Volume 17, Number 5, 2024. pp. 577-586

Jordan Journal of Physics

ARTICLE

Epoxy Composites for the Use in Radiation Protection Applications: A Comparison between Baso4, and Zno Nano-Composites and Micro-Composites

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Doi: **https://doi.org/10.47011/17.5.6**

Received on: 15/05/2023; Accepted on: 06/09/2023

Abstract: In this work, epoxy composites were prepared containing zinc oxide and barium sulfate to protect against high-energy electromagnetic waves, specifically X-rays and gamma rays. Two types of epoxy composites were developed: one with nanomaterial fillers and the other with micromaterial fillers. A thermal processing technique was employed to prepare one of the two types of composites. Various ratios of barium sulfate, zinc oxide, and epoxy resin were used. For each ratio of epoxy resin composites, multiple characterization techniques were applied and analyzed. X-ray diffraction (XRD) was used to examine the crystalline structures of the composites, while energy-dispersive X-ray analysis (EDX) determined the elemental weight ratios in the samples. Additional techniques included a simple density meter to measure the volumetric density of the epoxy composite samples and micrometers to measure the sample thickness. The two types of prepared epoxy composites, containing either nanofillers or microfillers, were tested for their effectiveness in protecting against gamma rays and X-rays. The measured volumetric densities were 1.0634 kg/m^3 for pure epoxy, 3.2365 kg/m^3 for nano-filled epoxy composites, and 4.1672 kg/m^3 for micro-filled epoxy composites. The epoxy composite with nanomaterial fillers exhibited a linear attenuation coefficient of approximately 0.17 cm^{-1}, while the composite with micromaterial fillers showed a linear attenuation coefficient of approximately 0.15 cm^{-1}. This indicates that the epoxy composite with nanomaterial fillers provides better shielding performance compared to the composite with micromaterial fillers.

Keywords: Epoxy, Barium sulfate, Linear attenuation coefficient, Zinc oxide, Epoxy composites, Gamma-ray, Radiation protection, Composites.

1. Introduction

Epoxy is a type of the polyepoxides or epoxy resin, which consists of polymers and pre-polymers containing epoxide groups. The epoxide group is a group that has a triple cyclic ether ring. So, the epoxy is mainly an ether group compound. This polymer is one of the important polymer classes used for multiple applications such as painting, buildings, civil engineering, coating, etc. Epoxy composites also have diverse applications and can incorporate metals, oxides, semiconductors, and more. Epoxy resins have been widely studied and utilized across multiple fields, as illustrated by the following examples. Sahebi *et al.* [1] used the epoxy with other compounds for root canal treatments. Zhao *et al.* [2] employed epoxy with zinc oxide to reduce drag and enhance buoyancy. Huang *et al.* [3] used epoxy resins for wear resistance and anti-corrosion applications. Yao *et al.* [4] discussed epoxy's potential in superconducting applications. Zhong *et al.* [5] investigated epoxy resins for wood flame-

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retardant coatings. Dai *et al*. [6] discussed the use of epoxy resins for encapsulating power modules. Ascione *et al*. [7] discussed epoxy's applications in civil engineering. Oglat *et al.* [8] showed the application of epoxy resins in computed tomography. Xie *et al.* [9] developed epoxy-derived materials for automotive oil filtration. Karunakaran *et al.* [10] examined epoxy resins for high-temperature applications. Zotti *et al.* [11] explored epoxy-derived materials in aeronautical applications. Wang *et al*. [12] discussed epoxy's potential use in pavement mixtures. Mabuchi and Xiaohong [13] used epoxy resins with some of its nano-composites for the electrical insulatioн using mica. Watanabe *et al.* [14] used epoxy resins in the electronic applications for the high-frequency techniques. Natarajan *et al*. [15] discussed the properties of the epoxy resins for possible applications in unreinforced concrete. Gao *et al*. [16] discussed the possible applications of epoxy resins in the encapsulation of the LEDs, i.e., the light-emitting diodes. Cheng *et al*. [17] discussed the epoxy resin composite with graphene for possible applications in the study of conductive ink. Ogbonna *et al*. [18] reviewed the possible use of the composites of the epoxy resins for the core rod insulator used in the high voltage techniques. Phua *et al*. [19] discussed the functionalized carbon black in the composites of epoxy resins. Bisoyi *et al*. [20] discussed some of the electrical and mechanical properties of one of the composites of the epoxy resins. Wu *et al*. [21] demonstrated the use of epoxy resin composites for cryotank applications. Pan *et al*. [22] employed epoxy resins in cyclotetrasiloxane systems. Muñoz *et al*. [23] showcased multifunctional applications of epoxy resin composites containing ceramic nanoparticles. Polymer composites influence various physical and chemical properties of polymers, such as electrical screening properties [24] and structural properties like specific bond volume [25]. Polymer composites [26] can be synthesized by incorporating different materials, including nanocomposites [27, 28]. Numerous studies on epoxy composites have explored aspects like thermal properties [29].

