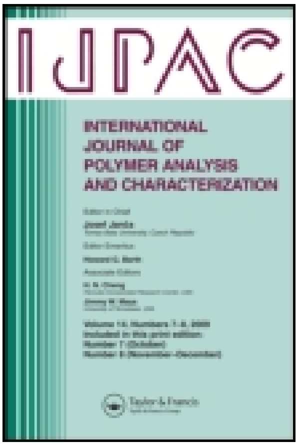

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X-Ray, Gamma, and Neutron Radiation Tests on Epoxy-Ferrochromium Slag Composites by Experiments and Monte Carlo Simulations

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Radiation shielding effects of ferrochromium slag loading hardened epoxy resin samples were investigated. Five different samples including different percentages of epoxy resin and ferrochromium slag were produced. X-ray, gamma ray, and neutron particle transmission experiments were performed for epoxy-ferrochromium slag composites. Also, FLUKA Monte Carlo simulations were made to obtain absorbed doses. As a result, radiation shielding performance increases with increasing ferrochromium slag additive in epoxy.

Keywords: Epoxy resin; Ferrochromium slag; FLUKA Monte Carlo code; Polymer reinforcement; Radiation shielding; Waste recycling

INTRODUCTION

Many shielding materials have been designed against the harm of different types of radiation to the human body; lead and concrete-based materials have been especially preferred for this. Today, polymer-based lightweight composites such as polyethylene, polystyrene, and rubber have been chosen by the radiation protection industry. Epoxy is a chemically adhesive resin that is resistant against water, acids, and alkali and does not lose strength over time. Epoxy is commonly adapted to many uses beyond fiber-reinforced polymer composites. It is widely used in textile manufacturing, food industry, pharmaceutical industry, automobile services,

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petrochemical plants, printers, laboratories, bottling and filling facilities, hospitals, aircraft hangars, rubber factories, warehouses, warehousing, TV studios, electronic installation areas, plastics industry, and terrace coatings, among many other applications. There are many advantages to using epoxy as the base material in composite fabrication.[1]

Recently, the use of epoxy resin as a structural material in the nuclear safety and radiation application area has become widespread due to its good thermodynamic and mechanical properties. In the literature, epoxy resin has been widely investigated as a shielding material. In addition to mechanical properties of epoxy resin, low-dose irradiation effects on it were researched.[2] In another study, nanocarbon-epoxy composites were evaluated as electromagnetic (EM) shielding materials, and effects of carbon filler type on EM radiation shielding properties were investigated.[3] Cosmic radiation shielding tests for ultrahigh molecular weight polyethylene fiber/nano-epoxy composites were performed by Zhong et al.[4] for a NASA spacecraft safety mission. A study about attenuation of electromagnetic radiation (EMR) by graphite-epoxy composites was performed; it was found that electromagnetic shielding efficiency slightly increases at increasing EMR frequency.[5] A new radiation protection material including nano-poly (lead acrylate) epoxy resin was produced, and gamma energy spectrum measurement was carried out to evaluate its radiation-shielding properties. High gamma ray mass attenuation coefficient values were obtained, but an important disadvantage of the studied samples was their lead content.[6] A study of the properties of boron-containing ores/epoxy composites for slow neutron shielding was made, and three samples were irradiated by gamma rays by ^{60}Co and slow neutrons. Obtained cross section values are notable.[7] Commercial epoxy resin was used as concrete additive in addition to hematite and colemanite minerals against gamma radiation; mechanical tests were also performed.[8] Finally, in another study, B_4C-loaded epoxy resin was suggested as a nuclear reactor shielding material; thermal neutron shielding capacities of samples including epoxy resin were determined.[9] Gamma radiation effects of several samples including polymer concretes and epoxy resin were studied.[10] Proton irradiation effects on magnetically oriented epoxy resin were investigated in a different study.[11]

Ferrochromium (FeCr) is an alloy obtained from chromium and iron metals. It includes 50–70% chromium and 30–50% iron. FeCr is usually known as a waste material and is used to give strength to iron and to prevent corrosion and oxidation. Recycling of FeCr slag after metal processing units is an important issue.

