High-Performance Concretes with Normal and Heavy Aggregates for γ-Radiation Shielding

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ABSTRACT:

The radiation-shielding capabilities of high-performance concrete (also known as HPCs) were investigated experimentally by several different variables. The production of HPCs with varying compressive strengths is required using three different low water-to-cementitious material ratios (w/cm) and several distinct types of normal and heavyweight aggregate. To calculate the linear attenuation coefficients of radioactive 137Cs at 0.663 MeV, a NaI(Tl) scintillation detector was used. We found that the compressive strength of heavyweight HPCs plays a significant role in the enhancement of γ-ray attenuation. It is possible to draw a linear conclusion about the relationship between the compressive strength and the attenuation of -rays.

Regarding regular concrete, the strength does not affect the amount of -radiation absorbed by the material—comparison of results from the US National Institute of Standards and Technology and mass attenuation coefficients. There was a reasonable amount of agreement between the two. Density affects γ-ray attenuation.

Keywords: high performance concrete, γ-ray attenuation, γ-radiation, mass attenuation coefficients.

INTRODUCTION:

According to the American Concrete Institute (ACI), high-performance concrete (HPCs) satisfies unique sets of durability and homogeneity standards that are impossible to consistently fulfil using standard components and customary combining, putting, and curing techniques. These standards apply to the homogeneity of the concrete and durability of the concrete. We can use conventional, large-sized aggregates or supplementary cementitious materials (SCM) to make it. High-performance concrete's material qualities significantly affect the design and building of HPC building elements (HPC). Therefore, the aggregates chosen require careful consideration, with extra focus on the aggregates' grading and maximum size.

Concrete that weighs a lot is one of the HPCs. It is said to be composed of concrete with a unit weight ranging from 2900 to 6000 kg/m3, which is significantly higher than the unit weight of regular-weight concrete, which ranges from 2200 to 2450 kg/m3.

Mostly, as per PCA, HPCs are more robust than regular concrete. Due to its inexpensive cost and effective shielding against radiation properties, concrete is in nuclear power plants, healthcare facilities, and other buildings where radioactive resistance is necessary. Heavy concrete is most commonly used as a radiation shield because it prevents leakage from radioactive constructions and shields individuals from the potentially harmful effects of X-rays and γ-rays. Heavyweight concrete tends to be employed when it is essential to minimise the amount of radiation protection, usually due to space issues. The aggregate used in concrete is crucial in adjusting the physical-mechanical characteristics of concrete and significantly impacts the material's protecting abilities. Heavy concrete has generally been the subject of several experimental studies. Ylmaz determined the gamma-ray depletion coefficients of 12 specimens of concrete at energies of 59.5 and 661 keV. These specimens could have additional cementitious materials added to them or not. Experiments carried out by Demir led to the discovery that, about concrete, the coefficients for linear attenuation () decrease as one increases the energy of the photons and that these coefficients depend on the photoelectric effect and Compton scattering at this energy. In addition, he realised that the barite crystal structure was stable at 663 keV. Using a NaI(Tl) scintillation detection system and a variety of small w/cm ratios (0.30-0.4) for the energy of the radioactive isotope 137Cs at 0.663 MeV, linear and mass attenuation coefficients were determined for both standard and heavy HPC in terms of radioactive dispersion. We compared each experiment's results to those of other studies and the values for the X-ray mass attenuation coefficient provided by NIST. The effect of compressive strength on γ-ray attenuation was also studied.

