International Journal of Civil Engineering, Construction and Estate Management

Vol.5, No.2, pp.13-23, May 2017

Published by European Centre for Research Training and Development UK (www.eajournals.org)

DETERMINATION OF MECHANICAL CHARACTERISTICS AND RADIATION ATTENUATION COEFFICIENTS OF HEAVYWEIGHT AND NORMAL-WEIGHT CONCRETES CONTAINING HEMATITE FOR 70 KEV AND 570 KEV Υ-RAYS

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ABSTRACT: *Heavyweight concrete has been widely used for the prevention of leakage and scattering of radioactive rays due to the harmful effects for human-beings (i.e., carcinogenic, etc.). Proper shielding is one of the important precautions in working with these radiations in structures that Υ-rays production instruments are located. To determine roof and wall thickness of such structures, it is necessary to measure amount of radiation absorbed. In this paper, accurate measurements have been made to determine radiation transmission of all mix designs for 70 and 570 keV on Υ-rays energies of ^{137}Cs radioactive isotopes by using NaI (Tl) scintillation detector. The mechanical characteristics of heavyweight concrete produced with hematite aggregates such as density, compressive strength, splitting tensile strength, flexural strength and permeability against water seepage were investigated. It was determined that linear attenuation coefficient (μ, cm^{-1}) increased with hematite concentration. Also results support the use of hematite aggregate as a structural concrete with radiological protection capability.*

KEYWORDS: Heavyweight concrete, Gama-ray shielding, Mechanical characteristics, Linear attenuation coefficient

INTRODUCTION

Application and development of nuclear science and technology in different fields such as cancer treatment centers, nuclear power plants, nuclear research reactors, particle accelerators, collegiate test reactors, national laboratories and research facilities has set human beings in serious exposures from ionization radiations, therefore provision of reasonable and adequate shielding in these places remains an important obligation in establishment of nuclear facilities [1,2]. Radiation safety practice is a special aspect of the control of environmental health hazards by engineering means, so population and workers exposure from radiations in working and public areas must be kept under the maximum permissible dose suggested by NCRP basic radiation safety criteria [3].Usually ordinary and heavy-weight concretes are used for radiation shielding, for both medical and nuclear purposes to prevent population and employment staff exposure versus ionization radiation. Depend on several factors such as cost and abundance of shielding materials, energy and type of radiation, various type concretes with and without dense mineral aggregates are utilized in protective shielding concretes against radiations [4]. Depending on the type of aggregate with various elemental and structural compositions, various heavy density concretes will obtain. By using of barite and magnetite ores the density of concretes will be over 3500 kg/m^3, which is much greater than that of ordinary concrete. Application of serpentine minerals with plenty of hydrogenous materials as aggregate in shielding concrete will result about 2600 kg/m3 in density which is close to ordinary concrete density that spans from 2200 to 2500 kg/m^3. This type of aggregate mostly is used for neutron shielding [5]. Planning the appropriate shielding for nuclear centers depends on several factors such as the type of radiation, energy and cost. Mostly high atomic number and high density

ISSN 2055-6578(Print), ISSN 2055-6586(online)