In this work different percentages of FeCr slag were added in epoxy resin, and X-ray, gamma, and neutron radiation-shielding performance of produced samples was evaluated by experiments and Monte Carlo simulations.

METHODOLOGY

In this study X-ray, gamma, and neutron transmission measurements were performed to calculate attenuation coefficients, and FLUKA Monte Carlo simulations were made to obtain doses absorbed by samples. We used epoxy resins, which have a large variety of applications. They exhibit good dimensional stability, high mechanical strength, and chemical resistance. They are used as floor paints in radiation facilities and for nuclear fuel casks because of their relatively high resistance to gamma rays. The selection of the type of epoxy resin was based on the requirement of curing at room temperature, heat evolved during curing on the low side, and pot life suitable for industrial applications. As a result, the hardener chosen is an aliphatic polyamine, an epoxy resin of the diglycidyl ether of bisphenol-A type used as an epoxy resin, purchased from System Three Resins (Auburn, AL). Its epoxide equivalent weight, viscosity at 25°C, and density are 210 g/eq, 1.10×10^3 cP, and 1.1 g/cm^3, respectively.

FeCr slag–loaded epoxy resin samples were produced in absence of water. Thus, before using FeCr slag, it was dried in an oven at 100°C for 24 h. Then, a laboratory-type Hobart mixer was used. Slag was put in the mixer bowl, the mixer was started, and while the mixer was running, the epoxy resin was added. The operation consists of two stages: mixing for 1.0 min at the paddle speed of 140 rpm, followed by 1.5 min at the speed of 285 rpm. After mixing, specimens with $10 \times 10 \times 2$ cm cm size were cast. After casting, the molds were subjected to vibration on a vibration table. Thus, air was evacuated from the samples. Produced specimens were kept at $23.0° \pm 3.0$°C for 7 days.

Prepared samples were irradiated by neutron particles, X-rays, and gamma rays. For the neutron irradiation process an alpha-initiated radioisotope neutron source (^{241}Am-Be) was used. It emits neutrons in the 2–10 MeV energy range. For the other irradiation processes 85 keV X-rays were obtained from an X-ray tube and 1250 keV gamma rays were taken from a ^{60}Co source. Experiments were carried out by using appropriate transmission geometries. First the detector was irradiated and then the samples were placed between radiation source and detector. Counts were read using a suitable detectors and compatible computer programs.

Recently, several Monte Carlo simulation codes have been used in addition in experiments of interactions between different types of radiations and materials. FLUKA[12,13] is one of these Monte Carlo codes that very precisely simulate electromagnetic, cosmic, and nuclear interactions in materials. It is very commonly used in areas such as high-energy experimental physics and engineering, radiation shielding, detector and telescope design, cosmic ray studies, dosimetry, medical physics, and radio-biology. Monte Carlo codes were used for radiation shielding studies successfully in our previous work.[14–18] Detailed information about FLUKA can be found at www.fluka.org. We used FLUKA Monte Carlo code to determine doses absorbed by samples after X-ray, gamma, and neutron irradiation.

RESULTS AND DISCUSSION

The linear attenuation coefficient (μ) is the fraction of a beam of X-rays or gamma rays that is attenuated (absorbed or scattered) per unit thickness of the material. The neutron removal cross section describes the eventuality that a fast or thermal neutron undergoes its first collision that removes it from the group of penetrating uncollided neutrons.[19] After X-ray, gamma, and neutron irradiation processes, transmission values were obtained. These values were used to calculate linear attenuation coefficients for X-ray and gamma irradiation and removal cross sections for neutrons by using the following equations:

$$I = I_0 e^{-\mu x} \tag{1}$$

$$N = N_0 e^{-\mu x} \tag{2}$$

In Equation (1) I_0 is the initial beam intensity, I is the intensity of X-rays and photons transmitted across some distance x, x is distance traveled, and μ is the linear attenuation coefficient. In Equation (2) N_0 is the initial neutron count, N is the count of neutron particles transmitted across the sample, x is the thickness of the sample, and Σ is the removal cross section. The unit of μ and

