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DETERMINATION OF GAMMA PHOTON ATTENUATION COEFFICIENT OF LIGHTWEIGHT BUILDING AND INSULATION MATERIALS USED FOR OVERBUILDING IN SERBIA

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Abstract: *Data on the protective properties of construction materials dwellings are being built of are among the most important ones to estimate consequences and risks to human health in nuclear and radiological emergencies. In this paper, building and insulation materials have been experimentally investigated in terms of mass attenuation coefficient for high-energy gamma photons of the cobalt-60 source. The lightweight autoclaved aerated concrete blocks known as Siporex blocks and stone wool slabs have been chosen for the research since they have been most commonly used for overbuilding of residential buildings in Serbian urban environments. Gamma radiation shielding capability of these materials was measured with the two different experiment designs: utilizing a gamma spectrometric system containing NaI(Tl) detector in narrow beam gamma-ray transmission geometry, and counter with pancake type Geiger-Muller probe in broad beam geometry. Linear attenuation coefficient, half-value, and tenth-value layer were also calculated. The results obtained indicated that the radiation protection properties of the materials investigated for high energy photon radiation are inferior in comparison to conventional building materials. Additionally, the data gained in this research could provide valuable information for practical shielding calculation.*

Keywords: *Gamma ray, radiation protection, half value layer, autoclaved aerated concrete, stone wool.*

1. INTRODUCTION

Rapid urbanization and industrialization in modern days unavoidably lead to the migration of the population to urban environments. Urban environments are already densely populated and suffer from space deficiency. Overbuilding the existing residential buildings is an efficient way to overcome this lack, and consequently, cities are growing vertically, rather than outwards. Structures that are subject to overbuilding were constructed at different times, using different construction materials and applying different standards, therefore to preserve their static characteristics, lightweight construction materials accompanied by materials with good insulation properties are the first and logical choice to build dwellings over or on top of existed structures.

In comparison to conventional concretes, aerated autoclaved concrete (AAC) has many advantages such as lower density, higher strength-to-weight ratio, lower coefficient of thermal expansion as well as good acoustic insulation. The AAC consisting of 80% air does not have coarse aggregates, and its main components are cement, sand, water, gypsum, lime, and expanding agents – Al or Zn powder. The chemical reaction of Al with $Ca(OH)_2$ forms a gas that makes a porous inner structure of AAC, i.e. cementations mortar surrounding disconnected air voids and microscopic bubbles. This makes AAC a versatile lightweight material typically cast as blocks (lightweight concrete masonry units) used for exterior and interior construction [1].

If only AAC blocks were used for building, insulation standards in most European countries would require very thick walls. Therefore, an additional outer envelope of material with highly effective thermal and sound insulation and fire protection characteristics is needed. One of such materials is mineral wool.

Mineral wool is a generic term for a wide range of artificial non-metallic inorganic fibers. Stone wool (SW), known also as rock wool is a type of mineral wool produced from naturally occurring volcanic rocks (diabase, basalt, or dolomite) and recycled of technological process waste with the addition of cement. The pulverized rock, limestone, and coke (as an energy source) are put in a cupola furnace where in the presence of oxygen, it is melted at a temperature of about 1500 °C. The most abundant chemical compounds in the composition of the raw materials are oxides of Si, Al, Ca, Mg and Fe. Fibers are created by projecting the molten mixture over a train of high-speed rotating disks. Resin binders, water repellents, and mineral oil are atomized over the fibers as they leave the discs. Formed and impregnated fibers go to a pressurized chamber where the primary SW sheet is formed. Such the sheet goes through the process known as batting creeping in order to increase the number of layers, after which a series of rollers compress the SW blanket to the desired thickness. After creeping, the oven blows air whose temperature is about 200 °C to polymerize the SW and the blanket gets its final thickness and consistency. Finally, the blanket is cut to a board of the required dimensions [2].

The construction industry is one of the fastest-growing branches of the Serbian economy. Statistical indicators showed that an increase in construction activity is quite remarkable in the most densely populated areas. For instance, the number of completed residential apartments in Vračar, the municipality of the City of Belgrade, where the population density is 19321 residents per km^2, increased from 9.6 completed apartments per 1000 residents in 2010 to 12.5 in 2020 [3].