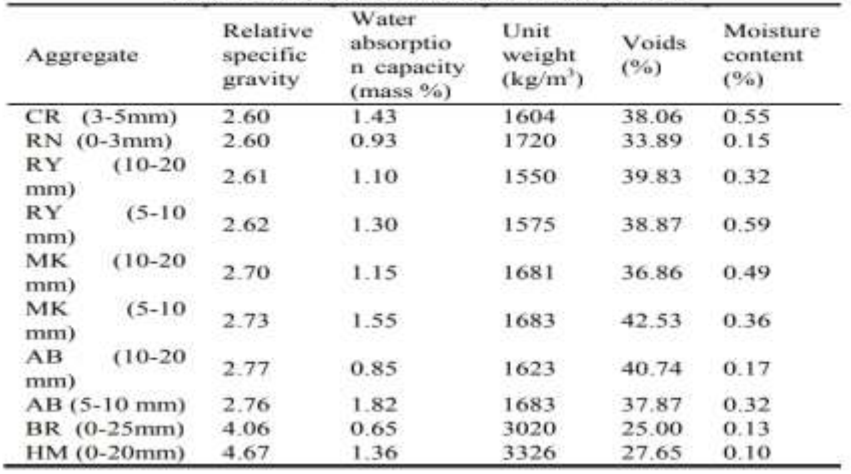
LABORATORY RESEARCH:

A. Methodology and Materials:

This part of the article covers the substance qualities of the constituents in HPC, mix layout by ACI 211.4R, and HPC strengthening techniques. In order to meet the standards set by ASTM C150, we use ordinary Portland-type I cement purchased from the Yammama cement factory in Riyadh. The mineral admixture employed in this experiment for all the mixes is micro silica, which has a specific gravity value of 2.27. Micro-silica employed in this study complied with ASTM C1240 criteria in terms of both the chemical constitution and physical qualities. The water-to-cementitious materials ratio (w/cm) was varied throughout the study from 0.30-0.40 to investigate the influence of compressive strength under the influence of various water-to-cementitious materials ratios. The study explored the impact of compressive strength on various water-to-cementitious materials ratios. To make the HPC feasible, an additive with an approximate specific gravity of 1.1 called Glenium 51, a high-performance concrete superplasticizer, was used. In the current study, there were a total of five different types of coarse aggregates (designated as 'RY', 'MK', 'AB', and 'BR'), as well as two different types of fine aggregate (designated as 'RN' and 'CR'). We decided to label the micro-silica with an "S." Riyadh, Makkah, and Abha are located in different parts of Saudi Arabia and are geographically distinct. These three cities were the primary sources for the three types of typical-weight coarse aggregates. Belgium-imported heavy-weight coarse aggregates with the designations "BR" and "HM" were used during the investigation. Standard coarse aggregate had a maximum particle size of 20 millimetres across all HPC configurations. The other half varied in size from about 5 to 10 millimetres, while the first was about 10 to 20 millimetres. Both hematite and barite were between 20 and 25 millimetres, and their respective portions measured between 0 and 25 millimetres and between 0 and 20 millimetres.

Two typical-weight fine aggregates from Riyadh were also collected. Aggregate 'RN' is a naturally occurring material that ranges in size from 0 to 3 mm and has a whitish tint. The second type of fine aggregate, given the designation "CR" for this study, is produced by crushing sedimentary stones. It ranges in size from 3-5 millimetres and is white. It is mixed with RN sand to acquire the finesses modulus of the fine materials required by ASTM. Table I lists the physical characteristics of the HPC ingredients utilized in the present study as defined by ASTM C33 standards.