In this work, we prepare epoxy resin composites with two fillers: barium sulfate and zinc oxide. The novelty of this preparation lies in combining the two fillers in specific fractions to provide protection against high-energy electromagnetic radiation, such as X-rays and gamma rays, as a lead-free alternative. Furthermore, the composites are prepared with two structural types: nano-structured and micro-structured.

The study is organized into four sections. In the second section, we describe the materials and methods used, both experimentally and theoretically. In the third section, we present and discuss the results. Finally, the fourth section provides the conclusions of the study.

Materials and methods

2.1 Materials

We used three materials in this study: two inorganic fillers for the polymer composite and the main polymer of the composite. The first material was barium sulfate with a molar mass of 0.2334 kg/mol, a melting point of 1850 Kelvin, and a volumetric density of 4490 kgm^{-3}. The second material was zinc oxide, with a molar mass of 0.0814 kg/mol, a melting point of 2247 Kelvin, and a volumetric density of 5606 kgm^{-3}. The last material was the main polymer of the composite which is the epoxy resin with its solidification agent. For the purpose of the preparation of the epoxy composite, we used a furnace for thermal processing with the temperature increased at a rate of 0.1 °C

2.2 Synthesis of the Epoxy Composites

We prepared a pure epoxy resin sample using epoxy resin with its solidification agent. We poured the epoxy resin into a mold with a circular shape with a thickness of 5 mm, then we added the solidification agent of the epoxy resin and left it for 24 hours to harden. The pure epoxy resin sample is shown in Fig. 1.

After preparing the pure epoxy resin sample, composite samples with microfillers of barium sulfate and zinc oxide were synthesized. Micro-powdered barium sulfate and zinc oxide were prepared and then mixed with the epoxy resin using magnetic mixers. The curing agent was added to the mixture, and mixing was continued to ensure uniform dispersion of the fillers. The mixture was then left to harden for 24 hours.

Multiple samples of the micro-composite were prepared. The epoxy composite samples with microfillers of barium sulfate and zinc oxide are shown in Fig. 2.

FIG. 1. The pure epoxy resin sample.

FIG. 2. The micro-fillers (barium sulfate and zinc oxide) epoxy resin composites.

For the final preparation of the epoxy resin composites, we prepared composite samples with nanofillers of barium sulfate and zinc oxide. First, we prepared nanopowders of barium sulfate and zinc oxide using a nanomiller. The nanobarium sulfate and zinc oxide were then mixed with the epoxy resin using magnetic mixers in a furnace, where the temperature was gradually increased at a controlled rate of 0.1 °C. Subsequently, the curing agent was added to the mixture, and the materials were mixed further to ensure uniform dispersion. The mixture was then left to harden for 24 hours. As with the micro-composite samples, multiple nanocomposite samples were prepared. The epoxy resin composites with nanofillers of barium sulfate and zinc oxide are shown in Fig. 3.

