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Experimental Investigation of Gamma Radiation Attenuation Coefficients for Kırklareli Marble

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Keywords
Kırklareli marble,
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Total linear attenuation coeffients,
NaI(Tl)

Abstract: The total linear and mass attenuation coefficients, half-value and tenth-value thickness of marble samples from Kırklareli Province have been investigated using different gamma ray energies. Three different gamma ray energies one at 661.7 keV from Cs-137 and others at 1173.2 and at 1332.5 keV from Co-60 have been used. The measurements were carried out using a gamma spectrometer containing a NaI(Tl) sintilation detector. Comparison between the results from measurements and from computer code of XCOM has also been performed with the results available in literature. The measurement results obtained from marble disks and tablets of limestone powder were also matched.

Kırklareli Mermerinin Gama Radyasyonu Zayıflatma Katsayılarının Deneysel Olarak İncelenmesi

Anahtar Kelimeler
Kırklareli mermeri,
Gama radyasyonu,
Toplam lineer zayıflatma katsayısı,
NaI(Tl)

Özet: Kırklareli İli mermer örneği için toplam lineer zayıflatma ve kütle zayıflatma katsayıları, yarı-değer ve onda bir-değer kalınlıkları, farklı gama enerjileri kullanılarak araştırılmıştır. Üç faklı gama enerjisi; biri Cs-137 radyoizotopudan 661.7 keV, diğer ikisi Co-60 radyoizotopudan 1173.2 keV ve 1332.5 keV, olmak üzere kullanılmıştır. Ölçümler gama sintilasyon detektörü NaI(Tl) kullanılarak gerçekleştirildi. Ölçümlerden ve XCOM bilgisayar kodundan elde edilen sonuçlar mukayese edilip, literatür ile de karşılaştırılmıştır. Mermer disklerin ölçümü ile elde edilen sonuçlar, kireç tozu tabletlerinin ölçümünden elde edilen sonuçlar ile de mukayese edildi.

1. Introduction

All living beings are exposed to radiation from natural sources such as cosmic rays, terrestrial radionuclides in soil, water, air and plants; and from artificial sources such as radioactivity from nuclear experiments and medical applications. Therefore radiological measurements and radiation protection are important nuclear studies specifically for nuclear power plants, detector manufacturers, accelerators, and other widespread use of radioactive isotopes in many fields, [1]. The shielding, which is implemented naturally or composite materially, is used widely and effectively for protecting from hazards of radiation. As naturally occurring materials, marbles have been examined widely in terms of gamma attenuation coefficients in literature [2-6] but the survey of Kırklareli marble is absent in literature.

The radiation shielding for any material can be determined in terms of the linear attenuation coefficients μ (cm^{-1}) and defined as the probability of a radiation interacting with a material per unit path length [7]. The attenuation coefficient for γ-ray is determined according to different energies in the medium of interest. The mechanisms of interaction between photons and the medium are: Photoelectric (PE), Compton (C), and Pair Production (PP). As a result, we are able to write the total linear attenuation coefficient (μ_t) as

$$\mu_t = \mu_{PE} + \mu_C + \mu_{PP}. \quad (1)$$

The unit of this coefficient is inverse length (cm^{-1}) for the corresponding energy of a photon per unit length in an attenuating material [8].

The linear attenuation coefficient varies depending on the density of the substance, even though material

*Corresponding auther: nnimetzaim@yahoo.com.tr is the same. The density values of the materials may vary according to the phase. In this context, if the linear attenuation coefficient is also considered to depend on the substance density, this value differs in the cases where different phases of the same material are used. Therefore, mass attenuation coefficient is defined as the ratio of the total linear attenuation coefficient to the material density (ρ) and it does not depend on the physical state of the absorbing material in a given photon energies. For this reason, the mass attenuation coefficient μ_m ($\mu_{t/\rho}$) is widely used to compare materials.