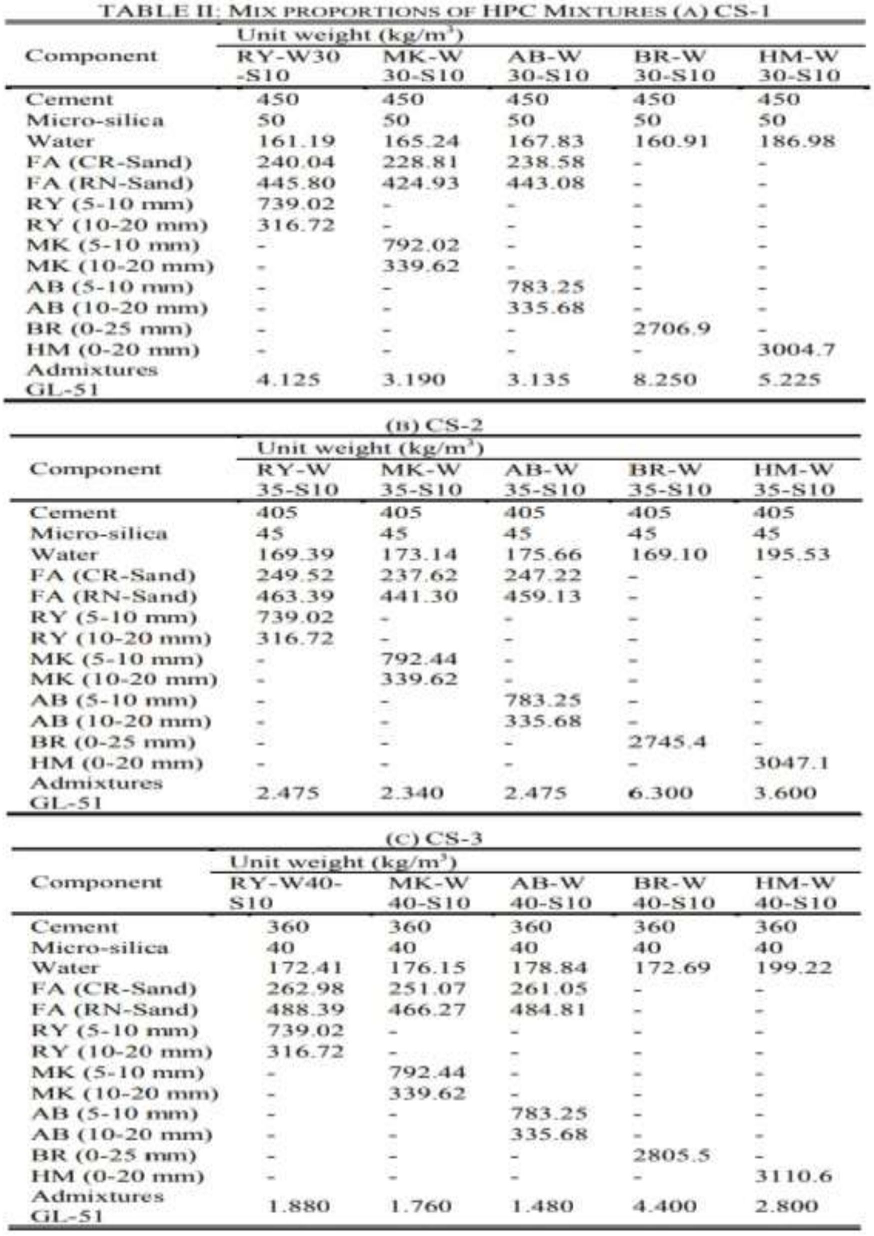
TABLE I: AGGREGATE MATERIAL PROPERTIES



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

Three distinct HPC series, designated CS-1, 2 and 3, have been developed using three low w/cm values. These values are 0.30, 0.35, and 0.40, respectively. Each set had three regular HPC and two heavy HPC, with the regular aggregates RY, MK, and AB and the heavy aggregates BR and HM making up the regular and heavy HPC, respectively. Each set of mixtures contained five variations, with the number of cementitious materials and water-to-cementitious ratio remaining constant. The number of cementitious materials was 500, 450, and 400 kg/m3 for w/cm of 0.3, 0.35, and 0.40, correspondingly. 10% micro-silica was utilized instead of cement. There are three different series of mixes, and their names are as follows: RY/MK/AB/BR/HM-W30-S10, RY/MK/AB/BR/HM-W35-S10, and RY/MK/AB/BR/HM-W40-S10. Tables 2(a), (b), and (c) detail the ACI-211.4R-labeled component proportions of all studied combinations.

