γ-Radiation Shielding Properties of High Strength High Performance Concretes Prepared with Different Types of Normal and Heavy Aggregates

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***Abstract*— This paper presents an experimental study on the gamma ray radiation shielding properties of normal and heavy high performance concretes (HPCs). HPCs were produced with different low water-to-cementitious materials ratios (w/cm) and tested for 0.663 MeV γ-rays energy of ^{137}Cs radioactive using NaI(Tl) scintillation detector. It was observed in this research that the compressive strength of heavy HPCs plays an important role in enhancing the attenuation of gamma rays. The compressive strength and attenuation of gamma rays in heavy weight HPCs have a near to linear relation. On the other hand, it was also found that the compressive strength of the normal concrete has almost no effect on the attenuation of gamma rays. The Linear and mass attenuation coefficients were calculated and compared with the past research and a good agreement has been found. However, the HPCs density considerably affects the attenuation of gamma rays. With the increase in the density, the attenuation coefficients increases linearly. This endorse that the relationship between the HPC density and the gamma attenuation coefficients is linear.**

***Index Term*— Aggregate types, attenuation coefficients, compressive strength, high performance concrete, water-to-cementatious materials ratio.**

I. INTRODUCTION

High performance concrete (HPCs) is a concrete meeting special combinations of performance and uniformity requirements that cannot be achieved routinely using conventional constituents and normal mixing, placing, and curing practices as per ACI [1]. It can be produced from normal and heavy weight aggregates with or without supplementary cementitious materials (SCM). The material properties of high performance concrete (HPC) directly affect the design and construction of HPC structural members. Therefore the selection of aggregates must be done carefully and closer control of aggregate quality with respect to grading and maximum size is necessary [2]. One of the HPCs is heavyweight concrete. It is defined as concrete with unit weight ranging from 2900 to 6000 kg/m^3 while unit weight of normal weight concrete varied between 2200 and 2450 kg/m^3 [3], [4], [5]. According to PCA [6], HPCs almost always has a higher strength than normal concrete.

In the nuclear power plants, medical units, and in structures where radioactive impermeability is required, the concrete is used widely as radiation shielding material because of its low price and good shielding performance. Heavyweight concrete is used principally for radiation shielding for the prevention of seepage from radioactive structures and protects against the harmful effects of X-rays, gamma rays…etc. [7], [6]. Overall, heavyweight concrete has been used where it is necessary to reduce the thickness of radiation shielding, generally because of space considerations [8], [9], [10], [11], [12], [13]. According to Lee, et al. [14] the aggregate of concrete plays an essential role in modifying physical-mechanical properties of concrete; it also affect significantly shielding properties of concrete [2], [6], [15]. In general, a number of theoretical and experimental studies have been conducted on heavy concretes [16], [17], [18], [19], [20], [21], [22].

Yılmaz et al. [9] measured the attenuation coefficients of gamma rays of 12 concrete samples with and without supplementary cementitious materials, at energies of 59.5 and 661 keV. Demir et al. [8] experimentally found that the linear attenuation coefficients (μ) decrease with the increasing the photon energy for their concretes and the linear attenuation coefficient depends on photoelectric effect and Compton scattering at this energy. He also concluded that barite was effective at 663 keV.

Enormous work regarding design and development of high performance concrete for containment structures is available in the literature [23]-[30]. In addition, the shielding properties were measured for different types of concrete [31]-[37]. Nevertheless, the effect of the strength of HPC with the use of lower water-to-cementitious materials ratios (w/cm), supplementary cementitious materials (SCM) and heavy weight aggregate together on gamma shielding properties is still limited. Therefore, this investigation aims at production of different types of normal and heavy HPC from different materials in order to calculate the linear and mass attenuation coefficients for each in terms of effect of the HPCs compressive strength as one of the main mechanical properties of the concrete.

This paper is a part of a research project supported through the NPST program by King Saud University, Project No. 08-ADV208-02.

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In this paper, the radiation transmission measurement has been conducted for normal and heavy HPC carried out with different low w/cm ratios (0.30-0.4) for 0.663 MeV energy of ^{137}Cs radioactive isotope by using NaI(Tl) scintillation detector and linear and mass attenuation coefficients were calculated. All the results have been compared with past research and X-ray mass attenuation coefficient values of NIST [38]. In addition, the effect of the compressive strength on the attenuation of gamma rays also was investigated.

II. EXPERIMENTAL WORK

A. Materials and sample preparation

The material properties of HPC ingredients, mix design as per ACI 211.4R [39] and procedures for strength of HPC are discussed in this section. Type I ordinary Portland cement from Yammama cement plant located in Riyadh in compliance with the requirements of ASTM C150 [40] has been used. Table 1 shows the chemical composition and physical characteristics of the cement. Micro silica with specific gravity of 2.27 is the mineral admixture was used in this investigation for all the mixtures. Chemical composition and Physical characteristics of micro-silica used in this research met the requirements of ASTM C1240 [41] as listed in Table II.

TABLE I
CHEMICAL COMPOSITION AND PHYSICAL CHARACTERISTICS OF CEMENT (TYPE-I OPC)

Chemical Composition	(mass %)	Physical characteristics	
SiO_2	19.96	Specific gravity	3.15
Al_2O_3	5.99	Consistency	23.7%
$Fe2O_3$	3.59	Initial setting time	50 mins
CaO	62.75	Final setting time	350 mins
MgO	0.59		
SO_3	2.73		
Alkalies	0.2		
C_3S	50.6		
C_2S	19.1		
C_3A	9.8		
C_4AF	10.9		

The water-to-cementitious materials ratio (w/cm) was varied from 0.30-0.40 for the experimental program so that the effect of compressive strength can be investigated deeply under the influence of different water to cementitious materials ratios. A high performance concrete superplasticiser (Glenium 51, a product of the BASF company, Saudi Arabia) based on modified polycarboxylic ether was employed as chemical admixture having relative specific gravity of 1.1 to make the HPC workable [42]. It is compatible with all types of cement. Five types of coarse aggregates (designated as 'RY', 'MK', 'AB', 'BR' and 'HM') and two sources of fine aggregate (designated as 'RN' and 'CR') with micro-silica (designated as 'S') have been investigated in this research.