The aim of this work is to determine experimental values of density depended total linear attenuation μ_t and mass μ_m attenuation coefficients of Kırklareli marble for different conditions such as photon energies.

2. Material and Method

In the present investigation, Kırklareli marble was collected from Pınarhisar district in Kırklareli Province located on the northwest part of Turkey. Thickness of the absorber is an important parameter of the degree of attenuation [9]. Marble samples have prepared in 8 different thicknesses, from 0.69 to 2.49 cm, to investigate our material.

Gamma transmission technique with narrow beam method is based on the penetrating gamma rays through materials [10]. The material is placed between the detector and gamma source on the same axis, Figure 1. The detector counts the beam of gamma radiation intensity, which comes from the source trough collimator-1 and -2. First initial baseline intensity in the absence of any materials is counted (I_0), at a specific energy. Then, each material with different thickness are placed between the detector and gamma source, above a lead collimator-2 and the gamma ray intensity is counted (I). The collimators have a 12 mm diameter holes. The result of intensity for each material are then compared with the initial baseline intensity (I/I_0) [11]. The attenuation coefficients are calculated by using Beer-Lamberts Law: $I = I_0 e^{-\mu_t x}$, where x is the thickness of the sample. The relative intensity, $Ln(I/I_0)$ versus thickness of material graphics were drawn, then linear attenuation coefficients (μ_t) and correlation coefficients (R^2) were calculated from the slope of graphics by using computer program namely Origin 9.

Mass attenuation coefficient is more useful than linear attenuation coefficient because the density is negligible and defined as $\mu_m=\mu_t/\rho$ (in $cm^2\ g^{-1}$), where ρ is the measured sample density [12]. The experimental mass attenuation coefficients can be calculated from the given equation. Theoretical mass attenuation coefficients were obtained from XCOM computer code, [13, 14]. XCOM that can be run on a PC computer is a database. To determine mass attenuation coefficients, it uses pre-existing data that are based on cross sections of photoelectric absorption, coherent and incoherent scattering, and pair production at photon energies of 1 keV-1 GeV (Berger and Hubbell, 1987) [15]. The results were examined, evaluated, and compared with the literature. The difference between experimental and theoretical results were clarified for different energies. The density of Kırklareli marble and limestone disk became 2.660 and 2.015 g cm^{-3} respectively.

The gamma-ray photon transmission through the samples were measured using gamma ray spectrometry with a 3''x3'' NaI (Tl) detector to a 13384-channel multichannel analyser. The energy resolution of the spectrometer was 2.1% for the 1332.5 keV gamma ray line of Co-60 (FWHM is 70.44 %). Analysis of the spectrum was performed with a spectrum receiving and analyzing software called ORTEC. Co-60 and Cs-137 point sources were used for the energy calibration of the system with gamma ray energies at 1173.2, 1332.5 and 661.7 keV respectively. The overall uncertainty in counted values was provided by the software and in the range of 2-4%.

Samples are investigated against Co-60 and Cs-137 radioisotope sources. Co-60 has two gamma peaks at 1173.2 keV and 1332.5 keV, Cs-137 has a single gamma peak at 661.7 keV. Co-60 gamma radioisotopes source has activity, 1 µCi and Cs-137 sources have two different activities, 1 and 12 µCi. Accumulation time was 3600 s for both Co-60 and Cs-137 gamma sources. All of the measurements were implemented three times in the same geometry. In experiments, different distances used between detector–sample and sample-source are (4 and 12 cm), (4 and 16 cm) and (8 and 16 cm).

The half value layer (HVL) and the tenth value layer (TVL) of a sample are described to determine the strength of gamma ray shielding. The HVL and TVL are the thicknesses of a sample that will decrease the intensity of primary photon beam in order of half, and tenth. These can be calculated [15]:

$$\mathrm{HVL} = \frac{ln2}{\mu_t},\quad \mathrm{TVL} = \frac{ln10}{\mu_t} \qquad (2)$$

The samples from limestone powder were produced by using hydraulic cold press under 40 MPa pressure. The average limestone particle size is less than 200 µm. The scanning electron microscope (SEM) views of samples are shown in Figure 2.a and 2.b. These pictures may explain small differences in measurements of the samples. However, compressed limestone samples are not durable, broken quickly, and investigated only at (4 and 12 cm) geometry, Table 1.

