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Physical and mechanical properties of concrete containing hematite as aggregates

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Abstract

Radiation limits above permission limit have harmful effects on living bodies (i.e., carcinogenic, etc.). Heavyweight concrete is used in facilities such as nuclear power plant and radiotherapy room where radioactive impermeability is required. Aggregate and cement play an essential role in both the shielding performance and the structural behavior of concrete. Concretes with 0% (control), 15%, 30%, 45% and 60% of conventional aggregate replaced by hematite aggregate for each control concrete, were fabricated with 300, 350, 400 and 450 kg/m^3 cement contents. Water-cement ratio was kept constant at 0.40. In addition to investigation of the mineralogical structure of hematite, physical and mechanical experiments were carried out on the concrete produced. The results show that slump and compressive strength, like other mechanical properties, increase as the hematite aggregate replacement volume increase.

Keywords: heavyweight concrete; hematite; mechanical property; radiation shielding.

1. Introduction

Concrete is one of the most important materials used for radiation shielding in facilities containing radioactive sources and radiation generating equipment [1]. The reason behind this is that concrete is a relatively inexpensive material, which may be easily handled and cast into complex shapes. It contains a mixture of many light and heavy elements and therefore has good nuclear properties for the attenuation of photons and neutrons [2]. In nuclear engineering, heavy concrete is used in biological shields or in shielding walls in a reactor vessel, as shown in [3]. Nuclear reactors are usually surrounded by thick layers of concrete. This concrete plays two roles: in supporting the reactor and its related equipments and in protecting surroundings from the high level radiations emitted from the reactor [4]. With the modernization of radiotherapy centers, Co-60 is largely replaced with medical linear accelerators in radiotherapy units, where radiation impermeability is required [5, 6]. In these facilities, the two most important features are: resistance against earthquake represented by strength of the building and resistance against radiation expressed as radiation attenuation. Since environmental protection is now a significant issue, more efforts must be made to understand heavyweight concretes and their structural behavior.

As far as shielding properties of concrete are concerned, physical and mechanical properties of concrete, which also affect its shielding performance, may vary depending on the composition of concrete. Aggregates are the largest constituent (about 70–80% of the total weight of concrete). Thus, aggregate type and content are important factors affecting concrete properties. Different types of natural and artificial aggregates are used to enhance the properties of the concrete [7]. Special heavy aggregates, such as hematite, ilmenite and cast iron or steel scrap, may be used to produce concrete shielding radiation [1, 8–10]. Here, each country has to gain its own experience, depending on the available cheap and effective local materials [7].

Concrete has many desirable properties from a nuclear radiation shielding point of view. These properties can be changed to suit special shielding needs. These needs fall into categories such as, higher neutron and gamma attenuating performance and higher temperature resistance [11, 12]. Hematite is a commonly used material as aggregate in making radiation shielding concrete to satisfy these demands. However, as well as radiation shielding characteristics of concrete containing hematite aggregates, physical and mechanical properties must be considered, since it is very crucial that concrete used in structures requiring radiation impermeability should have some enough engineering properties required, such as compressive strength, resistance against earthquake forces and prolonging service life of structures.

Concrete may be considered as a kind of three-phase composite material, with the three phases being hardened cement paste, aggregate and interfacial zone between the hardened cement paste and aggregate. As the compressive strength of concrete is mainly dependent on the adhesion between aggregate and cement paste, failures happen within the hardened cement paste and/or along the interfacial zone [13]. Therefore, attention should be paid to the effect of aggregate type on the bond.

In previous studies, radiation attenuation of concrete containing hematite [14] and the protective effect of concrete produced with hematite on rats [15] were investigated. However, limited studies have been reported on the mechanical properties of concrete containing hematite. In this study, the effect of hematite aggregate and cement content on the physical and mechanical properties of concrete have been investigated. Also, the mineralogical structure of hematite and the interfacial zone between cement paste and hematite aggregate were studied.