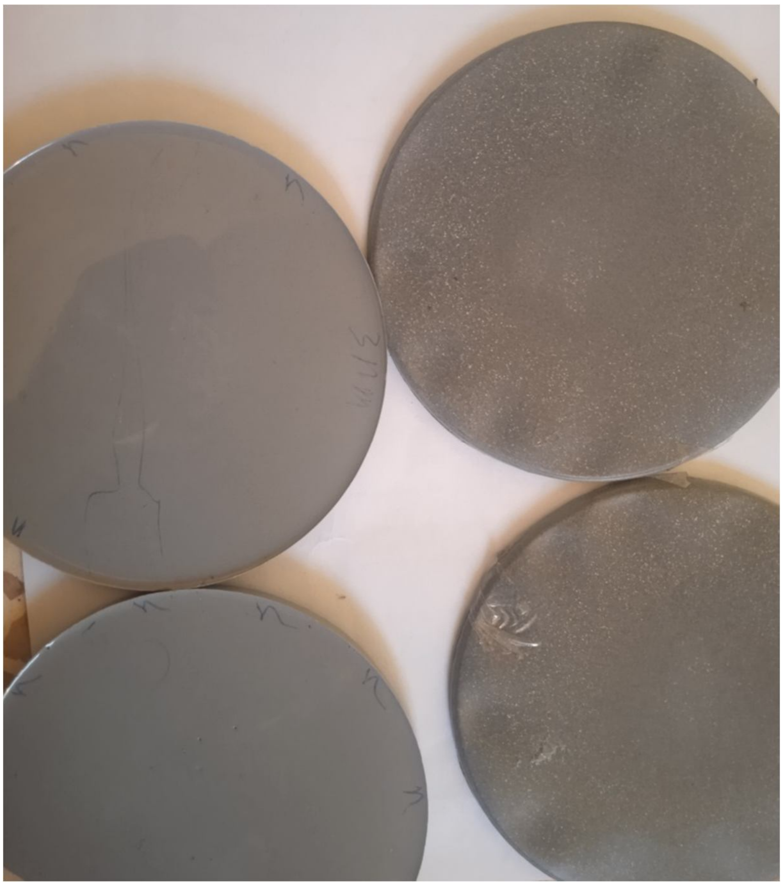

FIG. 3. The nanofillers (barium sulfate and zinc oxide) epoxy resin composites.

2.3 Characterization Techniques

After preparing the three types of epoxy resin samples, we used multiple techniques for the purpose of characterizing the samples. We used the scanning electron microscope (SEM), the energy dispersive X-ray analysis (EDX), the X-ray diffraction (XRD), and the volumetric density meter (VDM).

To evaluate the primary application of the prepared epoxy resin composites—protection against gamma rays and X-rays—we used two X-ray sources and one gamma-ray source (radioactive cesium). Ionization chamber detectors were utilized to measure the attenuation of both X-rays and gamma rays.

The attenuation of gamma rays or X-rays passing through a sample was determined using the exponential

where the rate of intensity of the gamma rays or the rays is given as follows:

$$\frac{dI}{dx} = -\mu I \qquad (1)$$

Here *I* represents the intensity of gamma rays or x-rays after passing through a sample of thickness x and μ represents the linear attenuation coefficient, which depends on the sample type, ray energy, and sample density. Integrating Eq. (1), we find that the intensity is given as follows:

$$I = I_0 e^{-x\mu} \qquad (2)$$

Where I_0 represents the initial intensity of the gamma rays or x-rays and e represents the base of the natural algorithm. Another important parameter of attenuation is the half-thickness, which is defined as:

$$x_{\frac{1}{2}} = \frac{\ln(2)}{\mu} \qquad (3)$$

2. Results and Discussion

In this section, we illustrated the main results of the epoxy resin-BaSO4-ZnO composites. First, Using the volumetric density meter, the densities of the prepared samples were measured. The results are summarized in Table 1, where S_0 refers to the pure epoxy sample, S_1 refers to the microfiller composite, and S_2 refers to the microfiller composite.

TABLE 1. The volumetric density of the epoxy resin samples.

The sample of epoxy	The volumetric density (kgm^{-3})
S_0	1.0634
S_1	3.2365
S_2	4.1672

The surface morphology of the epoxy resin composite samples was analyzed using a scanning electron microscope (SEM). Figure 4 presents SEM images of the micro epoxy resin composite at 2-micron resolution. Figure 5 presents SEM images of the micro epoxy resin composite at 5-micron resolution. Figure 6 presents SEM images of the nano epoxy resin composite at 2-micron resolution. Figure 7 presents SEM images of the nano epoxy resin composite at 7-micron resolution.