Table 1. Measured total linear and mass attenuation coefficients for Kırklareli marble and limestone sample and comparison between measured and theoretical values of mass attenuation coefficients at different energies Co-60 and Cs-137 radiosotopes gamma sources and geometries.

Energy (keV) and activity	(4-12) cm	(4-16) cm	(8-16) cm	μ_t (aver.) ±SD(cm^{-1})	μ_m ($cm^2\ g^{-1}$)	μ_m (XCOM)	
661.7 (1 µCi)	-	-	-0.21165 ±0.01482	0.19925 ±0.00563	0.07491	0.07749	
661.7 (12 µCi)	-0.20138 ±0.00216	-0.18509 ±0.00192	-0.19888 ±0.00362				
1173.2 (1 µCi)	-0.20755 ±0.0087	-0.1769 ±0.0105	-0.18503 ±0.00906	0.18983 ±0.00942	0.07136	0.05889	Kırklareli marbles
1332.5 (1 µCi)	-0.13547 ±0.0126	-0.1156 ±0.0121	-0.15033 ±0.01105	0.1339 ±0.01192	0.0503	0.05519	
661.7 (1 µCi)	-0.22979 ±0.00844	-	-	**-0.23013 ±0.00634**	**0.11427**	**0.07749**	
661.7 (12 µCi)	-0.23047 ±0.00424	-	-				
1173.2 (1 µCi)	-0.16264 ±0.0142	-	-	-	0.0807	0.05889	Compressed limestone samples
1332.5 (1 µCi)	-0.11034 ±0.00669	-	-	-	0.05477	0.05519	