The three normal weight coarse aggregates were taken from three different sources of Saudi Arabia, namely Riyadh Makkah and Abha located far apart from each other. Aggregate 'RY' is the most commonly used local aggregate, primarily used in the central region of Saudi Arabia and is composed of limestone, also known as calcium carbonate. Aggregate 'MK' is a mixture of quartz and basalt with the additions of plagioclase and chlorite minerals. The third type of aggregate named 'AB' in this research is of Meta sediment rock origin composed primarily of quartz along with some biotite contamination and schist layers, especially in the cracks.

TABLE II
CHEMICAL COMPOSITION AND PHYSICAL CHARACTERISTICS OF MICRO-SILICA

Chemical Composition	(mass%)	Physical characteristics	
(SiO2)	93.2	Specific gravity	2.27
(Al2O3)	<0.01	Density (mg/m3)	2.13
(Fe2O3)	0.05	Moisture content %	0.20
(CaO)	0.72		
(MgO)	0.14		
(SO3)	<0.01		
(Cl)	0.03		
(Na2O)	0.07		
(K2O)	0.15		
Loss on Ignition @ 950 oC	5.4		
$\frac{Calculated \quad compounds \ \& \ others}{Available \quad Alkalies \ (Na_2O + 0658 \ k_2o)} = 0.17$			

The remaining two types of coarse aggregate 'BR' and 'HM' are of heavy weight in nature and were imported from Belgium for the research under consideration. The aggregate 'BR' is a mineral consisting of barium sulfate ($BaSO_4$). The barite group consists of barite, celestine, anglesite and anhydrite. Barite itself is generally white or colorless, and is the main source of barium. The second type of heavy weight aggregate 'HM' consisted the mineral form of iron (III) oxide (Fe2O3), one of several iron oxides. Hematite crystallizes in the rhombohedral system, and it has the same crystal structure as ilmenite and corundum. The coarse aggregate 'HM' was a mineral colored reddish brown as the main ore of iron composed of friable material with light magnesium tinged and black streaked.

The maximum particle size of normal coarse aggregate was kept constant at 20 mm in all normal HPC mixtures. It was also separated into two size fractions, 5-10 mm and 10-20 mm. Hematite and barite were varied between 20 and 25mm and their fractions were 0-25 and 0-20 mm respectively. In the heavy mixtures the weight has been taken once and all the experimental calculations have been done to find the percentage of each mix.

TABLE III
AGGREGATE MATERIAL PROPERTIES

Aggregate	Relative specific gravity	Water absorption capacity (mass %)	Unit weight (kg/m^3)	Voids (%)	Moisture content (%)
CR (3-5mm)	2.60	1.43	1604	38.06	0.55
RN (0-3mm)	2.60	0.93	1720	33.89	0.15

RY (10-20 mm)	2.61	1.10	1550	39.83	0.32
RY (5-10 mm)	2.62	1.30	1575	38.87	0.59
MK (10-20 mm)	2.70	1.15	1681	36.86	0.49
MK (5-10 mm)	2.73	1.55	1683	42.53	0.36
AB (10-20 mm)	2.77	0.85	1623	40.74	0.17
AB (5-10 mm)	2.76	1.82	1683	37.87	0.32
BR (0-25mm)	4.06	0.65	3020	25.00	0.13
HM (0-20mm)	4.67	1.36	3326	27.65	0.10

The two normal weight fine aggregates were also taken from two different parts of Riyadh city. Aggregate ‘RN’ is natural and has whitish color with size of 0-3mm. It is one of the most commonly used local fine aggregate in Riyadh city. The second type of fine aggregate named ‘CR’ in this research is 3-5 mm in size and also whitish in color produced by crushing the sedimentary stones. It is used in mix with RN sand to obtain finesses modulus of the fine materials in compliance with ASTM requirements [43]. The physical properties of HPC ingredients used in this research were determined according to ASTM C33 [43] standards are given in Table 3. Three different series of HPC named as CS-1, 2 and 3 have been made using three low w/cm of 0.30, 0.35 and 0.40 respectively. Each series consisted of three normal and two heavy HPC produced from RY, MK and AB normal aggregates and BR and HM as heavy aggregates respectively. For each series of mixtures, cementitious materials quantity and water-to-cementitious ratio was kept constant and five mixtures made. For w/cm of 0.3, 0.35 and 0.40, the cementitious materials quantity was 500, 450, 400 kg/m^3 respectively. 10% micro-silica was used as cement replacement. The three series of mixtures were named as CS-1: RY/MK/AB/BR/HM-W30-S10, CS-2: RY/MK/AB/BR/HM-W35-S10 and CS-3: RY/MK/AB/BR/HM-W40-S10. Proportions of all mixtures ingredients used in this study were designated with ACI-211.4R [39] and given in the tables IV (a), (b) and (c).

TABLE IV

MIX PROPORTIONS OF HPC MIXTURES

(A) CS-1

Component	Unit weight (kg/m^3)				
	RY-W 30-S10	MK-W 30-S10	AB-W 30-S10	BR-W 30-S10	HM-W 30-S10
Cement	450	450	450	450	450
Micro-silica	50	50	50	50	50
Water	161.19	165.24	167.83	160.91	186.98
FA (CR-Sand)	240.04	228.81	238.58	-	-
FA (RN-Sand)	445.80	424.93	443.08	-	-
RY (5-10 mm)	739.02	-	-	-	-
RY (10-20 mm)	316.72	-	-	-	-
MK (5-10 mm)	-	792.02	-	-	-
MK (10-20 mm)	-	339.62	-	-	-
AB (5-10 mm)	-	-	783.25	-	-
AB (10-20 mm)	-	-	335.68	-	-
BR (0-25 mm)	-	-	-	2706.9	-
HM (0-20 mm)	-	-	-	-	3004.7
Admixtures GL-51	4.125	3.190	3.135	8.250	5.225