TABLE II: MIX PROPORTIONS OF HPC MIXTURES (A) CS-1



Component	Unit weight (kg/m^3)				
	RY-W30 -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-W40- 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

A. 180 L size rotating planetary mixer was used to make each combination. ASTM C143 required a slump test to verify the desired slump. All of the mixes of concrete used in this investigation had slumps ranging from 150 to 200mm. By ASTM C496, the concrete was poured into plastic cylinders immediately following the mixing procedure. These cylinders had a standard diameter of 150 millimetres and a length of 300 millimetres. Each HPC mixture produced many 150 mm cubic radiation-tested concrete samples. The compressive strength test also required the creation of cylindrical specimens with standard dimensions of 150 mm in diameter and 300 mm in height.

B. Assessment Techniques and Process
1) Radiation equipment and setup

Fig. 1 depicts the configuration of the experimental setup and the test block illustration, which lists all the components of the measurement system utilized in the test. 137Cs, a substance with radioactivity having an energy of 0.663 MeV, was used to perform radiation testing in this work. The amplitudes of γ-rays were measured using a NaI(Tl) scintillation sensor enclosed in a 16 mm thick lead jacket with a 5 mm holed collimator. The attenuation coefficients for the γ-ray emitted by the 137Cs emitter were calculated using Equation 1 and then tested.

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

where, μ is gamma-ray linear attenuation coefficient; I_0 is the intensity of first measurement without specimen; I is the intensity passing the specimen and x is the thickness of the specimen. The total mass attenuation coefficients, μ_m, are also given as follows:

$$\mu_m = \frac{\mu}{\rho} = \left(\frac{1}{x}\right)\ln\left(\frac{I_0}{I}\right)/\rho \quad (cm^2/g) \tag{2}$$

where, ρ is the density of the sample.

The incoming gamma ray with I0 intensity transmitted perpendicularly without specimen was determined employing a computerized counter. The intensity of gamma-ray I, as it passed through the HPC specimens, was then calculated. The counts I0 were determined on 150 mm cubic HPC specimens for each mixture simultaneously and under the same experimental and atmospheric conditions to avoid any inconsistencies. Preventing inconsistencies was the reason. Eqs. 1 and 2 determined these observations' linear (μ) and total mass attenuation (μm) coefficients.

2) Compressive Strength Assessment:

The specimens were removed from the curing tank after they reached the testing age and had their ends capped with a capping compound substance. The compression test must be carried out on the hardened concrete cylinders to comply with ASTM C 39.

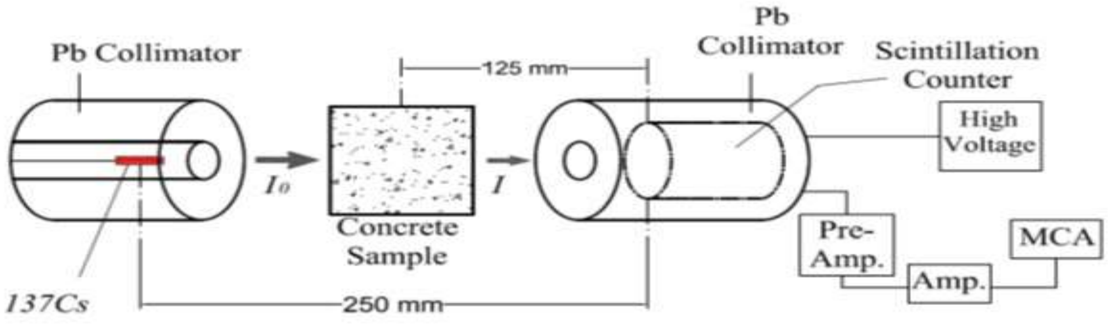


Fig. 1. Experimental setup for gamma radioactive test

III. RESULT AND DISCUSSION

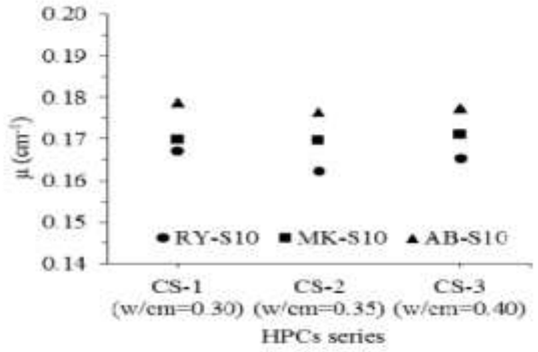
Using a 0.663 MeV incident photon, the linear and mass attenuation coefficients for each HPC series were calculated. We assessed these calculations. Table III is a list of the evaluated outcomes.