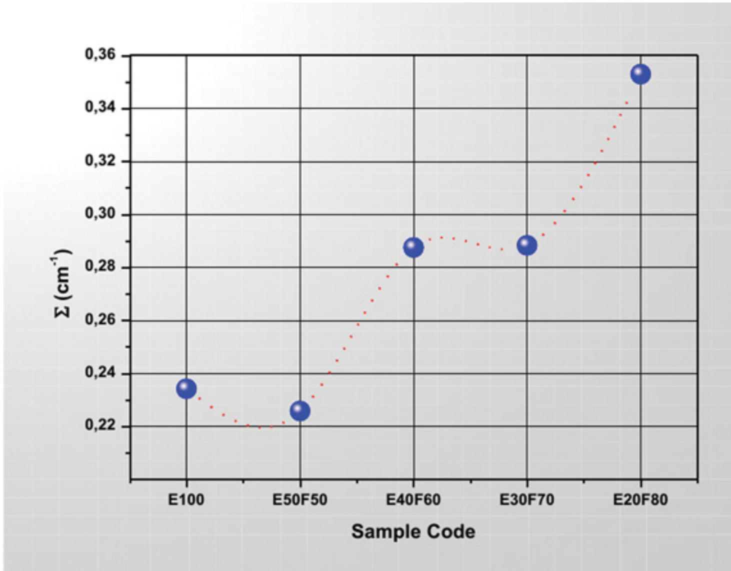

FIGURE 1 Neutron removal cross sections (color figure available online).

Σ is described as per length (cm^{-1}). Figure 1 shows the neutron removal cross sections of samples. Looking at this figure, it is seen that removal cross section value increases with increasing FeCr slag percentage in epoxy resin (up to 50% FeCr slag). The same result is also seen for X-ray and gamma ray in terms of linear attenuation coefficient value in Figures 2 and 3.

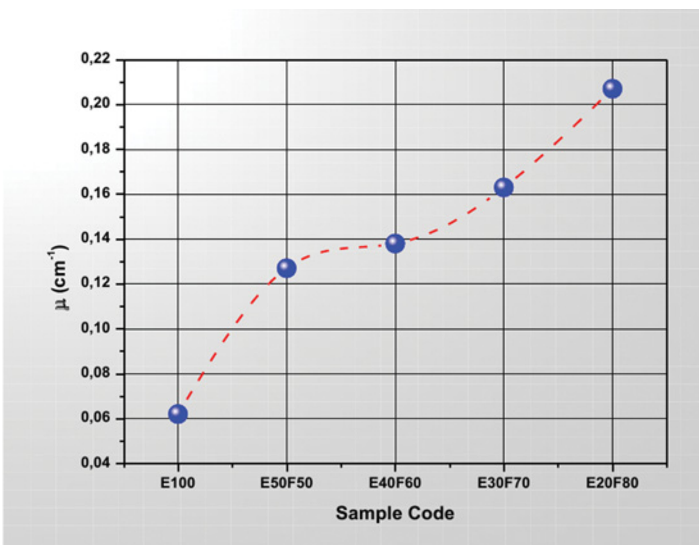

FIGURE 2 Linear attenuation coefficients for 85 keV X-rays (color figure available online).