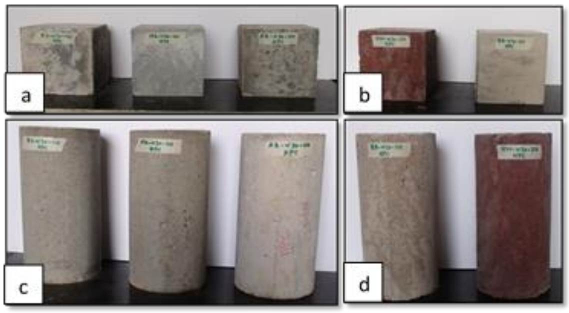
(B) CS-2

Component	Unit weight (kg/m^3)				
	RY-W 35-S10	MK-W 35-S10	AB-W 35-S10	BR-W 35-S10	HM-W 35-S10
Cement	405	405	405	405	405
Micro-silica	45	45	45	45	45
Water	169.39	173.14	175.66	169.10	195.53
FA (CR-Sand)	249.52	237.62	247.22	-	-
FA (RN-Sand)	463.39	441.30	459.13	-	-
RY (5-10 mm)	739.02	-	-	-	-
RY (10-20 mm)	316.72	-	-	-	-
MK (5-10 mm)	-	792.44	-	-	-
MK (10-20 mm)	-	339.62	-	-	-
AB (5-10 mm)	-	-	783.25	-	-
AB (10-20 mm)	-	-	335.68	-	-
BR (0-25 mm)	-	-	-	2745.4	-
HM (0-20 mm)	-	-	-	-	3047.1
Admixtures GL-51	2.475	2.340	2.475	6.300	3.600

(C) CS-3

Component	Unit weight (kg/m^3)				
	RY-W 40-S10	MK-W 40-S10	AB-W 40-S10	BR-W 40-S10	HM-W 40-S10
Cement	360	360	360	360	360
Micro-silica	40	40	40	40	40
Water	172.41	176.15	178.84	172.69	199.22
FA (CR-Sand)	262.98	251.07	261.05	-	-
FA (RN-Sand)	488.39	466.27	484.81	-	-
RY (5-10 mm)	739.02	-	-	-	-
RY (10-20 mm)	316.72	-	-	-	-
MK (5-10 mm)	-	792.44	-	-	-
MK (10-20 mm)	-	339.62	-	-	-
AB (5-10 mm)	-	-	783.25	-	-
AB (10-20 mm)	-	-	335.68	-	-
BR (0-25 mm)	-	-	-	2805.5	-
HM (0-20 mm)	-	-	-	-	3110.6
Admixtures GL-51	1.880	1.760	1.480	4.400	2.800

All mixtures were prepared in a rotary planetary mixer with capacity of 180 L. The coarse and fine aggregate and one third of the water were measured and placed into the mixer and mixed for 1 minute. After that the cement, micro-silica, super-plasticizer and the rest of the water were added and mixed for three minutes, followed by a 3 minutes rest. Finally after a 3-minutes rest, another 3-minutes mixing were followed. To determine whether the target slump has been reached, the slump test was performed as per ASTM C143 [44]. In this study, the slump of all concrete mixtures ranged between 150 and 200mm. After the mixing procedure was completed, the concrete was cast in standard 150 mm cubic and plastic cylinders of size 150 φ x 300 mm as per ASTM C31 [45]. Each mold was filled to half of its height, then placed on the vibrating table for 25 seconds, and then filled completely. From each HPC mixture, several 150 mm cubic concrete specimens for radiation test as shown in Fig. 1 (a) and (b). The standard cylinders of 150 mm φ x 300 mm height to run the compressive strength test were also produced. Refer to Fig. 1 (c) and (d) for further details. The specimens in the molds were stored in the laboratory environment at standard room temperature for the first 24 h followed by de-molding and then water cured under standard conditions until the age of testing.



a)150 mm normal HPCs Cubes for radiation test; b) 150 mm heavy HPCs Cubes for radiation test; c) 150 mm φ normal HPCs cylinders for compressive strength test; d) 150 mm φ heavy HPCs cylinders for compressive strength test;

Fig. 1. Concrete specimens produced from normal and heavy HPCs in three series

B. *Testing procedure*

1. *Radiation Apparatus*

The arrangement of experimental set up and test block diagram describing all the parts of the measuring system used in the test are shown in Fig. 2. The radioactive source used in this study to carry out radiation tests was ^{137}Cs with energy of 0.663 MeV. NaI(Tl) scintillation detector housed in a 16 mm thick lead jacket with a 5 mm diameter holed collimator has been used to measure the intensities of γ-rays. The attenuation coefficients for γ-ray of ^{137}Cs source was calculated from Lambert's law (see equation 1) [46] and measured using narrow beam experimental setup.

$$N = N_0 e^{-\mu_{linear} x} \qquad (1)$$

Where, μ_{linear} is gamma-ray linear attenuation coefficient; N_0 is the intensity of first measurement without specimen; N is the intensity passing the specimen and x is the thickness of the specimen. By taking natural logarithm both sides of Eq. (1), the linear equation can be obtained:

$$\ln \mathrm{N} = \ln N_0 \, (-\mu_{linear} x) \qquad (2)$$

The total mass attenuation coefficients, μ_t, are also given as follows:

$$\mu_t = \frac{\mu_{linear}}{\rho} = \left(\frac{1}{\rho . x}\right) \ln\left(\frac{N_0}{N}\right) \quad (cm^2 / g) \qquad (3)$$

Where, ρ is the density of the sample.

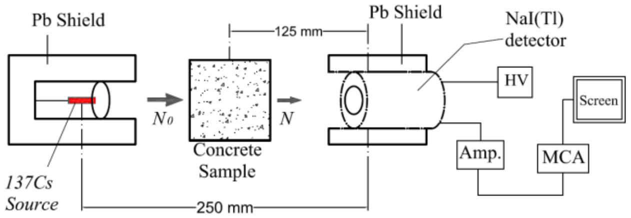
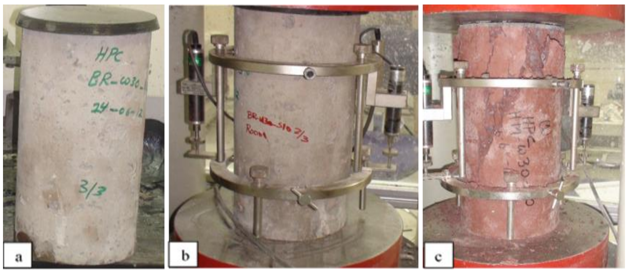


Fig. 2. Experimental setup for gamma radioactive test

Using the digital counter, the incident gamma beam with the intensity of N_0 applied perpendicularly without specimen was measured. After that, the measuring of the intensities of gamma beam N passed the HPC specimens were computed. In this study, the counts N_0 and N were measured carried out on 150 mm cubic HPC specimens for each mixture at the same time and under the same experimental and environmental conditions avoiding any inconsistency. From these measurements, the calculations of linear (μ_{linear}) and total mass attenuation (μ_t) coefficients were computed by means of Eq. 2 and 3 respectively.

