Determination of the Linear Attenuation Coefficient of Gamma Radiation for Construction Materials Modified with Recycled Additives: Emerging Metrological Challenges

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Abstract: The aim of the study was to evaluate the shielding properties of selected building materials against gamma radiation and to analyze the impact of their density and composition on the effectiveness of beam attenuation. Linear attenuation coefficients were determined based on spectrometric measurements for various materials using Cs-137 and Co-60 sources. Steel and concrete with lead additives proved to be the most effective, while other additives did not significantly improve protective properties.

Keywordse: shielding properties of materials, ionizing gamma radiation, linear attenuation coefficient, construction materials

1. Introduction

The measurement of the shielding properties of materials against gamma ionizing radiation constitutes an important component of planning radiological protection procedures through the optimization of shielding thickness and composition. Properly selected materials make it possible to reduce exposure to gamma radiation, minimize doses received by personnel working under exposure conditions and bystanders, enable early detection of uncontrolled releases of radioactive substances into the environment, comply with stringent regulatory requirements, and protect structural materials from degradation.

The effectiveness of radiation attenuation depends primarily on the type of radiation, the energy of its particles (and thus their penetration capability), and the properties of the shielding material. Owing to advances in science and technology, many high-performance radiation-protective materials have been developed. Radiation shielding materials can be classified into alloys, concretes, glass and ceramics, and polymer composites [1].

Material density is of the greatest practical importance in gamma radiation shielding. The most effective materials are those with high density and high atomic number, such as lead (Pb). Shielding effectiveness also depends on shield thickness and radiation energy. Recent literature critically evaluates the use of lead, citing disadvantages such as high toxicity, lack of chemical stability, weight, and hazardous post-service conditions. Polymer composites are considered a promising alternative due to their low weight, low cost, high elasticity, good mechanical strength, and attractive electrical properties [2].

Spanish researchers have demonstrated that recycled materials can serve as effective shielding and reduce the risk of radiation exposure, highlighting their potential within the circular economy framework. They developed panels containing polymer fractions recovered from electrical cables. The panels were arranged in a layered structure, which increased radiation attenuation efficiency. When two panels of the same material, each 1 cm thick, were used, the gamma radiation dose rate (isotopes: Ir-192 (300–600 keV) and Se-75 (100–400 keV)) was reduced by 50 %. Such panels are used in the design of new prototypes of armored facilities or containers for experimental industrial X-ray testing and gammagraphy [3].

In another study, researchers from Bangladesh presented the results of tests on commercial silica-based glass used in residential buildings. The results of their measurements are shown in Table 1. Photoelectric absorption at 59 keV and Compton scattering at 661 keV, 1173 keV, and 1332 keV were the dominant mechanisms of gamma radiation interaction and contributed to attenuation in the tested materials. Their study demonstrated that the glass samples are suitable for radiation shielding, as the obtained attenuation coefficients are comparable to those of steel and lead [4].

An extremely interesting experiment on the shielding properties of materials against radiation is described in a paper [5] concerning flexible structures made of tantalum and bismuth (Ta/Bi), electrodeposited in a galvanostatic process. Such a Ta/Bi structure is characterized by a high radiation absorption coefficient and effective shielding performance after exposure to various radiation sources (Co-60, Am-241, Cs-137), compared with traditionally used lead shields. The linear attenuation coef-

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Table 1. Measured values of shielding properties for different brands of white glass samples used in residential buildings in Bangladesh [4]
Tabela 1. Zmierzone wartości właściwości osłonowych różnych rodzajów próbek szkła białego stosowanego w budownictwie mieszkaniowym w Bangladeszu [4]

Type of material	Material density g/cm³	Isotope	Energy keV	Linear attenuation coefficient μ cm⁻¹
Rider glass	2.031	Am-241	59	0.971
		Cs-137	661	0.460
		Co-60	1173	0.387
			1332	0.378
PHP glass	2.289	Am-241	59	0.895
		Cs-137	661	0.422
		Co-60	1173	0.358
			1332	0.331
Nasir glass	1.396	Am-241	59	0.839
		Cs-137	661	0.391
		Co-60	1173	0.353
			1332	0.324
Osmania glass	1.800	Am-241	59	0.709
		Cs-137	661	0.348
		Co-60	1173	0.306
			1332	0.281

ficients determined for the Ta/Bi structure were 1.04228 cm^{-1} for Co-60, 58.91 cm ^{1} for Am-241 at 0.103 MeV, and comparable effectiveness for Cs-137 relative to conventional lead shielding. The most noteworthy result was obtained for the Co-60 isotope. The Ta/Bi structure proved to be the most effective in absorbing radiation from this isotope, as its attenuation coefficient exceeded that of lead [5].