materials are used for this purpose; but the latters are costly, hence their use is limited. The exploited materials are stainless steel and lead. Concrete is more applicable material than other radiation shielding materials because of its resistance and low cost. One of the concrete types used for radiation shielding is barite. Barite ($BaSO_4$) can be used directly or as an aggregate in concrete for shielding purposes. The shielding properties of this material against radiation are presented in terms of the linear attenuation coefficient (μ, cm^{-1}) and it is defined as the probability of a radiation interacting with a material per unit path length [6]. Heavyweight, or high density, concretes are largely used for shielding against radioactive rays in nuclear power stations, medical units, or wherever impenetrability against radioactive rays is needed. Thus, heavyweight concrete has also been known as radiation shielding concrete [7-9]. The first step in making heavyweight concrete is the selection of appropriate aggregates to obtain the required density. ASTM C637- 96 [10] and ASTM C638-92 [11] present properties of heavyweight aggregates that can be used in making concrete. The mix design of heavyweight concrete is similar to that of normal concrete [10]. The mix design for heavyweight concrete is described in Appendix (4) of ACI 211 [12] along with some examples. To obtain proper mix designs for heavyweight concrete, it is necessary to make more experimental specimens in order to assess optimum amounts of fine and coarse aggregates and also to diagnose possible problems that may arise. The type and quantity of aggregate and the cement dosage in concrete are important factors in terms of the radiation protection properties of concrete [13]. In general, the strength of the shield against radiation penetration has a direct relationship to the thickness of the shield. The most difficult problem to consider when designing a shield is fast neutrons [14,15]. The compressive strength is not a predominant factor because of the thickness of the radiation shields and the use of high quality concrete in the mixtures. Furthermore, the average shrinkage of heavyweight concrete is 30% higher than that of conventional concrete. In accordance with code Turkish Code (TS) 3440, conventional concrete should be durable against harmful water, fluids, and gases [16]. However, there is no such necessity in heavyweight concrete, only in those used as protectors against radiation [17]. Radiation transmission of heavyweight concretes including normal and barite aggregates measured for different ϒ-ray energies and calculated the linear attenuation coefficients. These results are about 0.138–0.157 cm^{-1} for barite concretes and are about 0.102–0.107 cm^{-1} at 1.25 and 1.33 MeV [18,19]. Radiation transmission and angular distribution for 25 MV X-rays by using LINAC has been studied [20]. Shielding properties of concretes including ilmenite and magnetite aggregates for neutron shielding by using ^{252}Cf radioactive source and BF_3 neutron detector were studied [21]. In National Council on Radiation Protection Measurements (2005), Tenth-Value Layers (TVLs) were reported for concrete, lead and steel at 6 MV and 18 MV beams. The TVLs of conventional concrete are 6–8 times lower than that of lead and 3.5–4.5 times lower than that of steel at 6 MV and 18 MV beams [22]. TVLs for heavyweight concretes with ferrophosphorus, limonite, ilmenite, magnetite and barite at 4 MV, 6 MV and 10 MV beams theoretically calculated by using Monte Carlo Simulation Code MCNP. Results showed that TVLs decreased with increasing density of the concrete [23]. In the present study, the mechanical characteristics of heavyweight concrete containing hematite were investigated. Another aspect of the study was measurement of radiation attenuation coefficients of heavyweight and normal-weight concretes produced by using hematite and normal aggregates for 70 KeV and 570 KeV ϒ-rays energies of ^{137}Cs radioactive isotope and calculation the linear attenuation coefficients (μ, cm^{-1}).

ISSN 2055-6578(Print), ISSN 2055-6586(online)

METHODOLOGY

Materials

In all mixtures, the same Ordinary Portland Cement (CEM II) was used. The chemical composition and physical properties of the cement are given in Table 1. Two different aggregates such as hematite and normal were used in this study. Hematite was supplied from hematite Mine Azardash Industry (in Iran). Figure 1 show the hematite fine sand and gravel aggregates. Table 2 presents the physical properties of the aggregates used in the experimental program. The maximum particle size of aggregate was kept constant at 20 mm in all mixtures. The water absorption capacity and the relative specific gravity of aggregates were determined according to .As expected the higher values of density are found for the hematite aggregates. In addition to that, it is important to remark the higher absorption obtained for the hematite fine sand 0/4, which is at least twice as big as the measured for the normal aggregates.

Fig. 1. Image of hematite fine sand and gravel aggregates

Table 1: Chemical composition and physical characteristics of the cement

Oxides	Composition (%)
Chemical composition	
Silicon dioxide (SiO_2)	21
Aluminum oxide (Al_2O_3)	5.3
Ferric oxide (Fe_2O_3)	3.3
Calcium oxide (CaO)	59.2
Magnesium oxide (MgO)	3.2
Sulfur trioxide (SO_3)	2.7
Loss on ignition	3.8
Physical properties	
Specific gravity	3.03
Blaine (cm^2/g)	3200
Initial setting time (min)	120
Final setting time (min)	190
Expansion in the Le Chatelier apparatus (mm)	4
Compressive strength (MPa)	
2-day	23.5
7-day	35.3
28-day	47

ISSN 2055-6578(Print), ISSN 2055-6586(online)

Table 2: The densities and water absorption values of aggregates

Type of aggregate	Particle density (g/m3)	Water absorption (%)
Limestone (0-5 mm)	2.64	2.00
Limestone (5-20 mm)	2.66	1.50
Hematite (0-5 mm)	3.22	4.50
Hematite (5-20 mm)	3.25	4.00

Nomenclature coding of the mixtures

The concrete mixtures were designated with the following codes: if the whole volume of aggregate is normal aggregate the concrete is called N – N; if it is hematite it is called H – H; if the coarse aggregate is normal and fine aggregate hematite it is called N – H; while coarse aggregate that is hematite and the fine aggregate normal it is H – N.