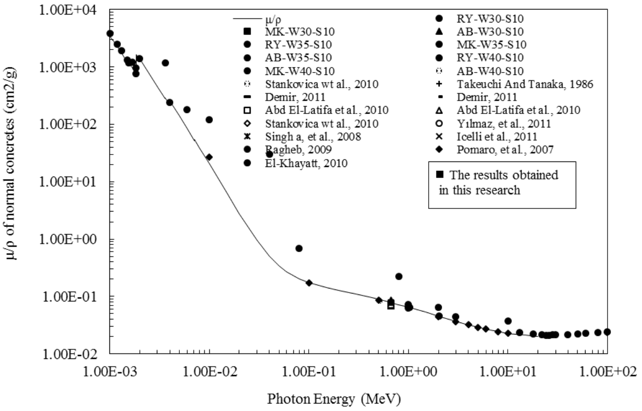


a) Capping of cylinder b) cylinder under compression test c) failed cylinder after test

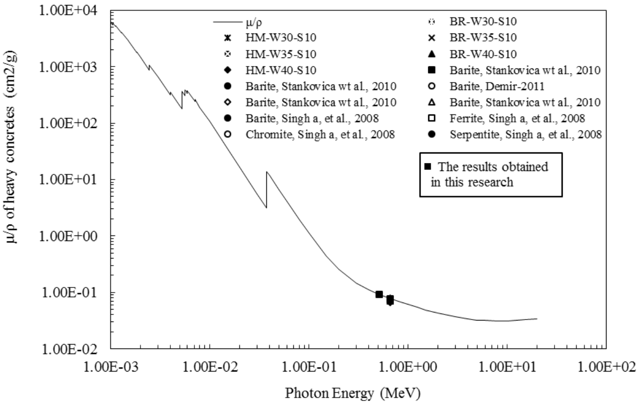
Fig. 3. Capping and test set-up for performing compressive strength test

2. *Compressive strength test*

At the age of testing, the specimens were taken out from the curing tank and were end capped with a capping compound material as in Fig. 3 (a). The compression test is conducted on the hardened concrete cylinders [47] as shown in Fig. 3 (b) and (c).



(a) Normal Concrete



(b) Heavy concretes

Fig. 4. Comparison of mass attenuation coefficients with past research plotted using NIST curve

To perform compression tests a 3000 kN capacity machine was used. All test specimens for a given test age were broken within the permissible time tolerances as prescribed by ASTM C 39 [47]. Before testing, capping of all the specimens was done at the top and bottom faces to take care of the surface roughness. The upper and lower surfaces of bearing blocks of the compression testing machine and the test specimen were wiped and cleaned. The test specimens were placed on the lower bearing block and carefully aligned with the axis of the specimen with the center of thrust of the spherically seated block (see Fig. 3). The load was applied until the specimen failed and the maximum load carried by the specimen during the test was recorded. The type of failure and the appearance of the concrete specimen after testing were also taken into consideration.

III. RESULTS AND DISCUSSIONS

The linear and mass attenuation coefficients (μ) for all the three HPC series have been measured and calculated at photon energy of 0.663 MeV and compared to the past research [8], [9], [15], [16], [17], [38] and [49]. The measured results are listed in tables 5 (a), (b) and (c). It can be seen that the highest mass attenuation coefficient values at 0.663 MeV γ-ray energy obtained from heavy HPCs (BR and HM) and they are close to X-ray mass attenuation coefficient values of NIST [38]. The mass attenuation coefficient value of the barite concrete (BR-W30-S10) is 0.0746 cm^2/g at 0.663 MeV γ-ray energy and the value of NIST is 0.0825 at 0.600 MeV. Among all normal HPCs, the HPC containing 'AB' aggregate obtained the highest density and highest mass attenuation values. It has also a good agreement with the values obtained by NIST for ordinary concrete. The mass attenuation coefficients obtained for normal and heavy HPCs in this research and for different concretes testes in the past research have been plotted for comparison on the graph created by NIST as shown in Figs. 4 (a) and (b). The mass attenuation coefficients values coincides with each other and very close to the curve. In the Figs. 4 (a) and (b), the raw indicate to the results of this research. The comparison with results found in the literature for similar concretes showed good agreement.

TABLE V
UNIT WEIGHT, LINEAR AND MASS ATTENUATION COEFFICIENTS AT 0.663 MEV Γ-RAYS OF HPC SERIES TESTED IN LAB CONDITIONS
(A) CS-1

Mix Ref.	Unit weight (gm/cm^3)	Linear atten. coef. (cm^{-1})	Mass attenuation coef. (cm^2/g)	
			Results of this research	NIST results
		0.663 MeV	0.663 MeV	0.600 MeV
RY-W30-S10	2.407	0.1672	0.0695	0.0824
MK-W30-S10	2.454	0.1698	0.0692	
AB-W30-S10	2.472	0.1788	0.0723	
BR-W30-S10	3.376	0.2519	0.0746	0.0825
HM-W30-S10	3.697	0.2661	0.0720	

(B) CS-2

Mix Ref.	Unit weight (gm/cm^3)	Linear atten. coef. (cm^{-1})	Mass attenuation coef. (cm^2/g)	
			Results of this research	NIST results
		0.663 MeV	0.663 MeV	0.600 MeV
RY-W35-S10	2.391	0.1622	0.0678	0.0824
MK-W35-S10	2.437	0.1696	0.0696	
AB-W35-S10	2.454	0.1764	0.0719	
BR-W35-S10	3.372	0.2446	0.0725	0.0825
HM-W35-S10	3.697	0.2578	0.0697	

(C) CS-3

Mix Ref.	Unit weight (gm/cm^3)	Linear atten. coef. (cm^{-1})	Mass attenuation coef. (cm^2/g)	
			Results of this research	NIST results
		0.663 MeV	0.663 MeV	0.600 MeV
RY-W40-S10	2.382	0.1653	0.0694	0.0824
MK-W40-S10	2.428	0.1709	0.0704	
AB-W40-S10	2.445	0.1775	0.0726	
BR-W40-S10	3.383	0.2369	0.0700	0.0825
HM-W40-S10	3.713	0.2473	0.0660	

The linear attenuation coefficients obtained in this research have been also compared with the results of different past research for similar normal and heavy concretes tested by the same energy source of gamma rays as shown in tables 6 and 7. The results obtained in this research lie considerably within limits of the results of the literature. It indicates that the attenuation of gamma rays in normal and heavy concrete does not change too much in the concretes with similar densities.