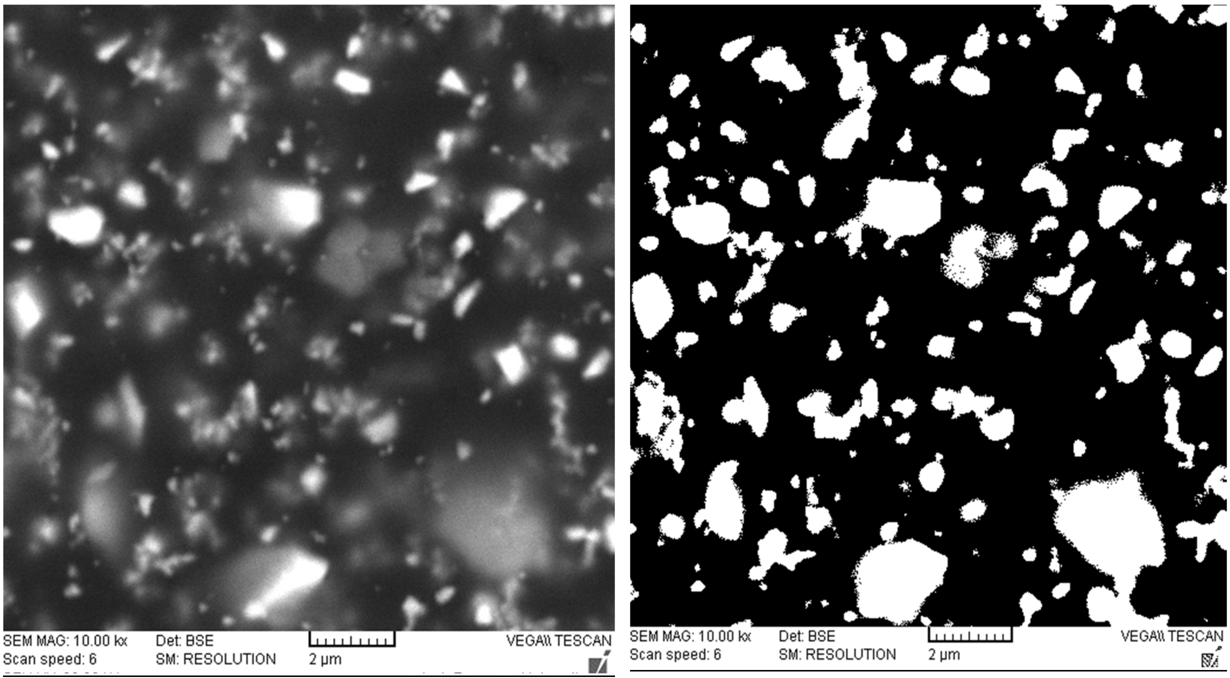

FIG. 4. The scanning electron microscope of the epoxy resin composites with microfillers of the barium sulfate and zinc oxide at 2-micron resolution.

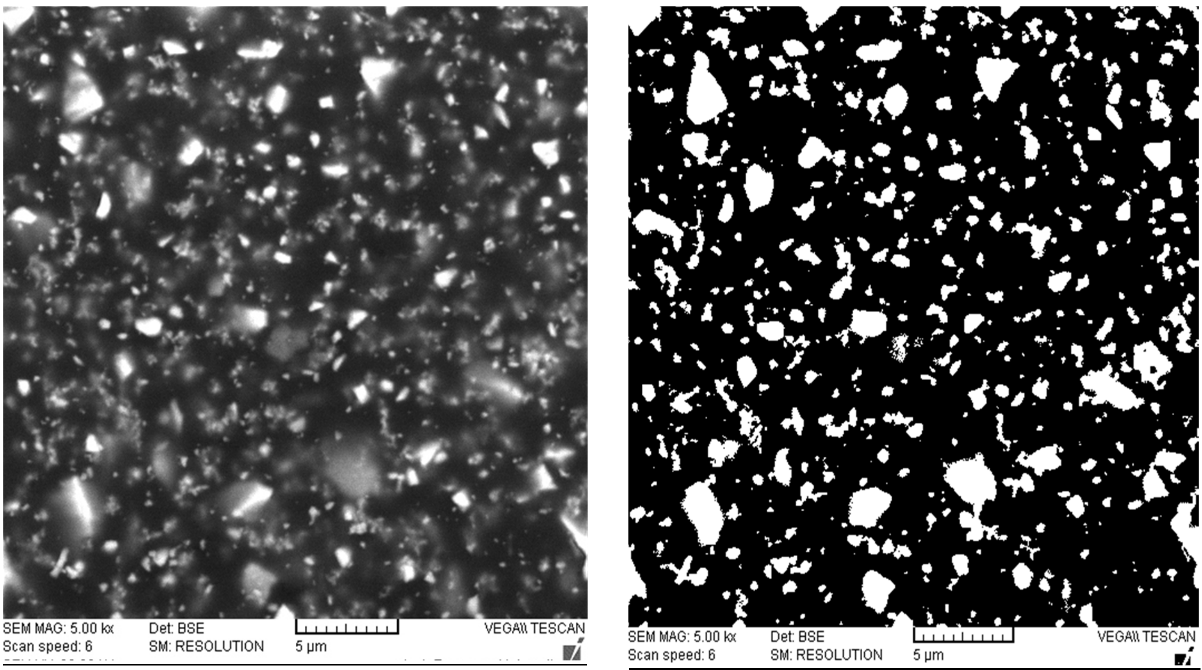

FIG. 5. The scanning electron microscope of the epoxy resin composites with microfillers of barium sulfate and zinc oxide at 5-micron resolution.