Data on the protective properties of construction materials dwellings are being built of are among the most important ones to estimate consequences and risks to human health in nuclear and radiological emergencies. Those data are also needed for practical shielding calculation in sense of radiation safety. Attenuation data for commonly used building materials are available in many resources, but data on photon attenuation of previously described materials are very scarce. Therefore, the aim of this work was to experimentally determine mass attenuation coefficient and calculate linear attenuation coefficient, half and tenth-value layer for the lightweight AAC blocks known as Siporex blocks for exterior structures and SW slabs for ventilated façades most commonly used for overbuilding of residential buildings in Serbian urban environments and the most represented on the Serbian market.

2. MATHERIALS AND METHODS

A collimated beam of mono-energetic gamma rays is attenuated in the matter according to the Lambert–Beer law, described by Eq. (1):

$$I_d = I_0 e^{-\mu_m d_m} \tag{1}$$

where I_d, is radiation intensity after passing absorber with mass thickness d_m, and I_0 is incident intensity. I_d and I_0 are expressed as count rate I_R/s^{-1}.

Mass thickness, d_m/kg m^{-2}, is obtained by multiplying the linear thickness of the absorber, d_l/m, by the absorber density, ρ/kg m^{-3}, according to Eq. 2.

$$d_m = d_l \rho \tag{2}$$

Mass attenuation coefficient, μ_m/m^2 kg^{-1}, is the most important quantity characterizing the transmission of gamma radiation, and for a given gamma-ray energy, the μ_m value does not vary with the physical state of a given absorber. The relationship between mass and linear attenuation coefficient, μ_l/m^{-1} is given by Eq. (3).

$$\mu_m = \frac{\mu_l}{\rho} \tag{3}$$

The thickness of any given material where 50 % and 90 % of the incident energy has been attenuated is known as the half-value layer ($d_{1/2}$) and tenth-value layer ($d_{1/10}$) thickness, respectively, both expressed in units of distance, and have been calculated applying Eq. (4) and (5):

$$d_{1/2} = \frac{\ln 2}{\mu_l} \tag{4}$$

$$d_{1/10} = \frac{\ln 10}{\mu_l} \tag{5}$$

Measurements were carried out using a gamma-ray source ^{60}Co with two lines with energies 1173.24 keV and 1332.50 keV. The activity of the source was 157 MBq. The source was enclosed in a 25 cm thick lead shield.

The geometry of AAC and SW absorber specimens was prism with the dimension of 20 × 20 × 10 cm^3, and 20 × 20 × 12 cm^3, respectively. The density of the AAC and SW absorbers was determined by the Archimedes method and were 0.50 g cm^{-1} and 0.10 g cm^{-1}, respectively. AAC blocks and SW slabs were purchased from the local market by the authors based on pieces of advice they are given by construction engineers who lead overbuilding construction sites at the time when this research had been planned. The types of materials and their manufacturers are known to the authors.

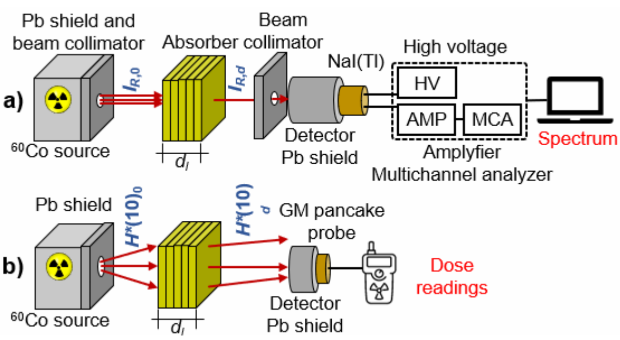

Figure 1. Experimental design for attenuation measurement: a) narrow beam geometry, b) broad beam geometry

The attenuation of gamma radiation was measured with the two different experimental setups illustrated in Figure 1. The narrow beam design depicted in Figure 1a) utilizes a well-collimated point ^{60}Co source collimated with the 10 cm lead panel with a 3 mm aperture placed after the source and in front of the detector. A 2″ × 2″

NaI(Tl) detector system (Thermo Scientific RIIDEye M-GN) was used to measure two discreet ^{60}Co gamma energies for the unshielded source and 1 to 6 10 cm thick AAC layers and 1 to 8 12 cm thick SW layers. The detector's energy resolution was 7.5 % at 661.6 keV and was integrally coupled to a photomultiplier tube. The detector was shielded by lead bricks of approximately 5 cm thickness. The amplified signal from the detector is recorded by a 256-channel multichannel analyzer. Obtained spectra were processed in ScintiVision 32 software. Each measurement (spectrum acquisition) was performed three times per 3 min, and results were expressed as net count rate under photopeak at 1173.24 keV and 1332.50 keV energy. Those measurements do not account for any secondary or scattered gamma radiation.