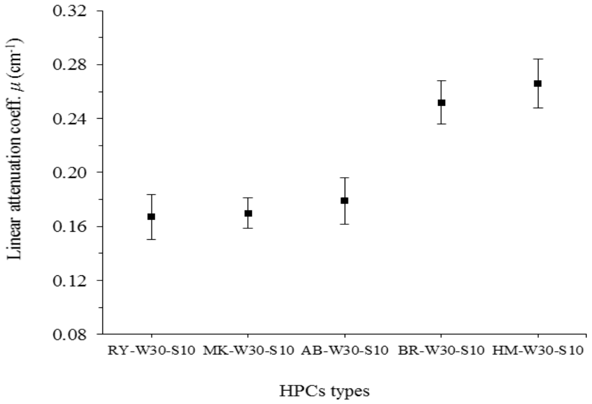
TABLE VI
COMPARISON OF LINEAR ATTENUATION COEFFICIENTS VALUES AT 0.663 MEV Γ-RAYS FOR NORMAL CONCRETES OBTAINED IN THIS AND PAST RESEARCH

S	μ (cm^{-1})		Authors
	Min.	Max.	
1	0.1840	0.1870	Demir, 2011 [8]
2	0.1570	0.2020	Yılmaz, 2011 [9]
3	---	0.2007	Gencel, 2011 [10]
4	0.1583	0.1807	Bakhsh, 2001 [15]
5	0.1030	0.1550	Demir, 2010 [16]
6	0.2120	0.2480	Akkurt, 2006 [17]
7	0.1960	0.2040	Akkurt, 2005 [48]
8	0.1765	0.1833	Singh, 2008 [49]
9	---	0.1871	Pomaro, 2008 [50]
10	0.1293	0.1930	El-Khayatt, 2010 [51]
11	---	0.1530	Ikraiam, 2009 [52]
12	0.1381	0.1408	Akkurt, 2010 [53]
13	0.1622	0.1788	This research

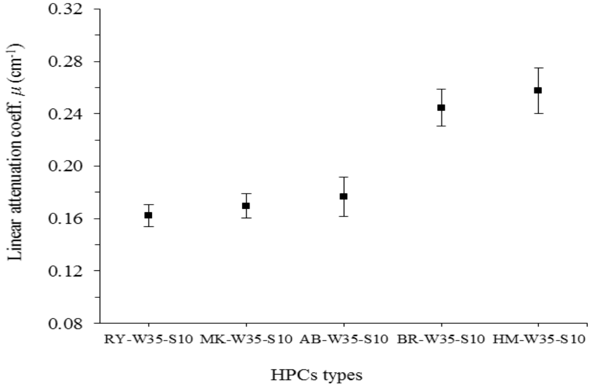
TABLE VII
COMPARISON OF LINEAR ATTENUATION COEFFICIENTS VALUES AT 0.663 MEV Γ-RAYS FOR HEAVY CONCRETES OBTAINED IN THIS AND PAST RESEARCH

S	μ (cm-1)		Authors
	min	max	
1	0.248	0.2610	Demir, 2011 [8]
2	---	0.2188	Gencel, 2011 [10]
3	0.2175	0.2347	Bakhsh, 2001 [15]
4	0.1320	0.1550	Demir, 2010 [16]

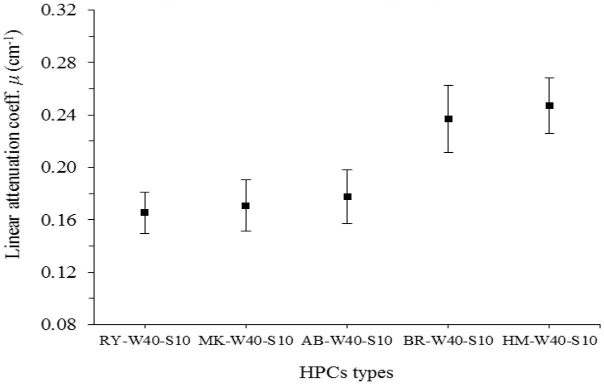
5	0.2480	0.2660	Akkurt, 2006 [17]
6	0.2800	0.2900	AKKURT, 2005 [48]
7	0.2570	0.2970	Akkurt, 2010 [53]
8	0.1805	0.1870	Mostofinejad, 2012 [54]
9	0.1727	0.1911	Bouzarjomehri, 2006 [55]
10	0.2369	0.2661	This research



(a) First concrete series (CS-1)

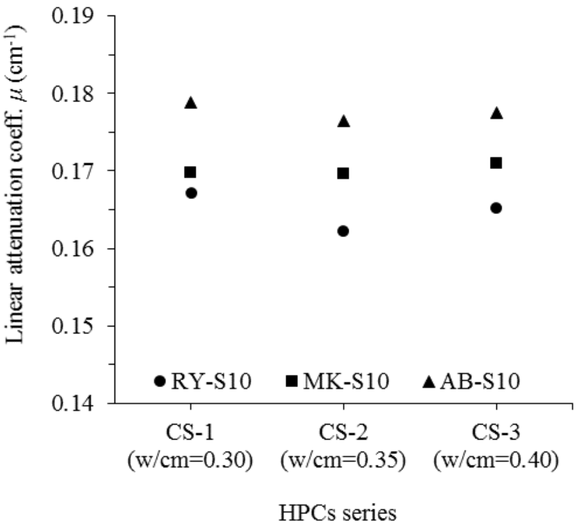


(b) Second concrete series (CS-2)

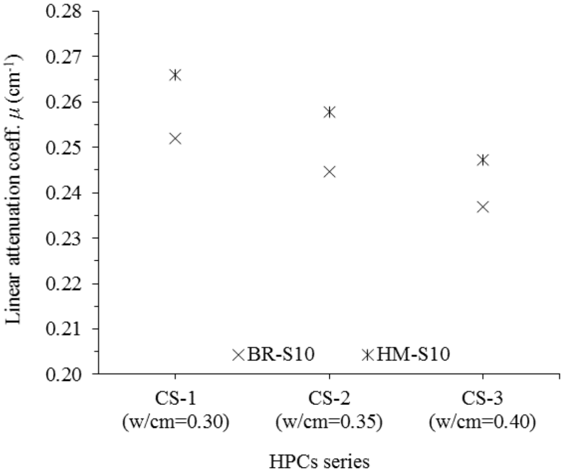


(c) Third concrete series (CS-3)