The selection of an appropriate shielding material is based on knowledge of its properties, which is particularly important in radiological protection of populations, for example in shelters. Modern shelters should be cost-effective, rapidly deployable, well monitored, and above all ensure public safety. In addition to ballistic protection and protection against chemical and radiological agents, shelters should also be equipped with CBRN monitoring systems and compatible filtration-ventilation systems [6, A1].

The measurement of shielding properties makes it possible to determine to what extent a given material blocks or attenuates harmfull radiation (including ionizing radiation). The primary reason for determining these characteristics is to identify ways to increase the safety level for people staying in facilities used for activities involving ionizing radiation or in collective protection structures, such as civil shelters and military facilities. The use of materials with confirmed attenuation effectiveness is also required by technical standards in order to prevent equipment failures and ensure safe operation.

2. Methodology and Results

The shielding properties of materials against ionizing radiation are determined by evaluating the linear attenuation coefficient of the gamma radiation beam (μ).

The intensity of gamma radiation as a function of the distance travelled in a shielding material is described by the exponential attenuation law:

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

where: I – beam intensity with shielding, I_0 – beam intensity without shielding, μ – linear attenuation coefficient of the beam, x – shield thickness

For our study, we used materials with different densities and structures. Gamma-ray beam intensity measurements were performed under laboratory conditions using a spectrometric device. A lead chamber (so-called "house") was used in the experiments to minimize the detector signal originating from background radiation. Measurements were taken for the signal collected directly from Cs-137 and Co-60 sources, as well as for the signal from Cs-137 and Co-60 sources attenuated by the shielding material. Each measurement was repeated several times. Depending on the tested material sample, its geometry and the positioning of the measurement setup were taken into account. It was important that, during repeated measurements, the distance between the device and the tested material remained constant, and that the material was positioned perpendicular to the radiation beam along its thickness axis, x. A schematic of the measurement setup for determining the gamma-ray beam attenuation coefficient is shown in Fig. 1.

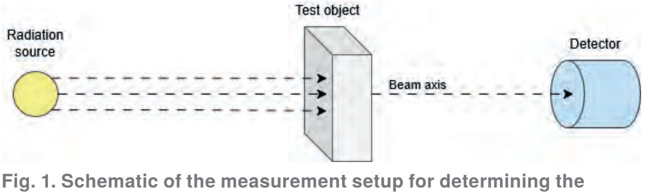

Fig. 1. Schematic of the measurement setup for determining the gamma-ray beam attenuation coefficient
Rys. 1. Schemat stanowiska pomiarowego do wyznaczania współczynnika osłabienia wiązki promieniowania gamma

The linear attenuation coefficient was determined by taking into account the thickness of the tested shielding and the measurement of the beam intensity, expressed as the number of counts recorded by the spectrometer analyzer across different channels corresponding to the energy quanta of the isotopes used. In our study, these were Cs-137 (661.66 keV) and Co-60 (1173.2 keV and 1332.5 keV).

Factors considered in the uncertainty budget included, among others, the geometry of the radiation beam and the tested material sample, the resolution of the detector used, and the thickness and homogeneity of the sample. The expanded uncertainty was calculated using the formula:

$$U = k \cdot u_c \tag{2}$$

where:

$$u_c = \sqrt{u_A^2 + u_B^2} \tag{3}$$

where: U – expanded uncertainty, k – coverage factor, u_c – combined standard uncertainty, u_A – type A uncertainty, u_B – type B uncertainty.

For the given uncertainty, a confidence level of 95 % was assumed, with a coverage factor of $k = 2$.

The uncertainty of the linear attenuation coefficient was determined at a 95 % confidence level.