2. Materials and methods

2.1. Aggregates

Aggregates typically constitute 70–80 wt% of concrete. Their type and gradation play an essential role in modifying concrete properties. Thus, the influence of aggregate type and gradation has become more important on the mechanical properties of concrete [16–18]. Plain concrete (PC), using limestone-based aggregates (L) with three different grain sizes: up to 3 mm size crushed stone (CSt-I), up to 7 mm size natural river stone (NRS) and 7–15 mm size crushed stone II (CSt-II), was produced. The aggregates were graded, washed and cleaned of clay and silts. To reduce the difficulties in producing, mixing and placing of concretes and to prevent segregation of heavyweight aggregate in the fresh concretes, the maximum aggregate size was selected as 16 mm diameter. Gradations of aggregates are presented in Figure 1.

In this study, hematite was adopted as a replacement for concrete aggregates. Hematite is a natural red rock that contains iron oxide. When pure, it has a Mohs hardness between 5.5 and 6.5 and a specific gravity between 4.9 and 5.5 g/cm^3. However, physical properties of rocks in which hematite is the main constituent, may vary considerably; the specific gravity of hematite ores can range between 3.2 and 4.3. Some ores are soft and produce dust in the course of being handled, which would make them a poor aggregate for heavy concrete. Hematite particles tend to be flaky, which is undesirable in regard to the workability of concrete [1].

Hematite was prepared as an aggregate by crushing and grounding the ore in a laboratory mill, then sorting it via sieves into two groups of coarse (H_c) and fine (H_f) aggregates (Figure 2). Specific gravity, water absorption and loose and dry rodded unit weight were determined according to ASTM C 127, ASTM C 128 and ASTM C 129 standards. Physical and mechanical properties of all aggregates are presented in Table 1. The chemical composition of hematite is presented in Table 2.

2.2. Cement

The cement used in the concrete mixtures was a normal Portland cement which corresponds to CEM II/A-M (P-LL) 42.5N Portland cement. Physical and mechanical properties and chemical analysis of cement are presented, respectively, in Tables 3 and 4. More than doubling of the compressive strength between 2 and 28 days, and nearly doubling the flexural strength in the same period, were noted.

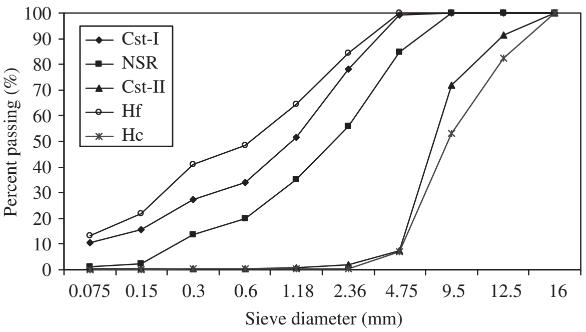

Figure 1 Particle size distributions of aggregates.

2.3. Superplasticizer

A superplasticizer based on a modified polycarboxylate was employed to obtain a satisfactory workability for the different mixes. Properties of the admixture are presented in Table 5.

2.4. Mix proportions

To investigate the effect of hematite aggregate on the physical and mechanical properties of concrete, PC and concretes containing hematite were investigated. Heavyweight concrete for radiation shielding can be prepared using the ACI method of absolute volumes developed for conventional concrete [19]. The absolute volume method is generally accepted and considered to be more convenient for heavyweight concrete [1, 20]. Hence, the absolute volume method to obtain denser concrete was used in the calculation of the concrete mixtures.

Theoretically, the water/cement (w/c) ratio is proposed as 0.30–0.50 for heavyweight concretes. Mixtures of concrete were chosen with w/c of 0.40. Four main groups (A, B, C and D) according to cement contents and five subgroups under each main group, according to hematite volume in the mixtures, were composed.

The cement dosage was accepted as 300, 350, 400 and 450 kg/m^3, which stand for the four main groups, respectively. In heavy concrete, the cement content is generally quite high, more than 350 kg/m^3. This helps to improve the shielding characteristics of the concrete because of the high bound water content of the paste [20].

Replacement ratios of hematite aggregate of 15%, 30%, 45% and 60% were used. The weights and volumes of used materials in the final mix design to obtain 1 m^3 of concrete for each mix proportion are displayed in Tables 6 and 7.