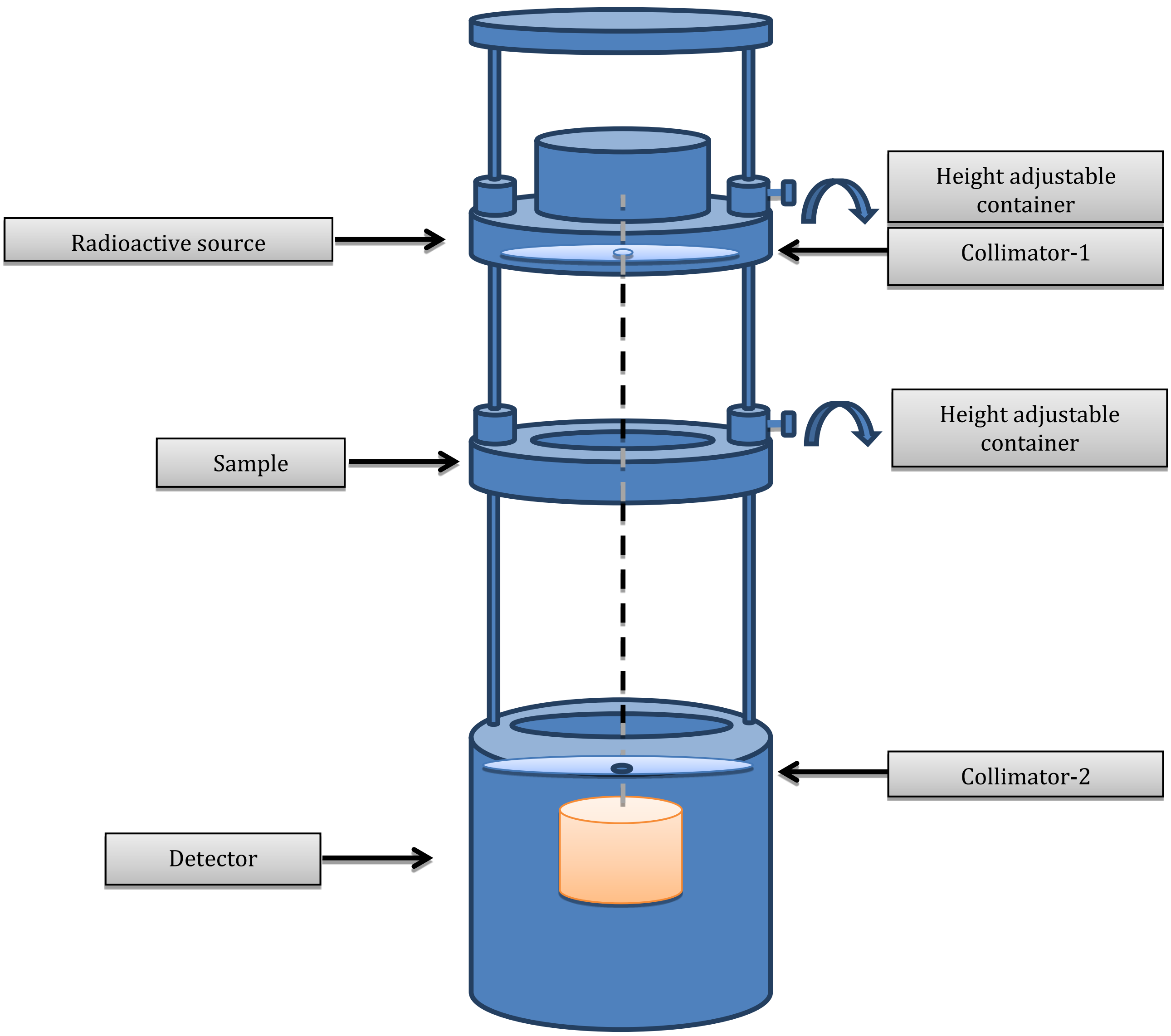
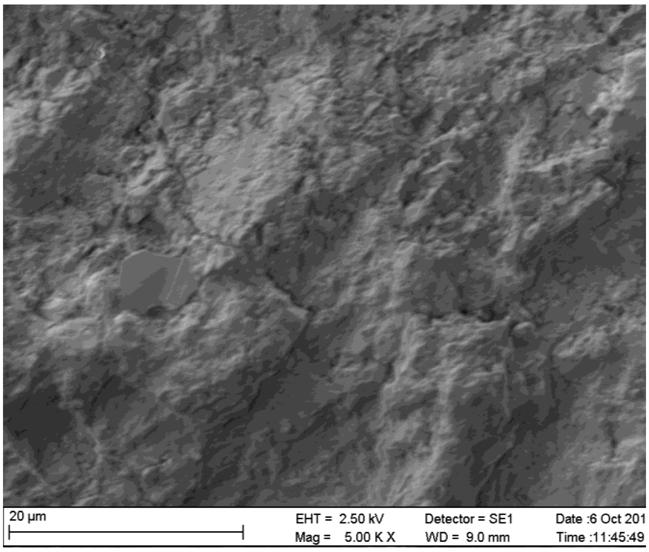
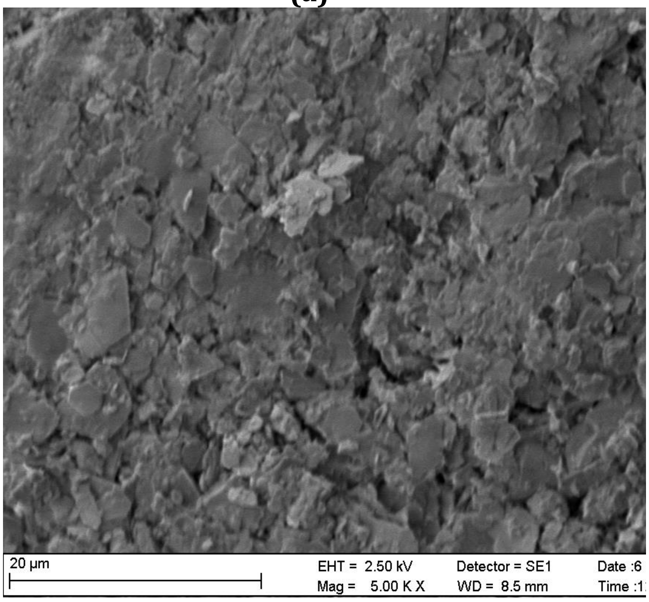