Mixture design and preparation of specimens

Four different series of concrete were prepared in the study. In all mixtures, cement and water content were kept constant as 404 kg/m^3 and 190 kg/m^3, respectively. Water/cement ratios in high density concretes are similar to those for ordinary concretes (approximately half time), but the aggregate/cement ratios will be significantly higher, because of the higher density of the aggregates. In this research, mix designs have been made according to ACI 211-1 [12]. All mixtures were prepared in a rotary planetary mixer with capacity of 60 L. The batching sequence consisted of mixing the all aggregates and cement for 1.5 min. After adding the total mixing water, the mixtures were also mixed for 2 min. After 1.5 min of rest, mixing for an additional 2 min was carried out. Hence, the total mixing time for the mixtures was 7 min. Percentage composition of four types of concrete studied at this research and their densities are given in Table 3. It should be mentioned that the mix designs have been adjusted on the basis of the 250-mm slump test. Each hardened concrete sample was divided using a disc cutter into 2 different thicknesses (1 and 3 cm) and radiation measurements were carried out on these samples. Fig. 2 exhibits the cutting area of a concrete with hematite aggregates.

Fig. 2. Cut specimens

ISSN 2055-6578(Print), ISSN 2055-6586(online)

Table 3: Specifications of the four mix designs for measuring Ɣ-ray attenuation coefficients and the mechanical characteristics

Mix design ρ (kg/m^3)	Ingredients (kg/m^3) C	FNA	CNA	FHA	CHA	W	W/C
H - H 3100	404	-	-	1321	1185	190	0.47
N - N ~ 2300	404	700	1004	-	-	190	0.47
H - N 2700	404	951	-	-	1155	190	0.47
N - H 2600	404	-	1082	924	-	190	0.47

C = cement, FNA = fine normal aggregate, CNA = course normal aggregate, FHA = fine hematite aggregate, CHA = coarse hematite aggregate, ρ = density of concrete

RESULTS AND DISCUSSION

Mechanical properties of concrete

In this study, through experimentation, the physical and mechanical properties of heavyweight concrete containing hematite were investigated. The procedures for testing most fundamental mechanical properties, such as compressive strength (ASTM C39-86) [24], splitting tensile strength (ASTM C496-87) [25] and rupture modulus (ASTM C293-79) [26] were used. The results of these experiments are listed in table 4. The hematite unite weight of approximately 3250 kg/m^3 found in physical experiments is the desired value for heavyweight concrete production. The inclusion of hematite aggregates in concrete does not increase the concrete's strength to reflect their aggregates' higher strength and higher density, as previously thought, because cracks propagate in the paste of concrete. Among those designated mixtures in the testing program, it is found that the H – H sample has lower compressive strength than other concrete samples. In fact, an inclusion of fine and coarse heavy aggregate reduces compressive strength to 7.2% and 48.8% that of conventional concrete, respectively.

Table 4: Results of mechanical experiments of produced heavyweight concretes

Mixture code	Compressive strength (MPa) 3 d	7 d	28 d	Tensile strength (MPa) 3 d	7 d	28 d	Rupture modulus (MPa) 28 d	Mixture permeability (m/s) 28 d
H – H	8.4	9.5	11.5	0.9	1.1	1.5	1.2	1.18×10^{-10}
N – N	19.5	20.7	26.8	1.6	1.9	2.5	4.8	1.18×10^{-11}

ISSN 2055-6578(Print), ISSN 2055-6586(online)

H – N 2.36×10^{-11}	14.8	16.1	18	1.4	1.7	1.9	4.1
N – H 7.08×10^{-11}	15.4	18.5	25	1.5	1.8	2.3	4.6

d = days

The splitting tensile test was used to determine the tensile strengths of concrete. From the test reported, considerable decrease in the 3, 7 and 28 days strengths caused by the incorporation of hematite aggregate can be easily found. Although the density of N - N sample is less than others, it gave us the best tensile strength. As shown in Fig. 3 cracking pattern occurs when the strength of aggregate is weaker than the paste. The fractured face of the split cylinder reveals many pullout cavities on the surface on which the hematite are located.

Fig. 3. Cracking pattern

The three-point bending flexural test is used to estimate the rupture modulus of heavy concrete (Fig. 4). Flexural strength followed the similar trend of compressive and tensile strengths and measured maximum value of modulus of rupture for all mixes (except for the specimen coded H – H). Moreover, results showed higher values of modulus of rupture in the mixes of N – N and N – H rather than other concrete samples.