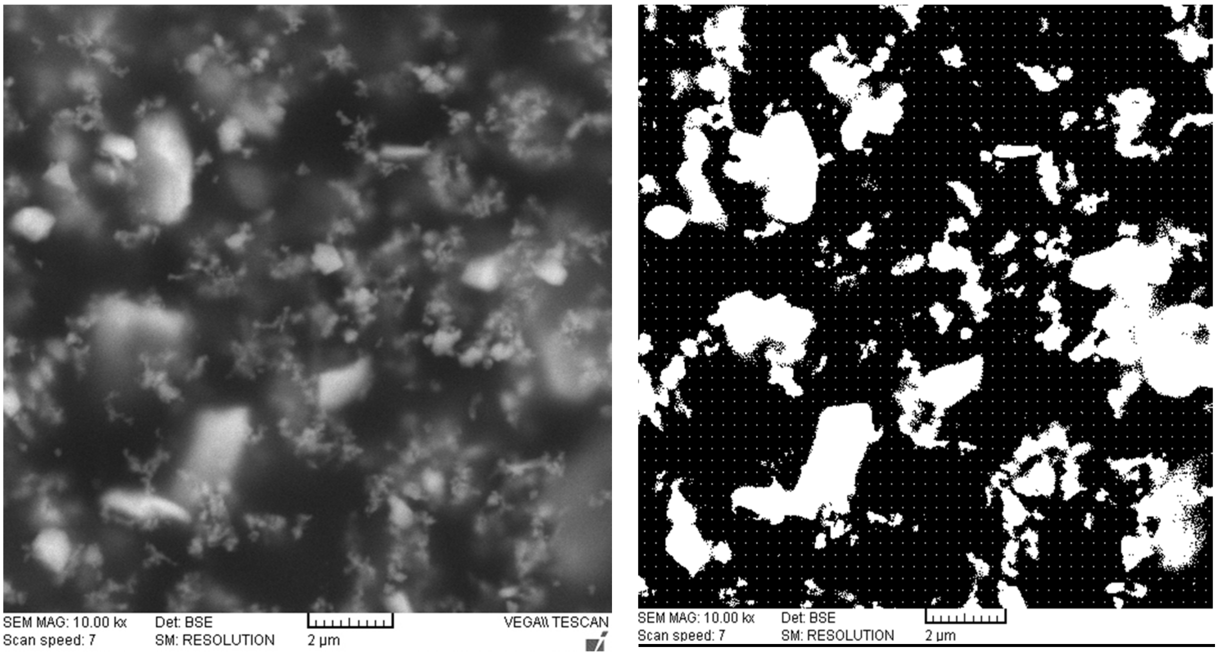

FIG. 6. The scanning electron microscope of the epoxy resin composites with nanofillers of the barium sulfate and zinc oxide at 2-micron resolution.