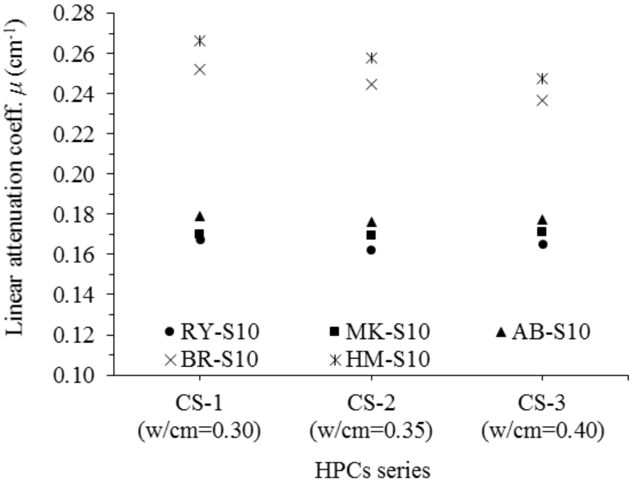
Fig. 5. Linear attenuation coefficients μ (cm^{-1}) of concrete mixtures for 0.663 MeV γ-rays



(a) Normal HPCs



(b) Heavy HPCs



(c) Normal and heavy HPCs

Fig. 6. Linear attenuation coefficients of gamma rays measured at 0.663 MeV γ-rays

The attenuation coefficients obtained in this research from all concrete series: normal, heavy and complete set of HPCs were plotted in Figs. 5, 6 and 7. The coefficient values have been plotted versus each concrete mixture as shown in Figs. 5 (a), (b) and (c). from Fig. 6 and 7, it is seen that the highest attenuation coefficients are obtained from the HPC samples produced in the first series (CS-1) for each mixture individually. While the lowest values were calculated in CS-3 samples, as shown in Fig. 6 (c). However, the difference is little in case of normal HPCs (Fig. 6 (a)). However, it is considerable in case of heavyweight HPCs and reached 8-10% more as shown in Fig. 6 (b).

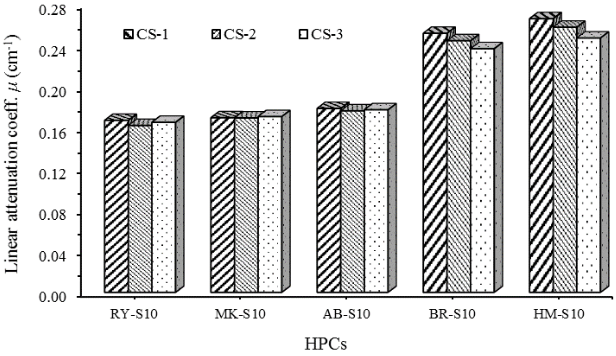
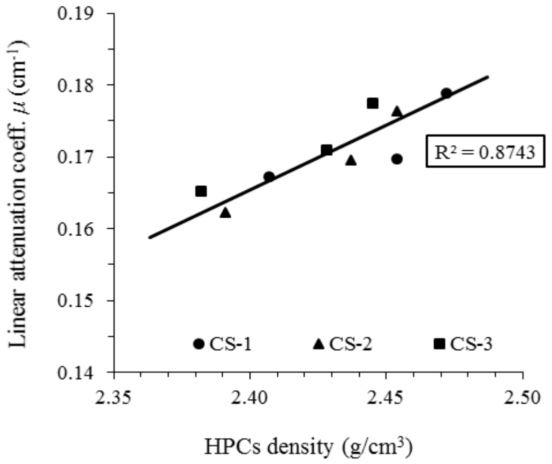
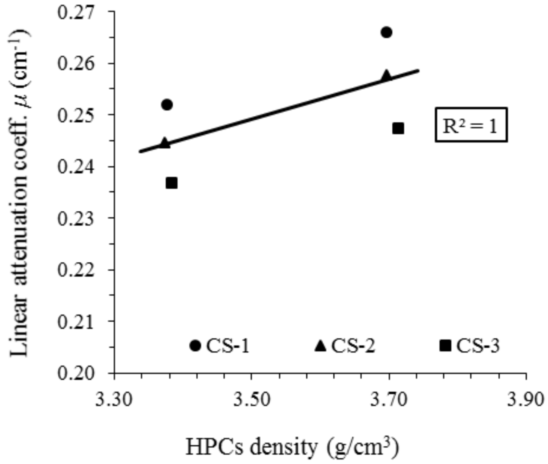


Fig. 7. Attenuation coefficients (μ) of normal and heavy HPCs

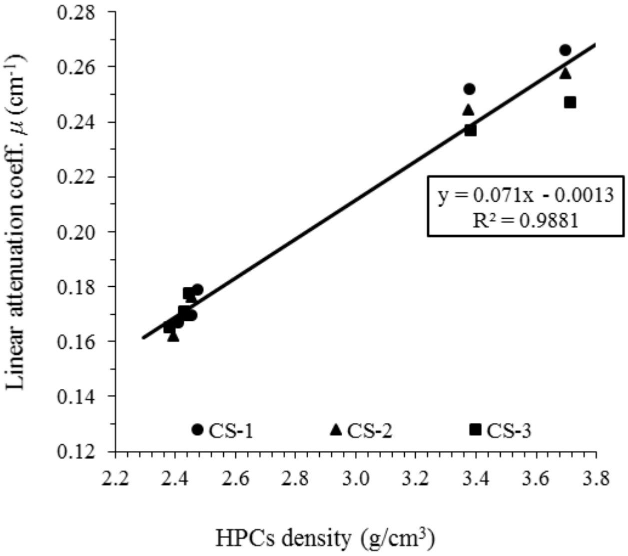
It is observed that the attenuation of gamma rays in normal and heavy HPCs is considerably affected by the concrete density, this is consistent with the previous literature [8], [56], [11], [57], [58], [14]. With a little increase in the density, a significant increase in the attenuation coefficients was observed as shown in Fig. 8 (a), (b) and (c). It is seen in this research that when the density of the high performance concrete (normal and heavy) increases, the attenuation coefficients increases with the same percent as shown in Fig. 8 (c).