TABLE III: UNIT WEIGHT, LINEAR AND MASS ATTENUATION COEFFICIENTS AT 0.663 MEV Γ-RAYS OF HPC SERIES TESTED IN LAB CONDITIONS

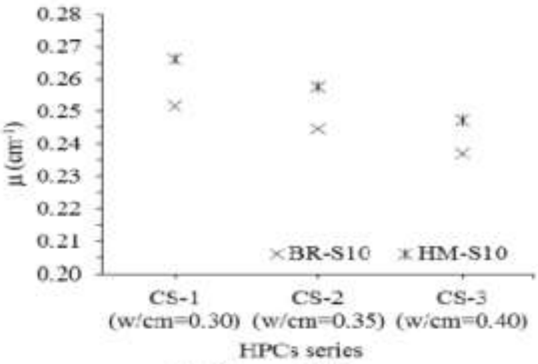
HPCs Series	Mix Ref.	Unit weight (gm/cm^3)	Linear atten. coef. (cm^{-1})	Mass attenuation coef. (cm^2/g)	
				This research	NIST results
			0.663 MeV	0.663 MeV	0.600 MeV
CS-1	RY-W30-S10	2.407	0.1672	0.0695	0.0824
	MK-W30-S10	2.454	0.1698	0.0692	
	AB-W30-S10	2.472	0.1788	0.0723	
	BR-W30-S10	3.376	0.2519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

Heavyweight HPCs (BR and HM) had the highest mass attenuation coefficient at 0.663 MeV γ-ray energy. These values match NIST's X-ray mass attenuation coefficient. The mass attenuation coefficient of barite concrete (BR-W30-S10) is 0.0746 cm2 /g when measured at 0.663 MeV, which is lower than the value given by the NIST, which is 0.0825 at 0.600 MeV. Out of all the normal HPCs, the one with the 'AB' aggregate had the highest density and mass attenuation values. It also matches NIST values for regular concrete. They plotted in Figs. 2a, 2b, and 2c are the attenuation coefficients obtained in this paper from all concrete series: normal, heavy, and the complete set of HPCs.

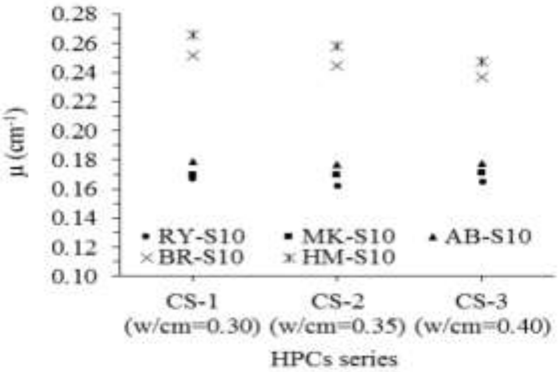
HPC samples from the first series (CS-1) for each unique mixture had the highest attenuation coefficients. While the CS-3 samples had the lowest values overall, as shown in Figure 2, the lowest values were calculated (c). The difference is negligible in the case of typical HPCs, as shown in Figure 2(a). On the other hand, it is significant in the case of heavyweight HPCs and reached 8-10% more, as Fig. 2 demonstrates (b). The concrete density significantly affects the number of γ-rays attenuated in typical and heavy HPCs. As shown in Figure 3(a), (b), and (c), even a marginal increase in density resulted in a sizeable jump in the attenuation coefficients. Even though the density was relatively constant, this study shows that increasing the density of regular and heavy high-performance concrete increases the attenuation coefficients by the same percentage shown in Fig. 3. (c). However, looking at Fig. 3(c), one can see a roughly linear relationship between the HPC density and the γ-ray attenuation. Concrete AB has the highest density of all the normal HPCs because of the specific gravity of the coarse aggregate. As a result, concrete AB is the normal HPC most suitable for shielding objectives in this study because it received the highest attenuation values. The results obtained with it are 5 and 3 per cent higher than those obtained with the concretes RY and MK, respectively.