Table 2. Measurement results of the linear attenuation coefficient for materials of different densities
Tabela 2. Wyniki pomiarów liniowego współczynnika osłabienia dla materiałów o różnej gęstości

Type of material	Material density g/cm³	Isotope	Energy keV	Linear attenuation coefficient μ cm⁻¹
Concrete A	2.7	Cs-137	662	0.272 ±0.008
		Co-60	1250	0.132 ±0.007
Concrete B	1.79	Cs-137	662	0.120 ±0.006
		Co-60	1250	0.085 ±0.020
Concrete C	2.22	Cs-137	662	0.149 ±0.005
		Co-60	1250	0.116 ±0.004
Concrete D	1.45	Cs-137	662	0.055 ±0.009
Steel	7.19	Cs-137	662	0.546 ±0.008
		Co-60	1250	0.408 ± 0.047

In the study, we used materials of different densities, as shown in Table 2:
- Concrete A – polymer concrete doped with lead,
- Concrete B – polymer concrete,
- Concrete C – concrete doped with silicone fibers (sample provided by BEWA Beton Sp. z o.o.),
- Concrete D – concrete with a cavity filled with polyurethane (PU) foam,
- Steel – S235.

The results of the linear attenuation coefficient measurements show differences depending on the isotopes and the density of the materials. These studies indicate that the S235 steel sample, due to its atomic structure arranged in a crystal lattice, has the highest density, resulting in the greatest linear attenuation coefficient for both isotopes. Concrete A exhibits higher shielding effectiveness than Concretes B, C, and D, primarily due to the increased density from adding metallic lead. Concrete B shows no significant change in gamma radiation attenuation. Concrete C, doped with silicone fibers, displays similar characteristics. Concrete D, a commercially used concrete, contains a cavity filled with polyurethane foam. While this may improve the insulating properties of the material, the addition of PU does not enhance radiation shielding; in fact, it reduces it. The addition of metallic lead in Concrete A is significant for shielding but environmentally unfriendly. Therefore, using this type of material as a shielding material in collective protection facilities is not the optimal solution.

3. Discussion and Conclusions

We conducted research on the use of various organic substances (PU foam) and industrial waste to modify the properties of concrete- and steel-based construction materials to enhance their gamma radiation shielding. The results encourage further studies on alternative additives that could improve shielding, such as recycled materials from photovoltaic panels and mobile phones (after metal extraction). These additives are less toxic than commonly used lead but have high density, which may enhance the material's radiation shielding properties.

Considering the measured linear attenuation coefficients and literature values, we can identify the direction for future research to ensure that construction materials used for collective protection provide adequate shielding against CBRN threats. Achieving high-density materials remains the fundamental approach for effective solutions in this research area. A promising direction for further work is incorporating circular economy principles in selecting additives for shielding materials, which would optimize material recycling by defining new application areas.

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A1 Rozporządzenie Ministra Spraw Wewnętrznych i Administracji z dnia 4 listopada 2025 r. w sprawie warunków technicznych dla budowli ochronnych oraz warunków technicznych ich użytkowania i usytuowania, https://dziennikustaw.gov.pl/D2025000154801.pdf

Wyznaczanie współczynnika osłabienia promieniowania gamma dla materiałów konstrukcyjnych z domieszkami pochodzenia wtórnego – nowe wyzwania metrologiczne

Streszczenie: Celem pracy była ocena osłonności wybranych materiałów konstrukcyjnych przed promieniowaniem gamma oraz analiza wpływu ich gęstości i składu na skuteczność osłabienia wiązki. Wyznaczono liniowe współczynniki osłabienia na podstawie pomiarów spektrometrycznych dla różnych materiałów, wykorzystując źródła Cs-137 i Co-60. Najwyższą skuteczność wykazała stal oraz beton z dodatkiem ołowiu, natomiast inne domieszki nie poprawiły istotnie właściwości osłonnych. Wyniki wskazują na konieczność poszukiwania mniej toksycznych, wysokogęstych dodatków zgodnych z ideą gospodarki o obiegu zamkniętym.

Słowa kluczowe: osłonność materiałów, promieniowanie jonizujące gamma, liniowy współczynnik osłabienia, materiały konstrukcyjne

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