The important feature of narrow beam geometry is that only gamma rays from the source that escape the absorber without any interaction can be counted by the detector. Real-life scenarios include more diffuse, non-collimated sources; hence it is needed to account for gamma rays emitted directly from the source as well as photons scattered in the absorber and other types of secondary photon radiation. In that sense, I_0 and I_d are more convenient to express in terms of dose rate, e.g., ambient equivalent dose rate, $H^*(10)$/Sv h^{-1}.

The broad-beam design given in Figure 1b) utilizes a non-collimated ^{60}Co source and dose rate meter (Thermo Scientific RadEye B20 with pancake type Geiger-Muller probe with dose equivalent filter) to measure $H^*(10)$ attenuation for AAC and SW layers. For each thickness of selected absorbers, ten measurements of 60 s were obtained. Data acquired with this arrangement accounts for attenuation of primary and any secondary radiation which passes through the AAC and SW absorbers. Those measurements are of greater importance and more indicative of many real-world applications of radiation sources and radiological and nuclear emergencies where the goal is to reduce the total dose to humans.

4. RESULTS AND DISCUSION

4.1. Primary radiation attenuation

The dependence of the measured gamma count rate from the mass thickness of the AAC and SW absorbers at 1173.24 keV and 1332.50 keV is given in Figure 2. As expected, the count rate decreased exponentially with increased mass thickness. That decline was more notable for the AAC than for SW for the same linear thickness which is the consequence of a five times greater density of AAC material. Also, the decline in count rate was sharper at 1173.24 keV due to the slightly higher contribution of the photoelectric effect to total gamma-ray attenuation.

For both absorbers studied at both energies, fitting of experimentally obtained results with the exponential function given by Eq. (1) was satisfactory with the coefficient of determination R^2 greater than 0.999.

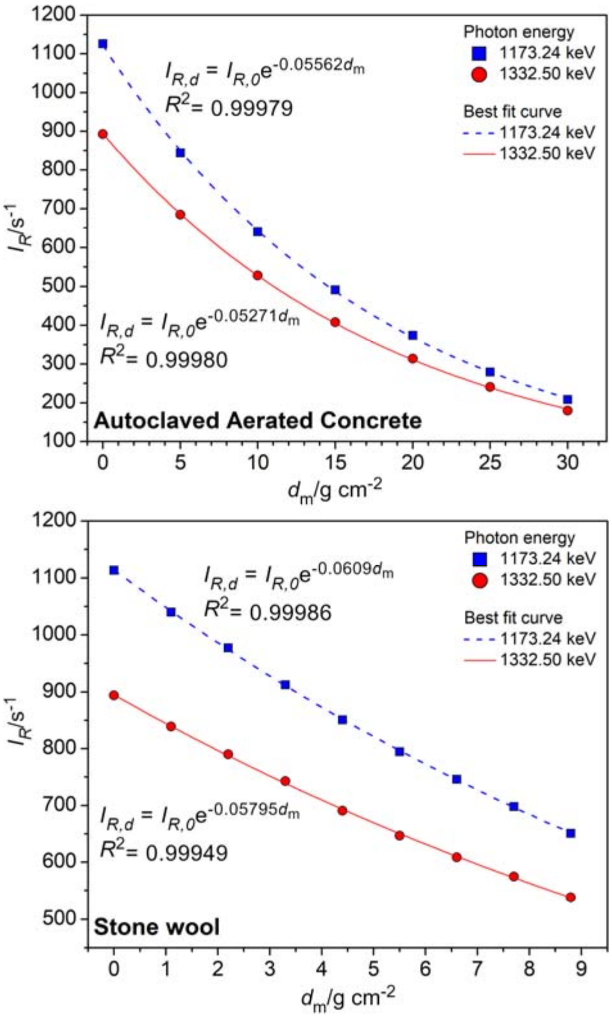

Figure 2. Count rate (I_R) as a function of the mass thickness (d_m) of the investigated absorbers at two ^{60}Co gamma energies

The experimental values of photon attenuation indices studied in this research for investigated building materials at two ^{60}Co energies are presented in Table 1.

