the mass attenuation coefficient is approximately 77.6% in relation to that of lead at an energy of 118 keV. In addition, the composite had a tensile strength 2.6 times greater than lead, so the E/FC composite, with 30% Bi_2O_3, is an excellent option as a barrier to low energy photon radiation (up to 150 keV). Therefore, the objective of this research was achieved. The determination of mechanical resistance as a function of radiation dose could be a focus of future research.

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