2.5. Mixing, casting, curing and testing specimens

The procedure for mixing heavy concrete is similar to that for conventional concrete. In a typical mixing procedure, the materials were placed in the laboratory mixer with a capacity of 60 dm^3 in the following sequence: first course aggregates, fine aggregates followed by cement, initially dry material mixed for 1 min and finally addition of water. After 1.5 min of mixing, chemical admixtures were finally introduced to the wet mixture.

The initial mixing time is more important for polycarboxylate based admixtures due to their dispersing mechanism. In order to sustain the equilibrium viscosity, longer mixing times are required, but because of high density of hematite, segregation is a danger. In order to prevent fresh concrete from segregation, the mixing duration was kept as low as possible. For each mixture, a good workability and sufficient strength gain were achieved.

After the mixing procedure was completed, a test was conducted on the fresh concrete to determine slump test

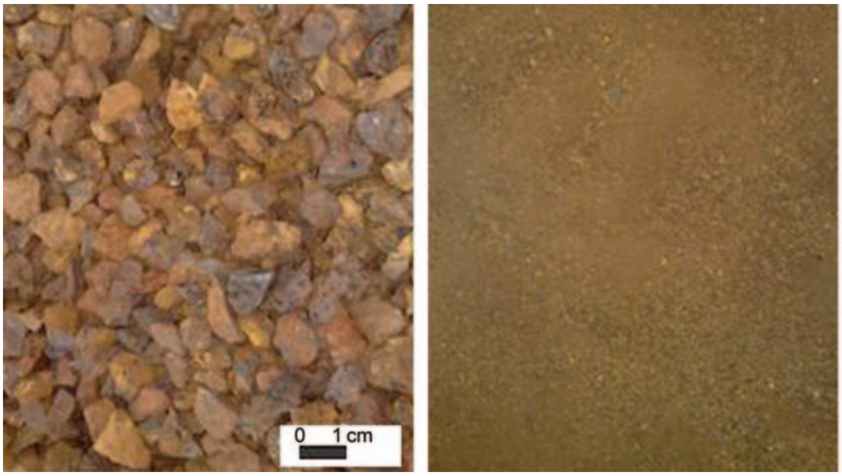

Figure 2 Coarse (left) and fine (right) hematite aggregates.

Table 1 Physical properties of aggregates.

Aggregate codes	Specific gravity (g/cm^3)	Water absorption (%)	Loose unit weight (kg/m^3)	Dry rodded unit weight (kg/m^3)
CSt-I	2.69	2.91	1913	2151
NRS	2.67	3.02	1830	1974
CSt-II	2.7	0.93	1676	1594
H_f	4.18	1.6	1956	2130
H_c	4.29	0.8	1733	1929

(ASTM C 143). Then, from each concrete mixture, six specimens were cast in three layers in cylindrical molds of 150 mm diameter and 300 mm height, each layer being consolidated using a vibrating table. However, the high specific gravity of hematite is such that excess compacting vibration, which can cause segregation, must be avoided. Casting of specimens was done in according with ASTM C 192. Six 150 mm cubes were cast. The cubes were used for the compressive strength, ultrasonic pulse velocity tests and Schmidt hardness and the cylinders were used for the splitting tensile strength test. After casting, the concrete specimens were covered with wet burlap and polyethylene sheets and kept in the laboratory at room temperature for 24 h. After demolding, they were placed in a saturated limewater bath until the time of testing. Curing was done in accordance with ASTM C 511. It is well recognized that adequate curing of concrete is very important, not only to achieve the desired compressive strength, but also to make durable concrete. The compressive strength tests were carried out in accordance with ASTM C 39 at 28 days. The splitting tensile strength tests were done according to ASTM C 496 at 28 days. The Schmidt hardness measurements were done after 28 days of curing. Schmidt hardness was done according to ASTM C 805-85.

Table 2 Chemical composition of hematite.

Compound	Weight %
Fe_2O_3	82.26
MnO	0.13
MgO	1.54
TiO_2	0.03
Al_2O_3	0.57
CaO	4.68
SiO_2	4.15
LOI*	5.63

*Loss of ignition.

Table 3 Physical and mechanical properties of Portland cement.