Table 1. Gamma photon attenuation properties for absorbers of interest at two energies of ^{60}Co gamma rays

Energy	μ_m/ 10^{-2} cm^{-2}g	μ_l/ 10^{-2} cm^{-1}	$d_{1/2}$/cm	$d_{1/10}$/cm
Aerated autoclaved concrete				
1173.24	5.56 ± 0.04	2.78 ± 0.02	24.92 ± 0.16	82.8 ± 0.5
1332.50	5.27 ± 0.03	2.64 ± 0.02	26.30 ± 0.16	87.4 ± 0.5
Stone wool				
1173.24	6.09 ± 0.03	0.609 ± 0.003	113.8 ± 0.5	378.1 ± 1.6
1332.50	5.80 ± 0.05	0.580 ± 0.002	119.6 ± 0.9	397 ± 23

The most important mechanisms of interaction between gamma radiation and matter are photoelectric absorption, Compton scattering and pair production. Generally, at high energies, like energies of 1173.24 keV and 1332.50 keV, the Compton scattering mechanism, and pair production phenomena are dominant. In this case, this prevalence is a consequence not only of exposition to high-energy gamma-rays, but also of the low atomic number of elements that are the most abundant in the AAC and SW materials (Si, Al, Ca, Mg, Zn, and Fe).

Gamma attenuation coefficients are inversely dependent on gamma energy and directly proportional to the atomic number of the elements shielding material are made of. For both materials, mass and linear attenuation coefficients were lower at 1332.50 keV. Despite cross-section for Compton scattering being approximately equal for two energies, the photoelectric absorption is a slightly more dominant way of interaction between gamma rays and atoms of the interacting materials at 1173.24 keV leading to somewhat greater absorption at that energy.

The lower the half and tenth-value layer values, the better the radiation shielding materials are in terms of the linear thickness requirements. Values of $d_{1/2}$ for AAC at 1173.24 keV and 1332.50 keV were 24.92 cm and 26.30 cm, respectively, while for the SW these values were about 4.5 times higher (113.8 cm and 119.6 cm).

Materials used widely in the construction industry such as concrete with different densities, bricks, pumice, and lightweight concrete blocks, have also been characterized in terms of shielding properties against photon radiation in numerous research. To put our results in perspective, the results obtained for half and tenth-value determined in this work have been compared to corresponding values for commonly used building materials that were determined in a similar experimental set-up applied in this research.

Table 2. Half and tenth-value layer thickness values for standard building materials

Matherial; ρ/g cm^{-3}	1173.24 keV		1332.50 keV		Ref.
	$d_{1/2}$/cm	$d_{1/10}$/cm	$d_{1/2}$/cm	$d_{1/10}$/cm	
Gas concrete (AAC); 0.40	31.4	104.2	32.2	107.1	[7]
Pumice; 0.85	14.7	49.0	15.8	52.3	
Brick; 1.50	14.7	29.1	15.7	27.1	
Concrete; 2.25	5.2	17.3	5.5	18.3	
Concrete; 0.6–1.5	6.86	22.79	7.70	25.58	[8]
Concrete; 1.4–2.0	6.03	20.02	6.36	21.12	
Concrete; 2.0–2.5	3.98	13.23	4.20	13.95	
Concrete; 2.5–3.0	3.96	13.15	4.15	13.78	
Concrete; 3.0–4.0	3.85	12.79	4.08	13.54	

By comparison with the data presented in Table 2. it can be noticed that for AAC and SW material investigated in this work, the $d_{1/2}$ and $d_{1/10}$ values were less than those of commonly used concrete of different densities, standard bricks, and pumice blocks. Published results for $d_{1/2}$ and $d_{1/10}$ of gas concrete (equivalent to AAC), but of lower density than AAC material of interest for this work, were 26 % and 23 % higher at 1173.24 keV and 1332.50 keV respectively, than the values determined here. Therefore, for a shielding effectiveness achieved with standard building materials, a larger thickness of the AAC blocks and SW slabs would be required.