Figure 1. Experimental setup for measuring linear attenuation coefficients



(a)



(b)

Figure 2. (a). The SEM of Kırklareli marble **(b)** The SEM of limestone sample

3. Results

The linear and mass attenuation coefficients, with the half and tenth value layer have been measured at photon energies of 661.7, 1173. 2 and 1332.5 keV for Kırklareli marble in Turkey. The results were also tabulated in Table 1.

In experiments, when the distance between detector–sample and sample-source were chosen as (4 and 12 cm), (4 and 16 cm) and (8 and 16 cm) for 1173.2 keV gamma line, linear attenuation coefficient (μ_t) were measured as 0.20755±0.0087, 0.1769±0.0105 and 0.18503±0.00942 cm^{-1} respectively, mean value was 0.18983±0.00942 cm^{-1} with standard deviation of 0.013 and for 1332.5 keV gamma line (μ_t) were measured as 0.13547±0.0126, 0.1156±0.0121 and 0.15033±0.01105 cm^{-1} respectively, mean value was 0.1339±0.01192 cm^{-1} with standard deviation of 0.014. The same surveys were repeated for 661.7 keV gamma line with 12 µCi activity at the same geometries, the measured linear attenuation coefficient were 0.20138±0.00216, 0.18509±0.00192, 0.19888±0.00362 cm^{-1} respectively and with 1 µCi activity at only (8 and 16 cm) location linear attenuation coefficient was 0.21165±0.01482 cm^{-1}, mean value was 0.19925±0.00563 cm^{-1} with standard deviation of 0.009, as shown in Table 1. The uncertainty for linear attenuation coefficients was found about 5% for samples.

The values of experimental mass attenuation coefficient (μ_t/ρ) with their uncertainties, in marble samples were determined as shown in Table 1, together with theoretical values, determined from the XCOM database. The experimental results were for 1173.2, 1332.5 and 661.7 keV, 0.07136, 0.0503 and 0.07491 cm^2 g^{-1} respectively.

The measured linear and mass attenuation coefficients versus photon energy have been displayed in Figure 3 for Kırklareli marble. As it can easily be observed that the linear attenuation coefficients decreases with the rising gamma energy. This is due to, in these energy regions, the three photon-matter interaction processes: 1- The photoelectric absorption dominate below 100 keV, 2- Compton scattering dominate between 100 keV-5 MeV and 3- pair production dominate above 5 MeV [15]. It is observed that, at the beginning, μ_t of marble sample decreases slowly and then sharply in the medium energy region. This happens because of the Z-dependence of different photon interactions, and we can say that Z-dependence of Compton scattering is dominant in this region [16]. As expected, mass attenuation coefficients for marbles varied more slowly than linear attenuation coefficients.

The transmission rate of Kırklareli marbles as a function of thickness of material for different geometries has been displayed in Figure 4. As we see from these figures, minor changes in positions do not have much effect on the results. And R^2 were founded 0.99 at 661.7 keV for 12 µCi and 0.82 at 661.7 keV for 1 µCi, while about 0.90 at 1173.2 keV and over 0.80 at 1332.5 keV for 1 µCi. In Figure 4, some degree of spreading could be observed between 0.5-1 cm thickness of the sample. This is because the absorption is weak due to the thickness especially at (4-16) cm, distances between sample and source.