(a) Normal HPCs



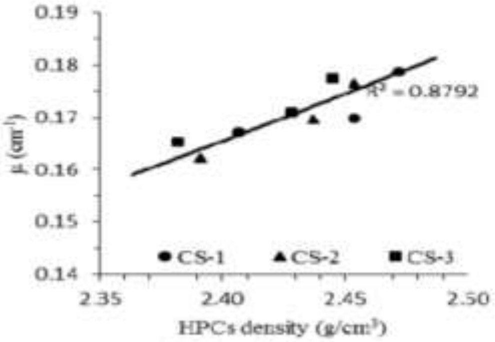
(b) Heavy HPCs



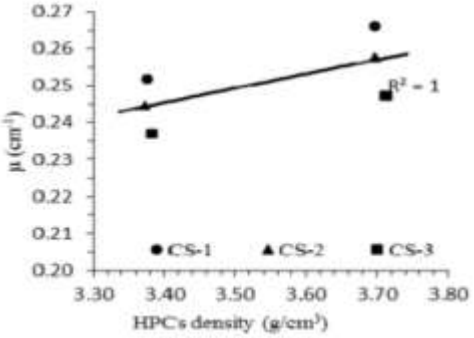
(c) Normal and heavy HPCs

Fig. 2. Linear attenuation coefficients of γ-rays measured at 0.663 MeV γ-rays

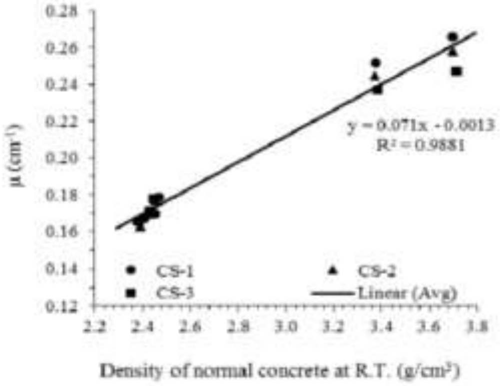
Typically, concrete weighs between 2200 and 2450 kg/m3 per unit. This work created typical HPCs with unit weights ranging from 2382 to 2472 kg/m3. One could make the case that these values are essential for the structures that contain nuclear radiation. As researchers have found, attenuation caused by γ-rays can be improved significantly by increasing the unit weight of concrete by even a modest amount. Therefore, it advised that typical HPCs produced using normal materials with higher specific gravities. However, it is essential to note that the density is not a constant but depends on the material's physical state.



(a) Normal HPCs



(b) Heavy HPCs



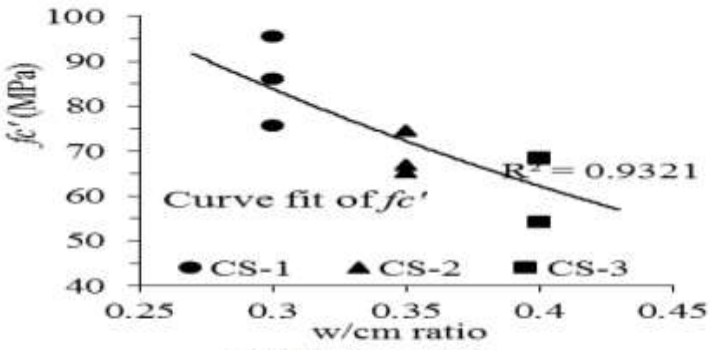
(c) Normal and heavy HPCs

Fig. 3. Linear attenuation coefficients versus density of normal and heavy HPCs at 0.663 MeV γ-rays