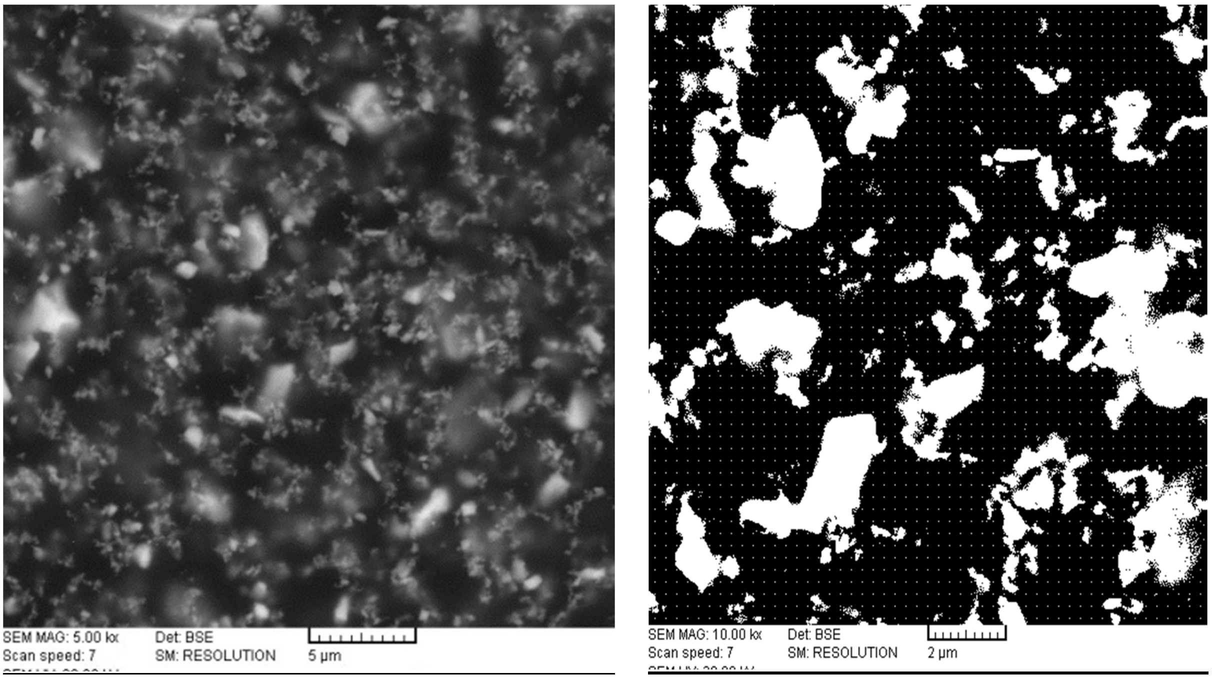

FIG. 7. The scanning electron microscope of the epoxy resin composites with nanofillers of barium sulfate and zinc oxide at 5-micron resolution.

Also, we measured the X-ray diffraction curves for the three samples of the epoxy resin. We illustrated the results of the X-ray diffraction for the three samples in Fig. 8. Fig. 8 shows three curves: the lowest curve corresponds to the X-ray diffraction pattern of the pure epoxy sample without any filler, the middle curve represents the X-ray diffraction pattern of the epoxy resin composite with microfillers of barium sulfate and zinc oxide, and the highest curve represents the X-ray diffraction pattern of the epoxy resin composite with nanofillers of barium sulfate and zinc oxide.

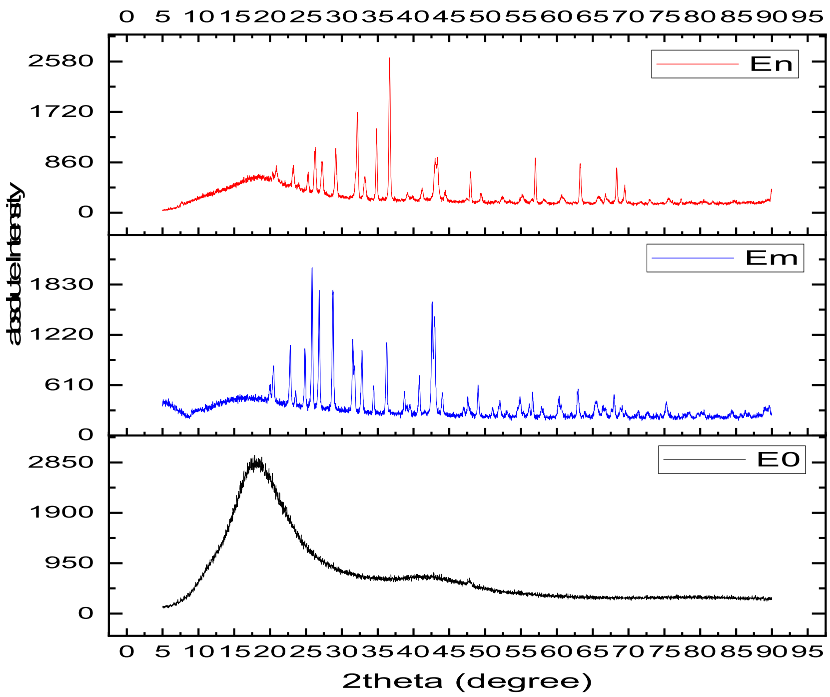

FIG. 8. The X-ray diffraction curves for the three samples of the epoxy resin.

Finally, we used radioactive cesium as a source of gamma rays, and we measured the attenuation of the gamma rays emitted by that radioactive source through the three samples of the epoxy resins. We plotted the natural logarithm of the rational intensity of the gamma rays versus the thickness of the sample to study the attenuation of gamma rays through the epoxy resin samples. We illustrated the gamma-ray attenuation curve for the pure epoxy resin sample in Fig. 9, for the microfiller composite of barium sulfate and zinc oxide in Fig. 10, and for the nanofiller composite of barium sulfate and zinc oxide in Fig. 11, where the y-axis represents the natural logarithm of the relative intensity of the gamma rays, and the x-axis represents the thickness of the sample for each case.