The linear attenuation coefficient (μ_t) measurements of Kırklareli marble was compared to limestone powder sample which has almost the same chemical structure after compression. Observed values of linear and mass attenuation coefficients, HVL and TVL displayed in Table 1. The results, at (4-12) cm location, for 1173.2 keV, linear attenuation and mass attenuation coefficients were 0.16264±0.0142 cm^{-1}, 0.0807 cm^2 g^{-1} and for 1332.5 keV linear attenuation and mass attenuation coefficients 0.11034±0.00669 cm^{-1}, 0.05477 cm^2 g^{-1} respectively (Table 1). At the same location, for 661.7 keV, at 1 µCi and 12 µCi, linear attenuation coefficients were 0.22979 cm^{-1} and 0.23047 cm^{-1} respectively and, average linear and mass attenuation coefficient also were 0.23013 cm^{-1} and 0.11427 $cm^2\ g^{-1}$. As we observe in Table 1, there are slight differences in terms of lineer attenuation coefficients for two samples.

When the mass attenuation coefficients in the marble were compared with results from XCOM, the slight differences were observed at 661.7 keV and 1332.5 keV energies, but the difference at 1173.2 keV were larger than others were. Differences between experimental results and results from XCOM at 661.7, 1173.2 keV for limestone samples were important. This is possibly due to the compositional variation and the density differences among the marble samples. However, for limestone samples, variation of the density may occur with the effect of pressure while preparing samples under high compression [6].

The HVL and TVL values for investigated materials have been calculated from the measured linear attenuation coefficients at photon energies 661.7 keV, 1173.2 keV and 1332.5 keV and the results were displayed in Table 2. The HVL results, for marbles are 3.48, 3.65 and 5.18 cm; the TVL results are 11.56, 12.13 and 17.20 cm at 661.7, 1173.2 and 1332.5 keV respectively. It is clear that the low-energy photons lose their energies at short distances while a long distance is needed for high-energy photons to lose theirs.

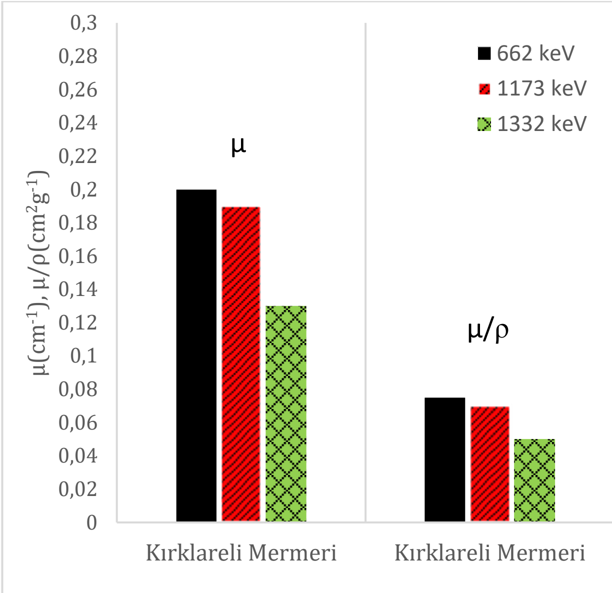
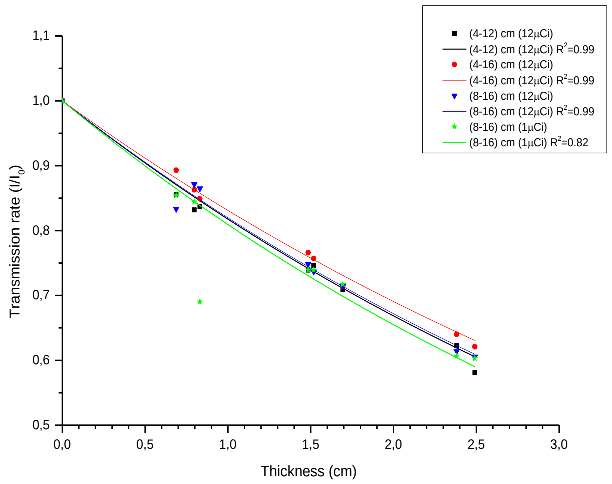