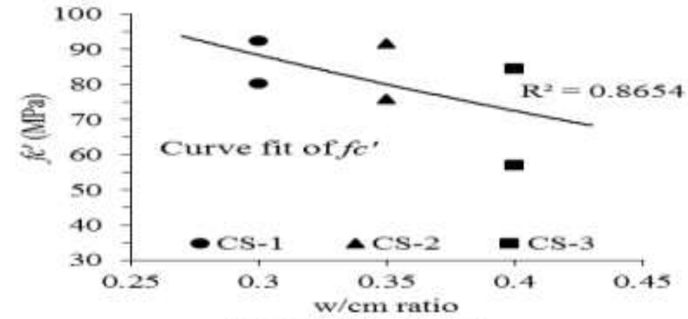
TABLE IV: %AGE OF COMPRESSIVE STRENGTH OF HPCS AT DIFFERENT W/CM RATIOS

HPCs	(CS-1)	(CS-2)	(CS-3)
Normal	1	0.81	0.74
Heavy	1	0.97	0.92

The mechanical attribute of HPCs that is the focus of this paper's investigation into how it affects shielding properties is their compressive strength. The mix design of the HPCs, which utilized three different low water-to-cementitious material ratios of 0.30, 0.35, and 0.40, produced a high compressive strength in the final product. The regular and heavy HPCs achieved high compressive strength in this research. The compressive strength of typical high-performance concretes (HPCs) ranged from 54 to 96 MPa, whereas the compressive strength of heavy concretes ranged from 57 to 92 MPa. These values for strength are in reasonable agreement with the Aitcin compressive strength against the suggested w/cm curve. Figure 4(a) and (b) depict regular and Heavy HPCs regarding their w/cm ratios, respectively, allowing one to observe the progression of strength.



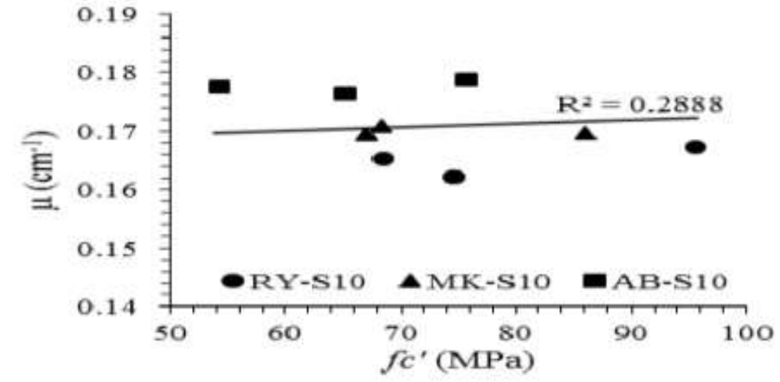
(a) Normal HPCs



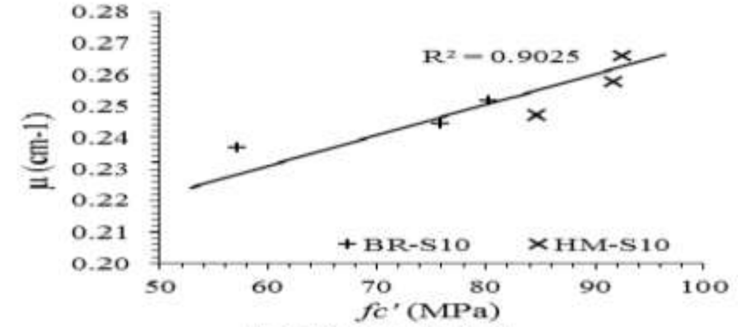
(b) Heavy HPCs

Fig. 4. Normal and heavy HPCs compressive strengths (*fc'*) versus different low w/cm ratios