Compressive strength (MPa)			Flexural strength (MPa)			Initial setting time (h)	Final setting time (h)	Le chatelier (mm)	Specific gravity (g/cm^3)	Blaine (cm^2/g)
2 days	7 days	28 days	2 days	7 days	28 days	2.25	3.15	1	3.15	4150
22.5	36.6	47.8	3.7	5.6	6.9					

Table 4 Chemical analysis of Portland cement.

Compound	Weight %
Total SiO_2	22.9
Al_2O_3	5.32
Fe_2O_3	3.63
CaO	55.83
MgO	1.99
SO_3	2.62
Cl	0
LOI*	4.2
Free CaO	0.82
Total admixture	19.45

*Loss of ignition.

Table 5 Properties of chemical admixture.

Specific gravity	pH	Solid content (%)	Main component
1.08	5.7	40	Polycarboxylic ether

3. Results and discussion

3.1. Physical properties of concretes

Along with the physical properties of concrete, hematite was also studied as a mineral. From Figures 3B and D, it can be determined that hematite consists of two zones: oxide (H_o) and fresh (H_{fr}). Hematite aggregates have high porosity (Figure 3A and C) – a consequence of voids which have appeared during formation of hematite. We also note that hematite has the form of flakes.

The effect of incorporating metallic aggregate into the concrete on concrete properties was evaluated by testing the concrete, containing different proportions of hematite and cement content.

Three are factors affecting mix proportions, which are water/cement (w/c) ratio, aggregate/cement (a/c) ratio and water content. The a/c ratios were 8.24, 6.74, 5.52 and 4.74 for groups A, B, C and D, respectively. As seen from Figure 4, the a/c ratio has decreased. However, if the w/c ratio is kept constant and the water content increases in the mixture, workability of fresh concrete increases. It was observed that slump values of concretes increased gradually, depending on the increment in hematite and cement content in the mixture. D5 had the highest slump value, which was 22 cm. The increment in hematite and cement content may increase the slump value due to the high specific gravity of hematite. However, the H_c may have a tendency to disturb the mixture homogeneity.

The result of the slump test was shown in Figure 4. An important consideration, whenever high strength is desired, is the obtaining of adequate workability according to the selected w/c ratio. In this respect, it can be said that concretes containing different proportions of hematite and cement had a high compressive strength and adequate workability.

3.2. Mechanical properties

3.2.1. Compressive strength Compressive strength is the most important and desired property of concrete, showing concrete quality. The results of compressive strength tests were presented in Figure 5. In general, inclusion of hematite raised the compressive strength, as seen from Figure 5. The compressive strength was also increased up to 65 MPa, depending on the cement content in the mixture. However, it should be kept in mind that

Table 6 Mixture proportions.

Group	Subgroup	Cement (kg/m^3)	Water (kg/m^3)	SP (kg/m^3)	CSt-I (kg/m^3)	NRS (kg/m^3)	CSt-II (kg/m^3)	Hf (kg/m^3)	Hc (kg/m^3)
A	1	300	117.0	3.0	528	524	1060	0	0
	2	300	117.0	3.0	449	445	901	246	253
	3	300	117.0	3.0	370	367	742	492	505
	4	300	117.0	3.0	290	288	583	738	758
	5	300	117.0	3.0	211	210	424	984	1010
B	1	350	136.5	3.5	504	500	1011	0	0
	2	350	136.5	3.5	428	425	859	235	241
	3	350	136.5	3.5	353	350	708	470	482
	4	350	136.5	3.5	277	275	556	705	723
	5	350	136.5	3.5	201	200	404	939	964
C	1	400	156.0	4.0	480	476	963	0	0
	2	400	156.0	4.0	408	401	819	224	230
	3	400	156.0	4.0	336	333	674	447	459
	4	400	156.0	4.0	264	262	530	671	689
	5	400	156.0	4.0	192	191	385	894	918
D	1	450	175.5	4.5	456	452	915	0	0
	2	450	175.5	4.5	387	384	777	212	218
	3	450	175.5	4.5	319	317	640	425	436
	4	450	175.5	4.5	251	249	503	637	654
	5	450	175.5	4.5	182	181	366	850	872

Table 7 Volumes of aggregates in the mixtures in %.