Figure 3. The variation of the linear and mass attenuation coefficients with the energy at 662, 1173, 1332 keV for Kırklareli marble

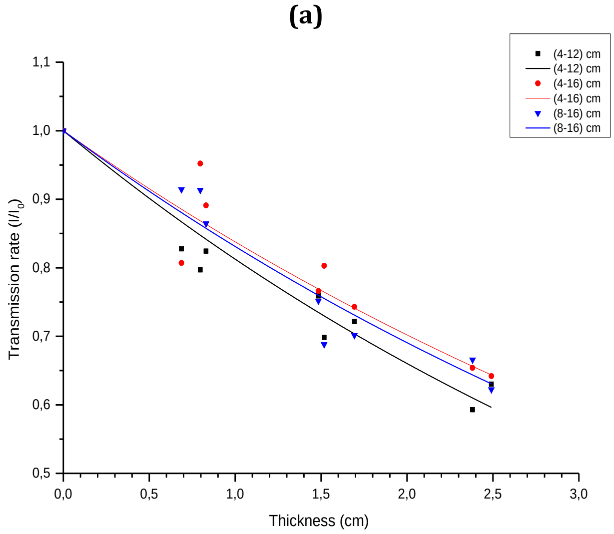
Table 2. Total linear and mass attenuation coefficients, HVL, TVL values of the studied materials, comparison with the literature values

Samples	661.7 keV				1173.2 keV				1332.5 keV			
	μ_t (aver.) (cm^{-1})	μ_m ($cm^2\ g^{-1}$)	HVL (cm)	TVL (cm)	μ_t (aver.) (cm^{-1})	μ_m ($cm^2\ g^{-1}$)	HVL (cm)	TVL (cm)	μ_t (aver.) (cm^{-1})	μ_m ($cm^2\ g^{-1}$)	HVL (cm)	TVL (cm)
Kırklareli Marble [present work]	0.1993	0.07491	3.48	11.56	0.18983	0.07136	3.65	12.13	0.1339	0.0503	5.18	17.20
Limestone [present work]	0.2301	0.11427	3.01	10.01	0.16264	0.0807	4.26	14.16	0.11034	0.05477	6.28	20.87
Finike White Marble [2]	0.189	-	-	-	-	-	-	-	0.1177	-	-	-
Marble (Turkey) [6]	-	0.075	-	-	-	0.057	-	-	-	0.053	-	-
Granite (Nero) [20]	0.214	-	-	-	0.161	-		-	0.132	-	-	-
Concrete (20% Isparta marble) [5]	0.1882	-	-	-	0.1198	-	-	-	0.1388	-	-	-
Concrete (different aggregates) [20]	0.212-0.266	-	-	-	-	-	-	-	0.1020-0.1495	-	-	-
Concrete (0% barite) [21]	0.257	-	-	-	0.174	-	-	-	0.165	-	-	-
Building material (in Egypt) [23]	-	0.061-0.072	-	-	-	0.050-0.058	-	-	-	0.050-0.053	-	-
Shielding concretes (in Syria) [17]*	0.146-0.189	-	3.67-4.75	12.18-15.77	0.124		4.33-5.59	14.39-18.57	-	-	-	-
Shielding concrete [22]*	0.1838-0.4004	0.07825-0.08058	-	-	0.1320-0.2791	0.05462-0.05741	-	-	-	-	-	-
Building material (Jordanian) [18] Limestone	0.217	0.086	3.197	-	0.171	0.068	4.073	-	0.140	0.055	4.963	-
Building material (Jordanian) [18] Concrete	0.138	0.073	5.051	-	0.123	0.066	5.631	-	0.112	0.060	6.198	-
Building material (Jordanian) [18] Bricks	0.148	0.078	4.698	-	0.138	0.072	5.039	-	0.108	0.057	6.410	-