(a) Normal HPCs



(b) Heavy HPCs



(c) Normal and heavy HPCs

Fig. 8. Linear attenuation coefficients versus density of HPCs at 0.663 MeV γ-rays

In general, it is concluded from Fig. 8 (c) that the relation between HPC density and attenuation of gamma rays approximately is linear. These results show that the gamma radiation attenuation of the HPCs increases in direct proportion to the HPCs density. In other words, high density HPCs attenuates more gamma radiation. Among the normal HPCs, concrete ‘AB’ has the highest density due to the specific gravity of the coarse aggregate and is the best normal HPC for shielding purposes in this research as it obtained the highest attenuation values.

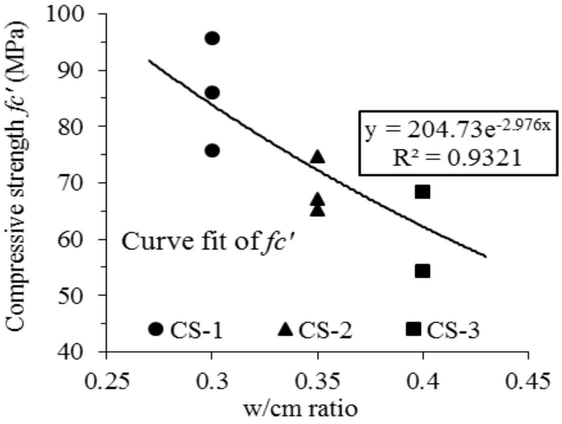
Its values are 5 and 3 percent higher than those obtained with concretes ‘RY’ and ‘MK’ respectively. Generally, the unit weight of normal concrete varies between 2200 and 2450 kg/m^3 [3]-[5]. In this research, normal HPCs were produced with unit weights ranges between 2382 to 2472 kg/m^3. It can be said that these values is important for nuclear radiation structures. It was found that even a little increase in the concrete unit weight positively affect the attenuation of gamma rays. Therefore, the production of normal HPCs using normal materials with higher specific gravity is recommended. However, it must be noted that the density often does not have a unique value but depends on the physical state of the material [5]. Therefore, care must be taken during the selection of sensitive worth density for special structures such as nuclear containment structural facilities (NCSFs).

TABLE VIII

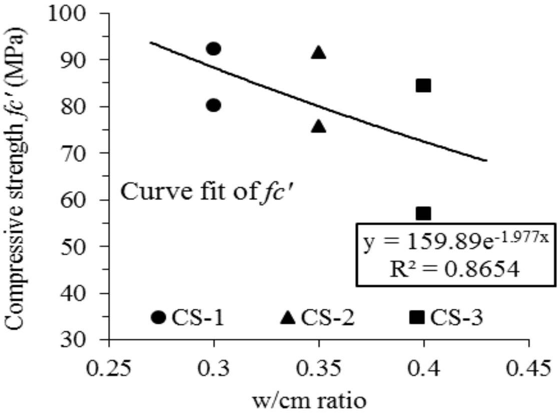
%AGE OF COMPRESSIVE STRENGTH OF HPCS AT DIFFERENT W/CM RATIOS

HPCs series HPCs type	(CS-1) w/cm= 0.30	(CS-2) w/cm= 0.35	(CS-3) w/cm= 0.40
Normal	1	0.81	0.74
Heavy	1	0.97	0.92

The compressive strength of HPCs is the mechanical property which targeted in this research to be studied in terms of its effect on the shielding properties. High compressive strength was a result of the HPCs mix design using three different low water-to-cementitious materials ratios 0.30, 0.35 and 0.40. The normal and heavy HPCs that produced in this research obtained high compressive strength. This compressive strength ranged between 54 and 96 MPa for normal HPCs and it was between 57 and 92 for heavy concretes. These values of strength have a good agreement with the curve developed by Aitcin [2] for compressive strength versus proposed w/cm. The strength development can be seen in Fig. 9 (a) and (b) versus w/cm ratios for normal and Heavy HPCs respectively. The values of strength of normal and heavy HPCs obtained in the three series with the three different low w/cm ratios used in this research is shown in Table 8 and Fig. 10.



(a) Normal HPCs



(b) Heavy HPCs

Fig. 9. Normal and heavy HPC compressive strengths (*fc′*) versus different low w/cm ratios

It can be seen that the concrete 'RY' and 'HM' obtained the highest strength of 96 and 92 MPa respectively with concrete 'AB' of CS-1 giving the lowest value (76 MPa). The third series (CS-3) shows the lowest strength values of normal and heavy HPCs compared to those produced in the two other series. Their strength values were ranged between 54 and 84 MPa. Nevertheless, the biggest variation appeared between the same concrete types in the three series (different w/cm ratios). It was noted that the strength increases with low w/cm ratio as expected. The maximum strength variations in each normal HPCs 'RY', 'MK' and 'AB' is about 28 percent from CS-1 to 3. But, it is low in the heavy HPCs 'HM' amounting to about 8 percent. Overall, although big variations in the strength of normal HPCs was observed but this variation does not affect the attenuation of gamma rays. The attenuation in all normal HPCs is not affected by the strength of the concrete. It is found that when the strength increases or decreases, the performance of the concrete to attenuate the radiation varies but not directly related to the strength.