Groups	Subgroups	Hematite ratio	CSt-I	NRS	CSt-II	H_f	H_c
A	1	0	25.00	25.00	50.00	0.00	0.00
	2	15	21.25	21.25	42.50	7.50	7.50
	3	30	17.50	17.50	35.00	15.00	15.00
	4	45	13.75	13.75	27.50	22.50	22.50
	5	60	10.00	10.00	20.00	30.00	30.00
B	1	0	25.00	25.00	50.00	0.00	0.00
	2	15	21.25	21.25	42.50	7.50	7.50
	3	30	17.50	17.50	35.00	15.00	15.00
	4	45	13.75	13.75	27.50	22.50	22.50
	5	60	10.00	10.00	20.00	30.00	30.00
C	1	0	25.00	25.00	50.00	0.00	0.00
	2	15	21.25	21.25	42.50	7.50	7.50
	3	30	17.50	17.50	35.00	15.00	15.00
	4	45	13.75	13.75	27.50	22.50	22.50
	5	60	10.00	10.00	20.00	30.00	30.00
D	1	0	25.00	25.00	50.00	0.00	0.00
	2	15	21.25	21.25	42.50	7.50	7.50
	3	30	17.50	17.50	35.00	15.00	15.00
	4	45	13.75	13.75	27.50	22.50	22.50
	5	60	10.00	10.00	20.00	30.00	30.00

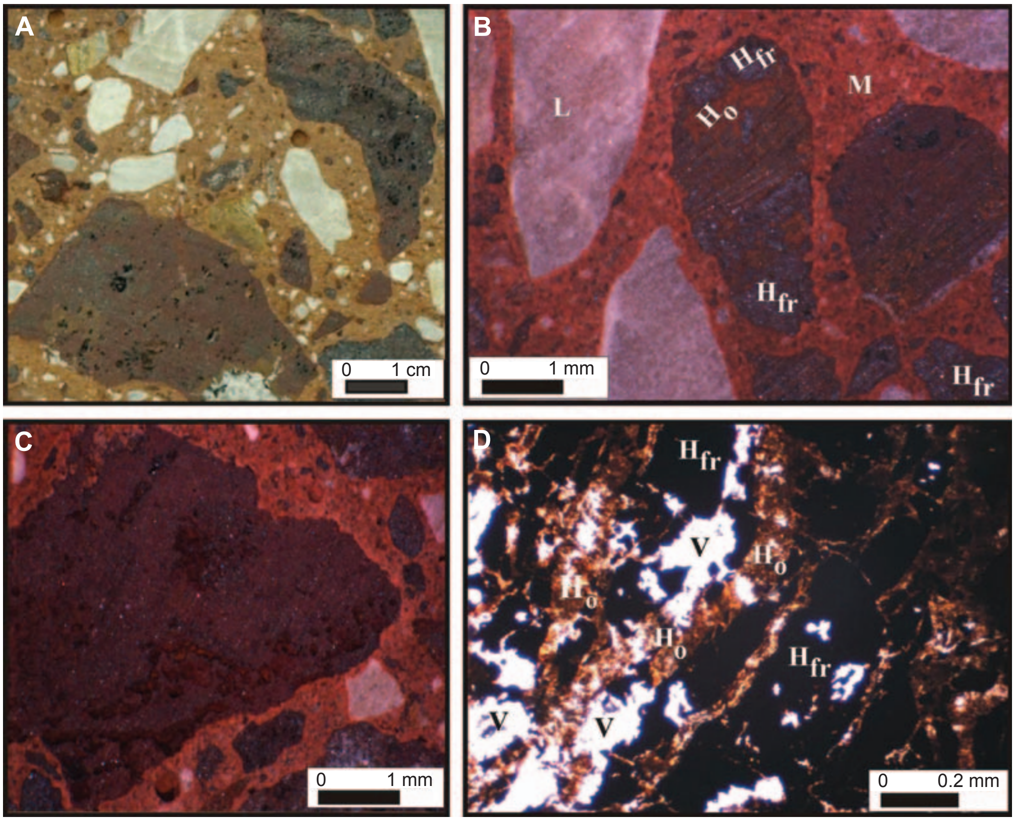

Figure 3 The microscopical view from the hematite showing its structural form.

cement contents over 450 kg/m^3 may cause high and rapid hydration heat and potential consequent cracking. It is well known that cracks in concrete negatively affect shielding performance.