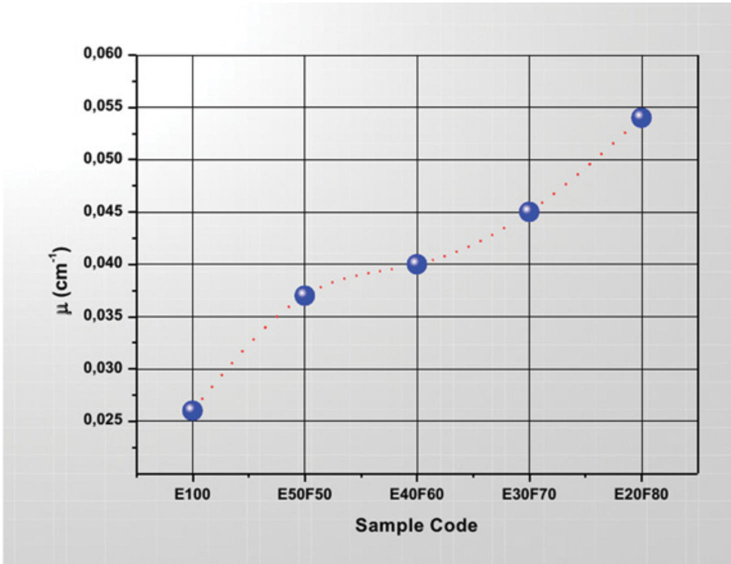

FIGURE 3 Linear attenuation coefficients for 1250 keV gamma rays (color figure available online).

We can easily say that if FeCr slag is added to epoxy resin at a high rate (up to 50%), X-ray-, gamma-, and neutron-shielding capacity of the epoxy resin increases.

Absorbed dose (*D*) is a physical quantity to measure the ionizing radiation energy absorbed by a unit mass of matter. The SI unit used to measure absorbed dose is the gray (*Gy*). It depends

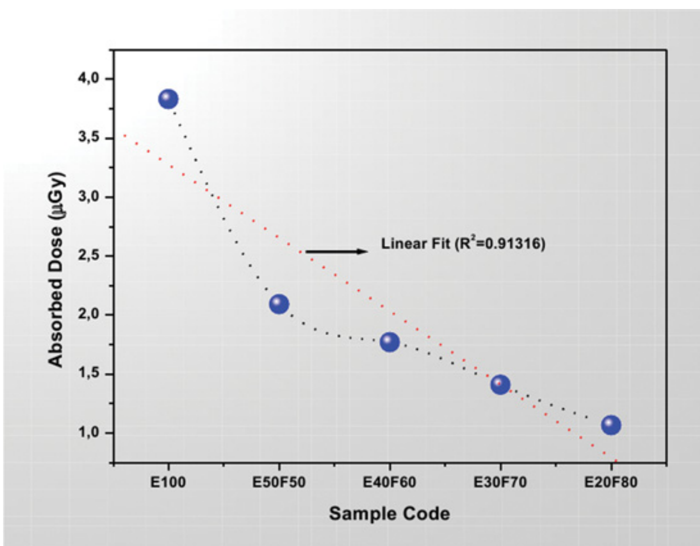

FIGURE 4 Absorbed doses for neutrons (color figure available online).

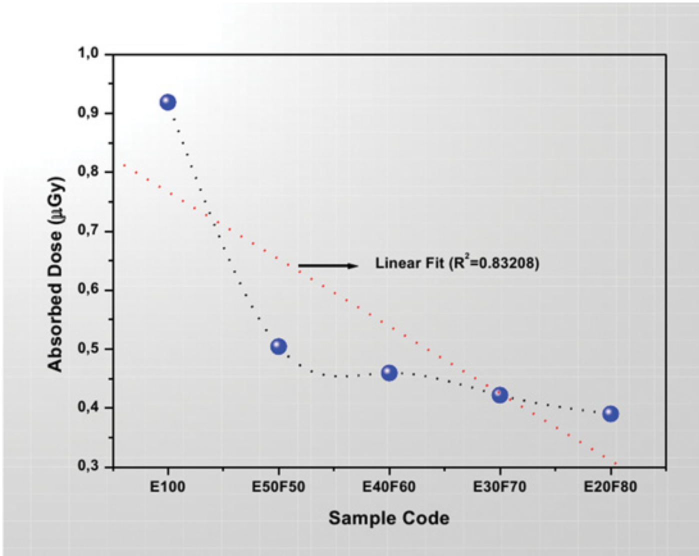

FIGURE 5 Absorbed doses for 85 keV X-rays (color figure available online).

