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Development of an Epoxy/Carbon Fiber Composite for Radiation Attenuation with a Dispersion of Micro Particles of Bismuth Trioxide (Bi_2O_3)

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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 impact, such as soil contamination [1], materials are highly sought after for radiological protection that can be used as a replacement for lead.
Several materials have been researched as an alternative to lead in radiological protection from low-energy photons (below 500 keV) [2], including barium titanium ($BaTiO_3$); bismuth trioxide (Bi_2O_3); bromine gas (Br_2); bromine iodide (BrI); and calcium tungstate ($CaWO_4$) [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 (Bi_2O_3) with a specific mass lower than lead, has 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 (Bi_2O_3) dispersion in the polymeric matrix for application as a low-energy photon barrier and to determine the mass attenuation coefficient of this composite. So this composite was showed an excellent substitute in relation a lead for shield for lower energy photons

2. Methodology

To reinforce the composites, 200 – 3k carbon fiber fabric (grammage of 0.200 $kg.m^{-2}$, bidirectional weave; thickness of 0.40 mm, with the same number of threads in the weft and warp) was 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, hardening time of the mixture at 25°C of 8 to 10 hours and total curing at 25°C in 7 days and RUV 6820 hardener (isophorone diamine) with the dispersion of bismuth trioxide microparticles in the proportions [5, 8, 9] shown in Table I.

Table I: Concentrations in the resin

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

Table II presents the concentrations present in the polymer composite, taking reinforcement into account.

Table II: 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 II that the reinforcement concentration used was low in comparison to that which is routinely used (60 to 70%) [10]. Because the focus of the research was radiation attenuation, as bismuth trioxide was dispersed in the matrix, for attenuation to occur a higher concentration of matrix was used 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 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 [11].

The quality of the X-ray beam is presented in Table III.

As can be seen in table III, the photon energy used was 48, 65, 82 and 118 keV, with dose rate of the 471, 191, 92.6 and 74.2 $\mu Gy.min^{-1}$, respectively [12].

Table III: 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.
As a radiation detector, a Radcal Corporation model 9010 radiation meter with a 1.8 L Radcal model 10x5 – 1800 ionization chamber was used.
The ionization chamber was placed at a distance of 2500 mm from the beam exit.

3. Results and Discussion

In Fig. 1, the horizontal axis represents the concentration, in mass percentage, of bismuth trioxide in the polymer composite and the horizontal axis represents the mass attenuation coefficient.

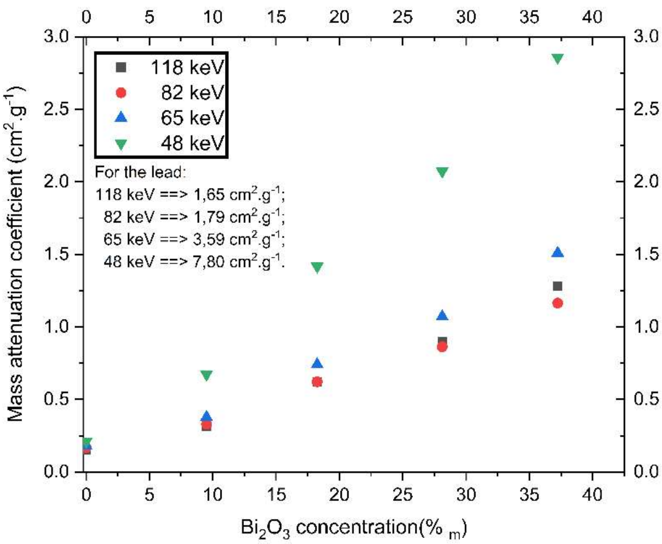

Figure 1: Mass attenuation coefficient as a function of photon energy and Bi_2O_3 concentration

From Fig. 1, it was determined that for an energy of 118 keV, the dispersion of Bi_2O_3 in the polymeric matrix increased the mass attenuation coefficient from 0.15 g.cm^{-1} (without dispersion) to 1.28 g.cm^{-1} (39.13% by mass of Bi_2O_3). 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 also 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 for a barrier to low energy photon radiation (up to 150 keV). The determination of mechanical resistance as a function of radiation dose could be a focus of future research.

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References

[1] Maghrabi, H. A., Vijayan, A., Deb, P. and Wang, L. *Bismuth oxide-coated fabrics for X-ray shielding*, Textile Research Journal **86**(6), 649–658 (2016).
[2] UNIVERSIDADE FEDERAL DO PARÁ. *ESPECTROSCOPIA DE RAIOS-X*, 2023, http://fisica.ufpr.br/grad/espectroscopia_rx.pdf (January, 24, 2024).
[3] Nambiar, S., Osei, E. K. and Yeow, J. T. *Polymer nanocomposite-based shielding against diagnostic X-rays*, Journal of applied polymer science 127(6), 4939–4946 (2013).
[4] Akman, F., Kaçal, M. R., Almousa, N., Sayyed, M. I. and Polat, H. *Gamma-ray attenuation parameters for polymer composites reinforced with $BaTiO_3$ and $CaWO_4$ compounds*, Progress in Nuclear Energy 121, 103257 (2020).
[5] Cao, D., Ge, Y., Bourham, M. and Moneghan, D. *Gamma radiation shielding properties of poly (methyl methacrylate)/Bi_2O_3 composites*, Nuclear Engineering and Technology (2020).
[6] Ambika, M. R., Nagaiah, N. and Suman, S. K. *Role of bismuth oxide as a reinforcer on gamma shielding ability of unsaturated polyester based polymer composites*, J of Applied Polymer Sci 134(13), app.44657 (2017).
[7] Chen, S., Nambiar, S., Li, Z., Osei, E., Darko, J., Zheng, W., Sun, Z., Liu, P. and Yeow, J. T. W. *Bismuth oxide-based nanocomposite for high-energy electron radiation shielding*, J Mater Sci 54(4), 3023–3034 (2019).
[8] Tijani, S. A. and Al-Hadeethi, Y. *The use of isophthalic-bismuth polymer composites as radiation shielding barriers in nuclear medicine*, Materials Research Express 6(5), 055323 (2019).
[9] MUNHOZ, P. M., NASCIMENTO, F. C., SILVA, L. G., GARY, B. C. and CALVO, W. A. *Simulation of radiation attenuation in polymer matrix composite with epoxy resin, reinforced with carbon fiber and dispersion of bismuth oxide (Bi_2O_3) nanoparticles*, presented at 6th Brazilian Conference on Composite Materials, 2022, Tiradentes, Universidade Federal de São João del-Rei.
[10] Marinucci, G. *Materiais compósitos poliméricos: fundamentos e tecnologia*, São Paulo: Artliber 1 (2011).
[11] ABNT - Associação Brasileira de Normas Técnicas. ABNT NBR IEC 61331-1:2018 – Dispositivo de proteção contra a radiação X para fins de diagnóstico médico - Parte 1: Determinação das propriedades de atenuação de materiais, ABNT - Associação Brasileira de Normas Técnicas (2018).
[12] Vivolo, V. *Desenvolvimento de um sistema de referência para determinação do equivalente de dose pessoal e da constância de feixes de radiação X*, PhD Thesis (2006).