Furthermore, another point to be considered is the interface zone between cement paste and coarse hematite aggregate. The surface texture of the coarse aggregate is partly responsible for the bond between the paste and the aggregate, due to

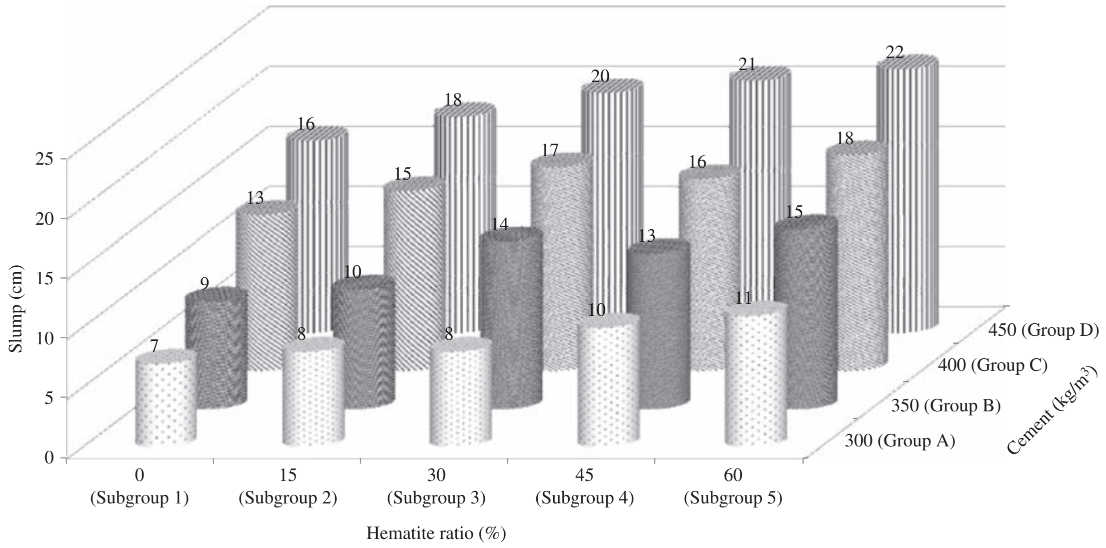

Figure 4 Slump variations of concrete with hematite and cement contents.

the mechanical interlocking. It has been determined that the mechanical properties of concrete are significantly affected by this bond. It can be seen in Figures 3A, B and C that hematite aggregates produced a great bond and transition zone due to their porous and rough surface texture. This is desirable for improving the mechanical performance of concrete. When compared to the study of Kan et al. [3], using iron shot in the concrete for shielding, hematite had increased the concrete properties. The investigation conducted by Oluokun and Malak [21] showed that the incorporation of ilmenite and hematite coarse aggregates into concrete mixes appeared to significantly increase the compressive strength, enhance the stress-strain behavior, and result in the production of tougher and more ductile concrete, with a compressive strength of about 36 MPa. Although Kaplan [1] reported that 20 MPa seems to be adequate for radiation shielding concrete, more is needed in regard to prolonging life and durability of seismic-resistant structures. In this study, the compressive strengths of the concrete produced, were greater than 60 MPa; this produced excellent aggregate gradation and mixture design.

In order to quantify the effects of hematite and cement content on the compressive strength of concrete, multiple regression analysis was applied to obtain the following equation:

$$f_{cs}=0.14056\ C+0.04233\ H+0.91;\ (R^2=0.85) \tag{1}$$

Here, f_{cs} is the compressive strength (MPa); C is the cement content (kg/m^3); H is the hematite content (%).