on the energy and intensity of radiation, texposure time, exposed area, and depth of deposited energy. *D* is a radiation shielding parameter like μ and Σ. We calculated absorbed doses after X-ray gamma and neutron irradiations by FLUKA Monte Carlo simulations. Figures 4, 5, and 6. show absorbed doses for neutrons, X-rays, and gamma rays, respectively. *D* values also

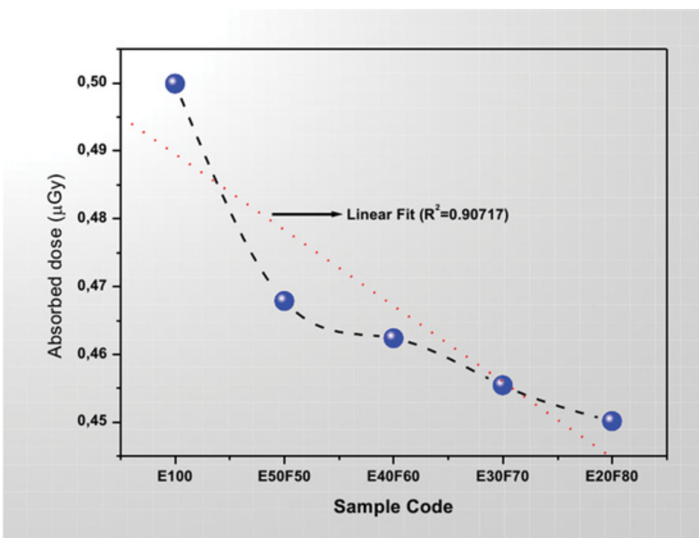

FIGURE 6 Absorbed doses for 1250 keV gamma rays (color figure available online).

TABLE I
Codes, ferrochromium percentages, and physical densities of samples

Sample code	*Ferrochrome (%)*	*ρ (g/cm³)*
E 100	0	1.1
E50F50	50	2.15
E40F60	60	2.36
E30F70	70	2.57
E20F80	80	2.78

decrease with increasing FeCr slag additives in epoxy resin at all three radiation types. This reduction supports the above results about linear attenuation coefficients for X-rays and gamma rays and removal coefficient for neutrons. Samples' codes used in the present study, FeCr contents and physical densities of samples can be seen in Table I.

CONCLUSIONS

Produced samples including commercial epoxy resin and ferrochromium slag were tested against X-ray, gamma, and neutron ionizing radiations. Attenuation coefficients and absorbed doses as shielding parameters were obtained by experiments and FLUKA Monte Carlo simulations. As a result, the addition of FeCr slag in epoxy resin up to 50% percentages improves X-ray-, gamma-, and neutron-shielding performance of epoxy resin. These samples may be used in radiation applications such as radiotherapy rooms, nuclear industry, and radioactive source containers.