We repeated the same procedures to study the attenuation of X-rays emitted from an X-ray tube for two different energies. The results of X-ray attenuation are similar to those for gamma rays and exhibit the same properties.

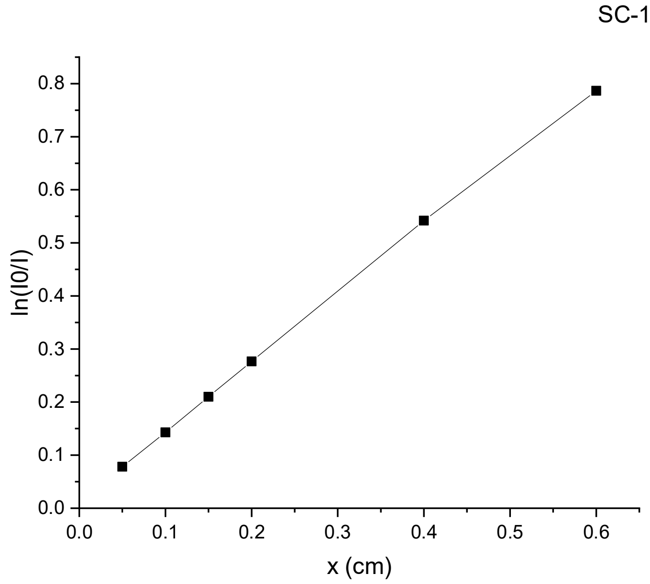

FIG. 9. The attenuation curve of the gamma rays emitted from the radioactive cesium for the pure epoxy resin sample.

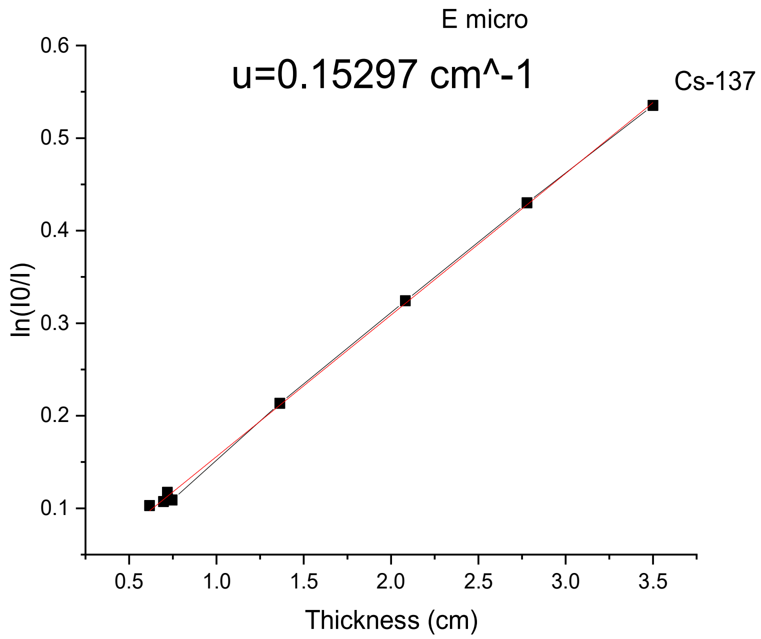

FIG. 10. The attenuation curve of the gamma rays emitted from the radioactive cesium for the epoxy resin of the microfillers composite sample.

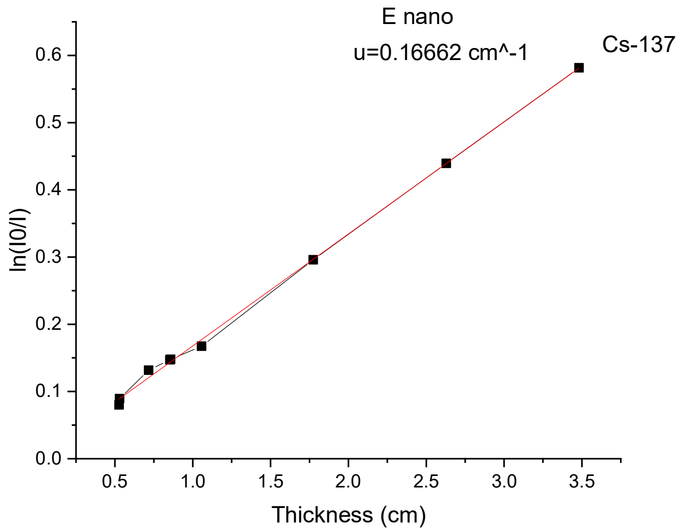

FIG. 11. The attenuation curve of the gamma rays resulted from the radioactive cesium for the epoxy resin of the nanofillers composite sample.