As can be seen, the concretes with the designations RY and HM achieved the highest values for their strengths, coming in at 96 and 92 MPa, respectively, whereas the concrete with the designation AB from CS-1 gave the lowest value (76 MPa). Compared to the values produced by the first and second series, the normal and heavy HPCs produced by the third series (CS-3) have significantly lower strength values. The measured values of their tensile strength ranged from 54 to 84 MPa. However, the same concrete types across all three series (different w/cm ratios) showed the most significant differences. Decreased w/cm ratio increased strength, as expected. From CS-1 to CS-3, the normal HPCs RY, MK, and AB have maximum strength variations that are approximately 28 per cent different. However, it only contains a small amount of the heavy HPCs known as HM, which amounts to about 8% of the total. Normal HPC strength variations did not affect γ-ray attenuation. The strength of the concrete does not affect the attenuation of any normal high-performance concrete (HPC). The performance of concrete to attenuate radiation varies with concrete strength, but not directly. Figs. 5(a) and 5(b) show normal and heavy HPC attenuation coefficients (cm-1) plotted against compressive strength (fc') (b). The compressive strength (fc') of typical HPCs with a low w/cm ratio has little effect on γ-ray attenuation across a wide range. Testing showed this. Thus, in typical HPCs, strength does not affect shielding in the w/cm range. For this work, shielding estimates can partially ignore the compressive strength (fc') of conventional HPCs built for shielding up to a certain level. The constraints of this work determine this level. As a result, one might recommend that if there are financial restrictions, the material be as weak as possible while still meeting the structural, mechanical, and other requirements. It is generally assumed, based on the findings presented in Fig. 4(a), that a more excellent w/cm ratio, such as 0.6, results in a typical concrete with a lower strength range (30-35), which may or may not have an impact on the attenuation of γ-rays. However, this is something that needs further investigation. More research is needed to determine the effect of low concrete strength on γ-ray attenuation in situations with high w/cm ratios.



(a) Normal HPCs



(b) Heavy HPCs

Fig. 5. Linear attenuation coefficients versus HPC compressive strengths

However, required is additional in-depth research for verification across a wide variety of w/cm ratios. However, in considerable weight HPCs, the scenario is different. As seen in Fig. 5(b), the strength significantly affects the attenuation of γ-rays. The magnetic field's intensity directly correlates to the degree to which the field weakens γ-rays. When compressive strength increases by 5% and 8%, attenuation coefficients increase by 4% and 7%. It is possible to draw a linear conclusion about the relationship between the compressive strength and the attenuation of γ-rays. As a heavy HPC's strength increases, its shielding abilities (BR and HM) develop even further. This investigation discovers the best linear attenuation coefficients in each series of heavy-weight HPCs. These coefficients gradually increase at the CS-3 level and reach their highest point at the CS-1 level. It displays a suitable HPC microstructure because of its linear association with concrete density at a low w/cm ratio, which affects the photon radiation energy absorbent. Heavyweight HPC microstructure was denser than others. Additionally, 'BR' and 'HM' concrete showed 33–54 per cent more absorption of γ-rays than standard concretes.

CONCLUSION:

We conduct experiments to test the hypothesis that the attenuation coefficients of γ -rays are affected by the compressive strength of light and heavyweight high-performance concretes (HPCs). We compared our findings to those found in the published scientific literature. The comparisons uncovered significant breakthroughs in addition to a good deal of concordance. We can draw the following conclusions:

- Boosting the compressive strength of dense concrete is an effective way to increase its ability to attenuate γ-rays. The strength of the γ-rays is diminished proportionally to their intensity. It is possible to draw a linear conclusion about the relationship between the compressive strength and the attenuation of γ-rays.
- Within the parameters of this article, the results of tests on normal concrete demonstrated that the compressive strength, denoted by fc', has almost no discernible effect on the shielding capabilities.
- The density of the concrete strongly affects how much γ-ray radiation HPCs absorb. There is an attenuation of γ-rays as concrete density rises.
- Heavy concretes of hematite and barite had more significant attenuation coefficients and displayed the finest shielding qualities. Their tremendous strength and density explain this.
- The compressive strength of sample AB, one of the conventional high-performance concretes, was the lowest of all the samples, but it performed better than the other samples at 0.663 keV. This research is still in the planning stages. However, verifying the relationship between strength and γ-ray attenuation for typical high-performance concrete over a wide range of w/cm ratios is still necessary.

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