3.2.2. Splitting tensile strength The results of splitting the tensile strength tests for all mixtures are presented in Figure 6. As seen from Figure 6, in general, the tensile strength increased as the cement and hematite content increased in the mixture. Group D had a rise or drop in the splitting

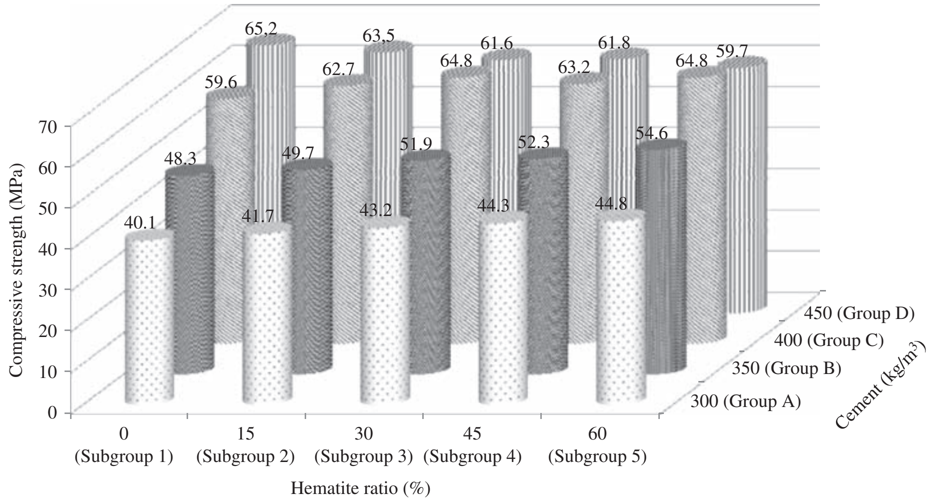

Figure 5 Compressive strength of concretes.

tensile strength, compared to the other groups. This may be due to the physical difficulties in providing a homogeneous distribution of the coarse hematite aggregate within this concrete group. The splitting tensile strengths of concretes containing hematite aggregate were higher than those of the PC, again probably due to stronger bonding between the cement paste and aggregate, as the splitting tensile strength was more sensitive to alteration of surface textures of coarse aggregate than the compressive strength.

The compressive strength and splitting tensile strength are two important indices used for characterizing mechanical properties of concrete. Furthermore, it has been widely reported that the splitting tensile strength can be estimated from the compressive strength of concrete [22]. This empirical relation can be summarized by the following general equation:

$$f_{spt}=A(f_{cs})^{B} \tag{2}$$

where f_{spt} is the splitting tensile strength (MPa); f_{cs} is the compressive strength (MPa); A and B are regression coefficients. In this study, the empirical relation obtained can be expressed as follows:

$$f_{spt}=0.43(f_{cs})^{0.63} \tag{3}$$

The coefficient of determination (R^2) of this proposed relation is 0.942, indicating a strong correlation.

3.2.3. Pulse velocity

The pulse velocity results are presented in Figure 7. The results show that the pulse velocity of concrete increased as the content of hematite increased. Because of the high specific gravity of hematite, the density of concrete is enhanced with increase of hematite content in the mixture and causes a decrease in pulse velocity time.

Whitehurst [23] classified the concretes as excellent, good, doubtful, poor and very poor for pulse velocity values of