*Values are for 662 and 1250 keV gamma lines energies



(a)



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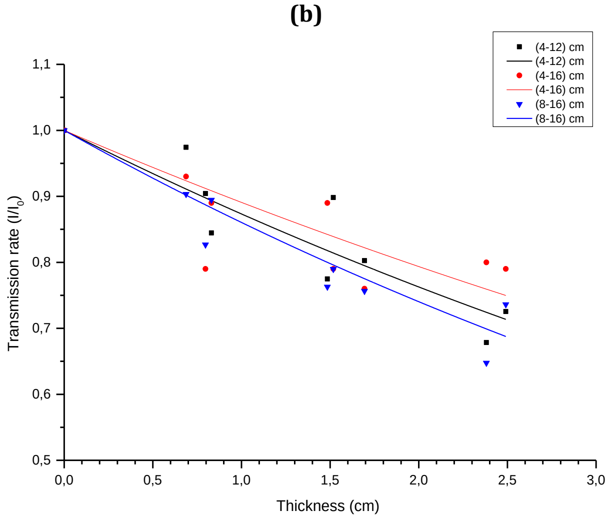

(c)

Figure 4. The radiation transmission rate as a function of thickness of Kırklareli marble at 662 keV **(a)**, 1173 keV **(b)** and 1332 keV **(c)** photon energy for different geometries

4. Discussion

Many studies were conducted with the literature dealing with linear attenuation coefficients of marble and other construction materials that are important for building. In order to test our investigations, we compared them with the marbles and building materials in the literature and displayed them in Table 2. By comparing with the published results, we observed that the linear attenuation coefficients for the Kırklareli marble is greater than Finike White marble [2], concrete with 20% Isparta marble[5], shielding concrete (in Syria) [17], building material (concrete, bricks Jordanian) [18] and less than granite (nero) [19], concrete (different aggregates) [20], concrete (0% barite) [21] and building material (limestone, Jordanian) [18] for 661.7 keV gamma ray. The same coefficient is greater than all coefficients except shielding concrete in Bashter's work [22], for 1173.2 keV. At the same time, it is higher than all of the coefficients except concrete (0% barite) [21] and limestone (Jordanian) [18] for 1332.5 keV gamma ray. In addition, the compressed limestone sample is suitable photon attenuator in terms of linear attenuation coefficient at the lower energy region.

The mass attenuation coefficient values for Kırklareli marbles are higher than building material (in Egypt) [23] and concrete (Jordanian) [18] for 661.7 keV, but it is lower than bricks (Jordanian) [18] for 1173.2 keV. It is also lower than all coefficients in these references for 1332.5 keV.

HVL is better than the values in this references for 1173.2 keV, while it is better than the values in this references except of (limestone, Jordanian) [18] for 661.7 keV and 1332.5 keV gamma ray. TVL values studied for different gamma line energies also have satisfying results.

The results of shielding parameters as a function of photon energy were displayed in Table 2, where one can easily see that limestone samples also have the photon attenuation coefficients at low photon energy.

5. Conclusion

- Kırklareli marble and compressed limestone samples were studied for γ-ray attenuation.
- It is clear from the results in the Table 2 that there are slight differences between the measured values of Kırklareli marble and the corresponding values in the references. This implies that marble can be used as a building material for radiation shielding.
- The limestone sample seems to be useable as gamma radiation shielding material when we compare it to the Kırklareli marble and contraction materials in the references.
- Kırklareli marble or cheaper limestone aggregates can be mixed in concrete to obtain construction materials with better shielding properties.
- The measurements at the small variations in geometries point out that different geometry do not affect the results and the linear attenuation coefficients. It is strongly depending on geometry of source to sample and sample to detector (related to scattering of radiation).

- Finally, we observed that the linear attenuation coefficients decreases with the increasing gamma energy. It is the general concept and not a new finding.

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