Fig. 4. Test setup for Flexural Strength

The permeability was conducted on three samples for all mixes and the hydraulic gradient (i) was measured and the average value was reported. Fig. 5 shows the permeability test set up

ISSN 2055-6578(Print), ISSN 2055-6586(online)

concrete samples. The control mix had a permeability of 1.18×10^{-11} m/s. The results indicated an increase in permeability with the increase in hematite content. For the H – H, H – N and N – H samples, the permeability increased by 10, 2 and 6 times, respectively. The reduction in permeability for the H – N sample is less severe. The results clearly indicate the diverse effect of hematite on blocking the interconnected voids, therefore, resulting in an increase in permeability.

Fig. 5. Test setup for permeability

Radiation transmission

If N_o ϒ-rays from a ϒ-ray source strike a body with a thickness of x, not all the ϒ-rays will pass through the body. If the number of output rays, N, is measured by a detector, it will be observed that the output rays, N, will be less than the input ones. In general, for all bodies, the amount of N decreases exponentially in proportion to its thickness, x; so that Eq. (1) holds between N and N_o [27]. In this equation, μ, known as ϒ-ray attenuation coefficient, is the slope of the curve that shows variations of $\ln(N_o/N)$ with respect to the thickness of the body.

$$\mu = \ln(N_o/N)/x \qquad (1)$$

Where x is the sample thickness and N and N_o are the number of counts recorded in the detector with and without the shielding targets, respectively. For our purposes, the Caesium – 137 sources in Pishgam-Tajhiz Company in city of Tehran was used to produce ϒ-rays. To measure the ϒ-ray attenuation coefficient, the amount of ϒ-rays detected by detectors was initially measured after 30 sec in the absence of concrete barriers (N_o). Concrete specimens of different thicknesses were then placed in the direction of ϒ-rays and the amount of ϒ-rays detected by the detectors after 30 sec were measured. $\ln(N_o/N)$ with respect to thickness. The slope of this curve designates the ϒ-ray attenuation coefficient. The source used in this study radiates two ϒ-rays at 70 KeV and 570 KeV energy levels .For the gamma and X-ray energies common in nuclear instruments used to test concrete, the absorption coefficient includes contributions from a scattering reaction, called Compton scattering, and an absorption reaction, called photoelectric absorption. The relative contributions of both are a function of the energy of the incident ray. The Compton scattering is the dominant process for gamma or X-ray energies in the range from 60 KeV to 15 MeV, while photoelectric absorption dominates below 60 KeV. In Compton scattering, a gamma or X-ray loses energy and is deflected into a new direction by a collision with a free electron. In photoelectric absorption, a gamma or X-ray is completely absorbed by an atom, which then emits a previously bound electron. The amount of Compton scattering that occurs at a given gamma or X-ray energy is function of the density of the sample being irradiated. Consequently, for the energy used in this investigation, the absorption coefficient will be function of the density of the concrete [28]. The schematic arrangement of experimental setup of the measuring system used in the present study is shown in Fig. 6. Fig. 7 shows the setup of the equipment used in the attenuation test.

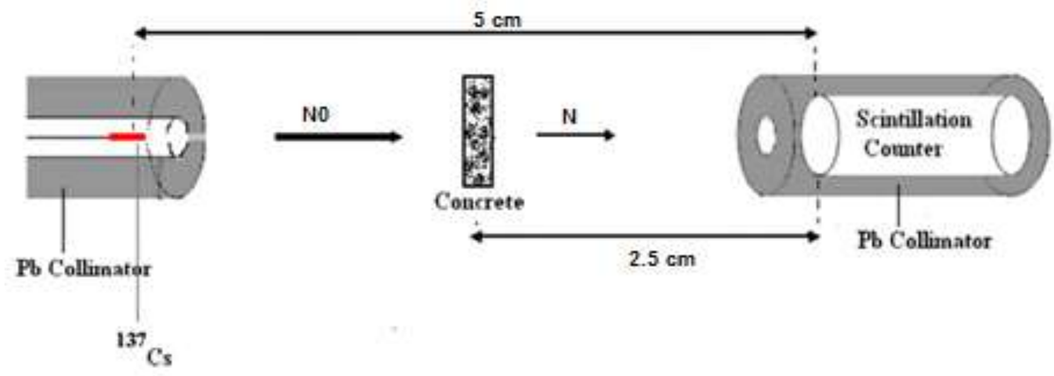

Fig. 6. Schematic diagram (describing the electronic part of the measuring system of NaI (Tl) scintillation detector with ^{137}Cs)

Fig. 7. Instruments which produces ϒ-ray and detector

The linear attenuation coefficients (μ, cm^{-1}) obtained for the mixes with hematite and normal aggregates are listed (Table 5, 6). Based on the results, it becomes clear that the concrete with hematite presents a greater shielding capacity than the conventional concrete. In fact, the value for the coefficient of radiological attenuation is increased approximately 30% in the former.