REFERENCES

1. Constantin, F., S. A. Gârea, T. Sandu, and H. Iovu. 2010. Characterization of novel epoxy composites based on hybrid inorganic/organic polyhedral oligomeric silsesquioxane. *Int. J. Polym. Anal. Charact.* 15: 119–128.
2. Kline, D. E. J. 1960. Dynamic mechanical properties of polymerized epoxy resins. *J. Polym. Sci.* 47(149): 237–249.
3. Vovchenko, L., L. Matzui, V. Oliynyk, V. Launetz, and A. Lazarenko. 2008. Nanocarbon-epoxy composites as electromagnetic shielding materials. *Mol. Cryst. Liq. Cryst.* 497: 378–386.
4. Zhong, W. H., G. Sui, S. Jana, and J. Miller. 2009. Cosmic radiation shielding tests for UHMWPE fiber/nano-epoxy composites. *Compos. Sci. Technol.* 69(13): 2093–2097.
5. Vovchenko, L., L. Matzui, V. Oliynyk, and V. Launetz. 2010. Attenuation of electromagnetic radiation by graphite-epoxy composites. *Phys. Status Solidi C* 7(3–4): 1260–1263.
6. Zhang, Y., Y. D. Dai, J. S. Li, H. Sun, and S. Q. Chang. 2010. Preparation of nano-poly(lead acrylate) epoxy resin based radiation-protection material and its properties. *Acta Polym. Sin.* 5: 582–587.
7. Li, Z. F., X. X. Xue, T. Jiang, H. Yang, and M. Zhou. 2011. Study on the properties of boron-containing ores/epoxy composites for slow neutron shielding. *Adv. Mater. Res.* 201–203: 2767–2771.
8. Gencel, O., W. Brostow, G. Martinez-Barrera, and M. S. Gok. 2012. Mechanical properties of polymer concretes containing different amount of hematite or colemanite. *Polimery* 57(4): 276–283.
9. Huang, Y. P., L. Liang, J. Xu, and W. J. Zhang. 2012. The design study of a new nuclear protection material. *Nucl. Eng. Des.* 248: 22–27.
10. Martínez-Barrera, G., E. Vigueras-Santiago, O. Gencel, and H. E. Hagg Lobland. 2011. Polymer concretes: A description and methods for modification and improvement. *J. Mater. Educ.* 33(1–2): 37–52.

11. Al-Haik, M. S., S. Trinkle, O. Momotyuk, B. T. Roeder, K. Kemper, M. Y. Hussaini, and K. J. Malloy. 2007. Nanocharacterization of proton radiation damage on magnetically oriented epoxy. *Int. J. Polym. Anal. Charact.* 12: 413–430.
12. Battistoni, G., S. Muraro, P. R. Sala, F. Cerutti, A. Ferrari, S. Roesler, A. Fassò, and J. Ranft. 2007. The FLUKA code: Description and benchmarking. *AIP Conf. Proc.* 896: 31–49.
13. Ferrari, A., P. R. Sala, A. Fassò, and J. Ranft. 2005. *FLUKA: A multi-particle transport code*. CERN-2005–10, INFN/TC_05/11, SLAC-R-773. Geneva, Switzerland: CERN.
14. Mann, K. S., and T. Korkut. 2013. Gamma-ray buildup factors study for deep penetration in some silicates. *Ann. Nucl. Energy* 51: 81–93.
15. Korkut, T., A. Karabulut, G. Budak, B. Aygün, O. Gencel, and A. Hançerlioğulları. 2012. Investigation of neutron shielding properties depending on number of boron atoms for colemanite, ulexite and tincal ores by experiments and FLUKA Monte Carlo simulations. *Appl. Radiat. Isotopes* 70(1): 341–345.
16. Gencel, O., A. Bozkurt, E. Kam, and T. Korkut. 2011. Determination and calculation of gamma and neutron shielding characteristics of concretes containing different hematite proportions. *Ann. Nucl. Energy* 38(12): 2719–2723.
17. Korkut, T., and H. Korkut. 2013. FLUKA simulations of DPA in 6H–SiC reactor blanket material induced by different radiation fields frequently mentioned in literature. *J. Fusion Energy* 32(1): 66–70.
18. Korkut, T., H. Korkut, A. Karabulut, and G. Budak. 2011. A new radiation shielding material: Amethyst ore. *Ann. Nucl. Energy* 38(1): 56–59.
19. Duderstadt, J. J., and L. J. Hamilton. 1974. *Nuclear Reactor Analysis*. New York: John Wiley & Sons.