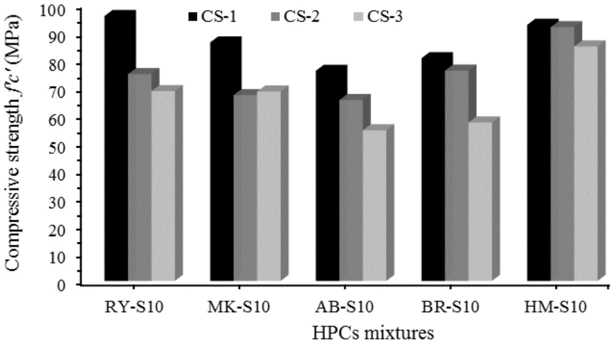
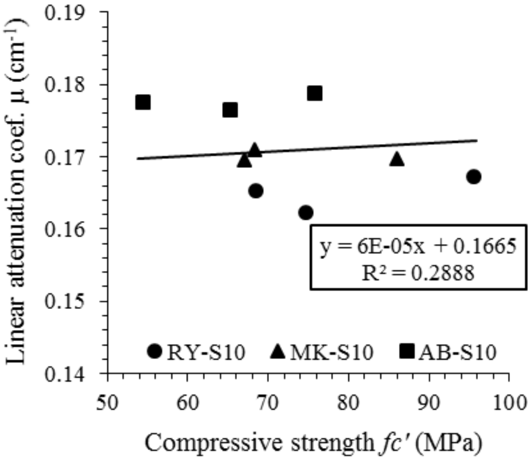


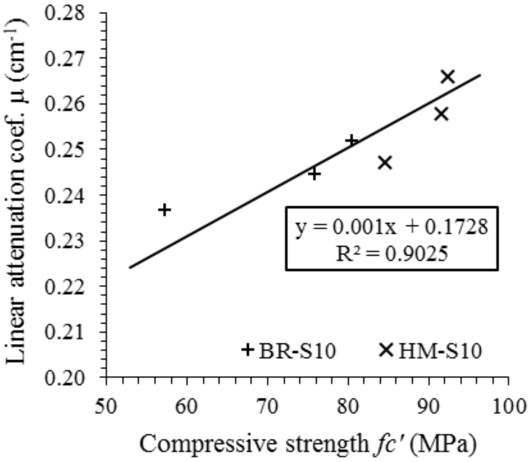
Fig. 10. Comparison of compressive strengths (*fc′*) of normal and heavy HPCs

In Fig. 11 (a) and (b), the attenuation coefficients μ (cm^{-1}) have been plotted versus the compressive strength (*fc′*) for normal and heavy HPCs. It was observed that the compressive strength (*fc′*) of normal HPCs produced using low w/cm ratio has very small effect on the attenuation of gamma rays within a wide range of strength. Therefore, it can be noted that in the normal HPCs, the strength does not have significant effect on the shielding properties in closer range of w/cm ratios. It means that within the constraints of this research, the compressive strength (*fc′*) of the normal HPCs designed for shielding can be partially neglected up to some extent in calculations of shielding properties. This has also been represented by [5], [59]. Therefore, it can be suggested that the lowest strength which can meet the structural, mechanical and other requirements can be utilized where there are economic constraints. In general, it is speculated from the results of Fig. 9 (a) that at higher w/cm ratio such as 0.6 produces a normal concrete having lower strength range (30-35) MPa and that may or may not affect the attenuation of the gamma rays. Further investigation on the effect of low concrete strength at high w/cm ratios on the attenuation of gamma rays is recommended.

According to the past research [2], increase of strength is obtained mainly through the drastic reduction of the porosity of hydrated cement paste. The porosity and the amount of mixing water can be reduced by adding more cement in addition to cementitious materials and through use of super-plasticizers replacement respectively. These are the reasons why HPC has high durability with a very dense microstructure. However, the w/cm ratio affect the microstructure of the concrete. That means whenever the low of w/cm ratio is used, the microstructure of the HPC becomes denser. According to Chaussadent, et al. [60] the microstructural characteristics between concrete pastes are very different for w/cm above and below 0.35-0.40. Therefore, it can be said that even if the strength of HPC differs for w/cm 0.35 and 0.40, the microstructure does not change a lot. This may give reasoning as to why the strength of the normal HPCs does not affect the attenuation of gamma rays. However, it is found that the microstructure of the normal HPCs produced in this research was dense [61] and does not vary too much with three closer different w/cm ratios (0.30, 0.35 and 0.40). Therefore, it can be concluded that an attention must be taken on the influence of the material variables on the interfacial transition zone microstructure in terms of their effect on the development of the strength and shielding properties.



(a) Normal HPCs



(b) Heavy HPCs

Fig. 11. Linear attenuation coefficients versus HPC compressive strengths (*fc′*)

The preceding discussion shows that the emphasis on these parameters that make strong correlation of normal HPCs microstructure with density and compressive strength is very important for proper assessment of its shielding properties. A further deep investigation for verification within a large range of w/cm ratios is still needed. However, the situation is different in heavy weight HPCs. The strength plays an important role in enhancing the attenuation of gamma rays as shown in Fig. 11 (b). The attenuation of gamma rays increases when the strength increases. It was found that when the compressive strength increases by 5 and 8%, the attenuation coefficients increases by 4 and 7 percent respectively. The compressive strength and attenuation of gamma rays have a near to linear relation. That means the shielding properties of the heavy HPCs (BR and HM) is improved more when its strength becomes high. In this research, the heavy weight HPCs in each series have the best linear attenuation coefficients and their gradual increase starts from CS-3 reaching the highest values at CS-1. It reflects a good HPC microstructure that effects on the photon radiation energy absorbent due to its linear correlation with concrete density at low w/cm ratio [8]. In addition, it was observed that heavyweight HPC microstructure such at CS-1 with w/cm 0.30 was denser as compared to the others and 'BR' and 'HM' concretes obtained attenuation of gamma rays 33-54 percent more than the normal concretes.

IV. CONCLUSIONS

The linear and mass attenuation coefficients of gamma rays for different normal and heavy weight high strength high performance concretes (HPCs) were experimentally investigated. The results have been compared with the results obtained in the past research for similar concretes and showed a good agreement along with significant findings. The following conclusions have been drawn:

- The heavy weight HPC strength plays an important role in enhancing the attenuation of gamma rays. The attenuation of gamma rays increases when the strength of heavy HPCs increases. It was found that, when the compressive strength increases by 5 and 8%, the attenuation coefficients increases by 4 and 7 percent respectively. Therefore, the compressive strength and attenuation of gamma rays have a near to linear relation.
- In the normal HPCs, the compressive strength (*fc′*) does not have a significant effect on the HPCs shielding properties in closer range of w/cm ratios.
- The heavy weight HPCs obtained from CS-1 have the highest strength and the best shielding properties.
- Among all the normal HPCs, concrete 'AB' was more effective at 0.663 keV.
- It was observed that the attenuation of gamma rays in HPCs is considerably affected by the concrete density. With a little increase in the density, a significant increase in the attenuation coefficients was observed.
- A further deep investigation to verify the relation of strength and attenuation of gamma rays within a large range of w/cm ratios is still needed for normal HPCs and remains as scope for future works.

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