ISSN 2055-6578(Print), ISSN 2055-6586(online)

Table 5: Unit weight of concretes and linear attenuation coefficients at 70 KeV Y-rays

Mixture code	Density (Kg/m^3)	Specimen depth (cm)	Intensity N_o (KeV)	Intensity N (KeV)	lnN_o /N	Linear attenuation coefficient (μ, cm^{-1})
H – H	3100	1	70	52	0.2973	0.1670
		2	70	44	0.4643	
N – N	~ 2300	1	70	59	0.1709	0.1264
		2	70	52	0.2973	
H – N	2700	1	70	55	0.2412	0.1571
		2	70	47	0.3983	
N – H	2600	1	70	56	0.2231	0.1542
		2	70	48	0.3773	

Table 6: Unit weight of concretes and linear attenuation coefficients at 570 KeV Y-rays

Mixture code	Density (Kg/m^3)	Specimen depth (cm)	Intensity N_o (KeV)	Intensity N (KeV)	lnN_o /N	Linear attenuation coefficient (μ, cm^{-1})
H – H	3100	1	570	433	0.2749	0.1708
		2	570	365	0.4457	
N – N	~ 2300	1	570	471	0.1908	0.1314
		2	570	413	0.3222	
H – N	2700	1	570	449	0.2386	0.1538
		2	570	385	0.3924	
N – H	2600	1	570	446	0.2453	0.1497
		2	570	384	0.3949	

The attenuation coefficient values for the H – H sample is 6.3% and 8.3% and also 11% and 14% higher than the average measured in mixes of H – N and N – H at photon energies of 70 and 570 KeV, respectively. The difference observed in the case of the H - H is explained solely by the higher density and the consequent enhanced capacity provided by the hematite aggregate to shield the gamma ray radiation. On the other hand, the average unit weights of the concrete specimens are 3100 kg/m^3, 2700 kg/m^3 and 2600 kg/m^3 for H - H, H - N and N – H samples, respectively. These results show that the radiation attenuation of the concrete increased in direct proportion to the density of the concrete. In other words, high density concrete attenuates more radiation. In fact, it is well known that the density of concrete increases with increasing hematite content.

SUMMARY AND CONCLUSIONS

The number of reinforced concrete building containing any source of radiation is increasing every day. Therefore, as is done in this study, application of nuclear physics research on concrete technology is important to determine the radiation resistance of concrete. In order to increase the use of hematite ore as aggregate in the concrete with structural responsibility and

ISSN 2055-6578(Print), ISSN 2055-6586(online)

for radiological shielding purposes, a series of tests and analysis were performed. The following conclusions may be derived from the study.

- The compressive and tensile strengths of heavy concrete decreases as hematite content increases. Among those designated mixtures in the testing program, it is found that the concrete including hematite aggregate has lower compressive and tensile strengths than conventional concrete, which implies a lower cracking resistance.

- The crack front in heavy concrete is similar to that in normal concrete. The beam crack appears shorter in the middle than at the sides due to bending. Also, it can be concluded that the values of modulus of rupture in normal-weight concrete are higher than other concrete samples.

- In relation to the density, the addition of hematite has a positive impact towards obtaining a heavyweight concrete. The density of mixes with hematite aggregate is approximately 35% higher than that of concretes with a limestone aggregate.

- By increasing concrete density, the value of ϒ-ray attenuation coefficient increases. This is witnessed by the fact that the value of the ϒ-ray attenuation coefficient in heavyweight concrete with hematite aggregate is higher than that of normal weight concrete with limestone aggregates. The results obtained from this study showed that ϒ-ray attenuation in concrete is directly related to concrete density. It is, therefore, concluded that every internal agent increasing concrete density will correspondingly increase the value of the ϒ-ray attenuation coefficient of the concrete.

- The results for radiological protection show that the attenuation coefficient of gamma rays for concretes with hematite are nearly 32% and 30% higher than for the conventional concrete at photon energies of 70 and 570 KeV, respectively. Thus, the hematite would be preferred to normal aggregate in concrete as materials for building construction of radiation oncology departments, radiology departments, nuclear reactors and radiation research laboratories against photon radiations.

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