As we can see from Figs. 4 and 5, the surfaces of the epoxy resin with microfillers of barium sulfate and zinc oxide are semi-homogeneous.

TABLE 2. The linear attenuation coefficient of gamma rays for the epoxy resin with microfillers.

x(cm)	μ(cm^{-1})	$x_{1/2}$(cm)
0.617	0.16691	13.7953
0.697	0.15387	14.9644
0.719	0.16309	14.1184
1.363	0.15659	14.7045
2.082	0.15575	14.7839
2.779	0.15476	14.8784
3.5	0.15292	15.0574

There are some granularity features present in the microfillers sample. From Figs. 6 and 7, we observe that the epoxy resin with nanofillers of barium sulfate has more pronounced granularity compared to the microfillers.

From the X-ray diffraction analysis, the pure epoxy resin sample shows a single peak with an amorphous pattern. In contrast, the two composites (microfillers and nanofillers) of barium sulfate and zinc oxide exhibit no distinct peaks, maintaining an amorphous pattern. The energy-dispersive X-ray analysis (EDX) provided the weight ratios of the elements, showing that barium had the highest weight ratio in both the microfillers and nanofillers composites. From the attenuation figures, we calculated the linear attenuation coefficients and the half-thickness values for gamma rays. Using Fig. 10 and Eq. (2), we determined the linear attenuation coefficient for the microfillers epoxy resin sample from the slope of the curve. The values are presented in Table 2. Similarly, the half-thickness of gamma rays for the microfillers sample was calculated using Eq. (3) and is included in the same table.

TABLE 3. The linear attenuation coefficient of gamma rays for the epoxy resin with nanofillers.

x(cm)	μ(cm^{-1})	$x_{1/2}$(cm)
0.717	0.18375	4.1080
0.853	0.17256	3.7722
0.858	0.17242	4.0168
1.057	0.15838	4.0201
1.774	0.16681	4.3765
2.629	0.16716	4.1553
3.482	0.16703	4.1466

The same procedures were applied to the epoxy resin with nanofillers of barium sulfate and zinc oxide, and the results are shown in Table 3.

From the attenuation figures for gamma rays passing through the two epoxy resin composites (microfillers and nanofillers), it is evident that the nanofillers composite is more effective in attenuating gamma rays compared to the microfillers composite.

Conclusions

In this study, we prepared two types of epoxy resin composites using barium sulfate and zinc oxide fillers. The first type of the epoxy resin composite which we prepared is the epoxy resin with microfillers. The other type is the epoxy resin with nanofillers. The primary aim of these preparations was to use the epoxy resin composites for protection against gamma rays and X-rays. We employed a thermal process for preparing the epoxy resin with nanofillers of barium sulfate and zinc oxide. We used three types of samples: the first two are epoxy resin composites with micro and nanofillers, and the third is pure epoxy resin.

Several characterization techniques were used to study the three samples, including scanning electron microscopy, energy-dispersive X-ray analysis, X-ray diffraction, and a volumetric density meter. The volumetric density for the pure epoxy resin was found to be 1.0634 kg/m^3, for the nanofillers epoxy composite it was 3.2365 kg/m^3, and for the nanofillers epoxy composite it was 4.1672 kg/m^3. We observed that the epoxy resin with microfillers of barium sulfate and zinc oxide exhibited lower granularity compared to the epoxy resin with nanofillers. Additionally, both types of epoxy resin composites exhibited amorphous structures.

For the main purpose of the study, which was the attenuation of gamma rays and X-rays, we used two energies of X-rays and one energy of gamma rays. We plotted the attenuation curves for gamma rays and X-rays for the two epoxy composites with microfillers and nanofillers and analyzed the curves. The linear attenuation coefficient for the gamma rays passing through the two epoxy resin composites was determined. The linear attenuation coefficient for the nanofillers epoxy composite was approximately 0.17 cm^{-1}, while for the microfillers epoxy composite it was approximately 0.15 cm^{-1}. We also calculated the half-thickness for both types of epoxy resin composites. These results indicate that the epoxy resin with nanofillers is more effective than the epoxy resin with microfillers for the attenuation of X-rays and gamma rays.

Competing interests

No conflicts of interest.

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