4.2. Dose attenuation

The mass attenuation coefficient is independent of the density of the target material and depends on the elemental composition of the material and photon energy [4]. Therefore, values of μ_m for a given photon energy are very similar, pointing out that equal masses of different materials should have nearly identical attenuation properties [5]. Nevertheless, the ratio of photoelectric absorption and Compton scattering varies in a different matter, therefore it is important to make difference between the attenuation of primary radiation (achieved in narrow beam geometry) and dose attenuation. The latter one involves the contribution of scattered photons and secondary radiation emitted at different angles and with various energies.

Scattered and secondary gamma radiation in some extent complicate the absorption law described by Eq. (1). The gamma photon attenuation coefficient calculated or experimentally determined for narrow (sometimes called "good" geometry) ignores the energy of secondary gamma radiation deposited in the detector. From the radiation protection point of view, it results in underestimation of shield thicknesses need to reduce dose to the desired level, especially for higher energy gamma radiation and lower atomic weight elements. In opposite to the well collimated beam, described situation is well characterized by broad beam or "bad" geometry.

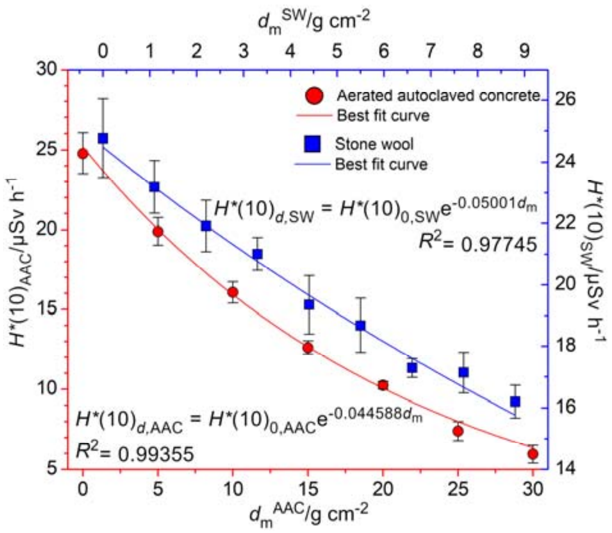

Figure 3. Ambient equivalent dose rate, $H^*(10)$, dependence on the mass thickness (d_m) of the investigated absorbers exposed to ^{60}Co gamma radiation

Figure 3. shows measured values of $H^*(10)$ as a function of different mass thickness of the absorbers of interest exposed to broad beam ^{60}Co gamma radiation along with exponential fitted function, while experimentally determined values of attenuation coefficient and half and tenth value layer thickness are listed in Table 3.

Table 3. Dose attenuation coefficients for absorbers of interest for ^{60}Co gamma rays

Absorber	μ_m/ 10^{-2} cm^{-2}g	μ_l/ 10^{-2} cm^{-1}	$d_{1/2}$/cm	$d_{1/10}$/cm
AAR	4.59 ± 0.14	2.29 ± 0.07	30.2 ± 0.9	100 ± 3
Stone wool	5.00 ± 0.26	0.50 ± 0.03	139 ± 7	460 ± 23

As it is stated in the literature, the difference in attenuation of primary radiation and dose attenuation is usually less than 10 to 15 % for high atomic number materials (Pb, Bi, etc.) and 30 to 40% for materials with a high abundance of elements with lower atomic number (e.g., Al, Fe). This is in consonance with the relative importance of the interactions based on photoelectric effect and Compton scattering in these different materials [6].

Experimentally determined values of mass and linear attenuation coefficient for dose reduction in this work were 15 % and 16 % lower than their values for primary radiation attenuation by AAC and SW, respectively, resulting in 18 % for AAS and 19 % for SW absorbers higher $d_{1/2}$ and $d_{1/10}$ values, respectively.

5. CONCLUSION

The gamma-ray shielding parameters such as half and tenth-value layer thickness, and linear and mass attenuation coefficients were experimentally determined for AAC and SW, two widely used lightweight building materials in Serbia, to define their effectiveness as gamma-ray shielding. The results gained in this study indicated that the shielding properties of the investigated materials against high-energy gamma radiation are inferior in comparison to conventional building materials. Most probably, in the case of nuclear or radiological emergencies involving photon radiation with energies greater than 1 MeV, AAC and SW materials would not provide adequate protection. Nevertheless, the data on their photon attenuation properties gained in this research could be used for practical shielding calculations necessary for establishing radiation safety program for authorized practices and sources within practices in premises already made with this type of materials.

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