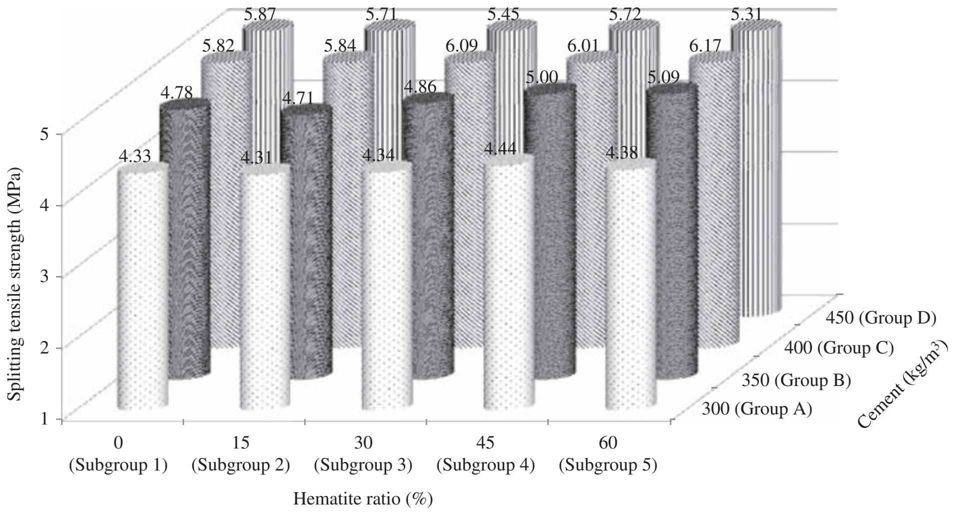

Figure 6 Splitting tensile strength of concretes.

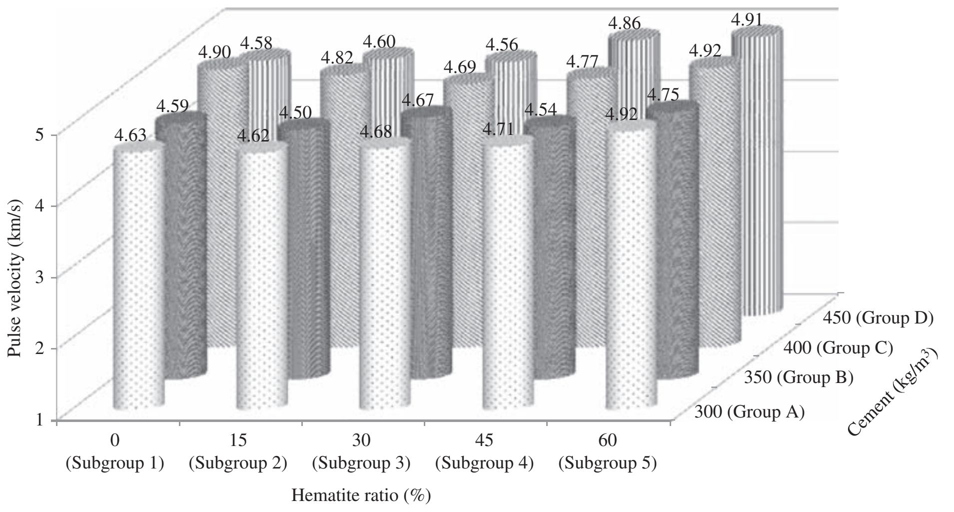

Figure 7 Pulse velocity of concretes.

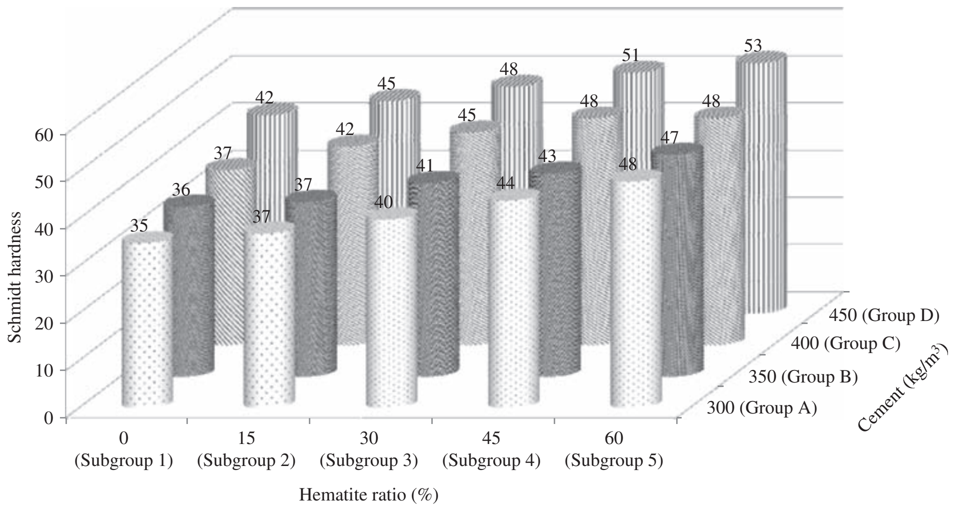

Figure 8 Schmidt hardness of concretes.

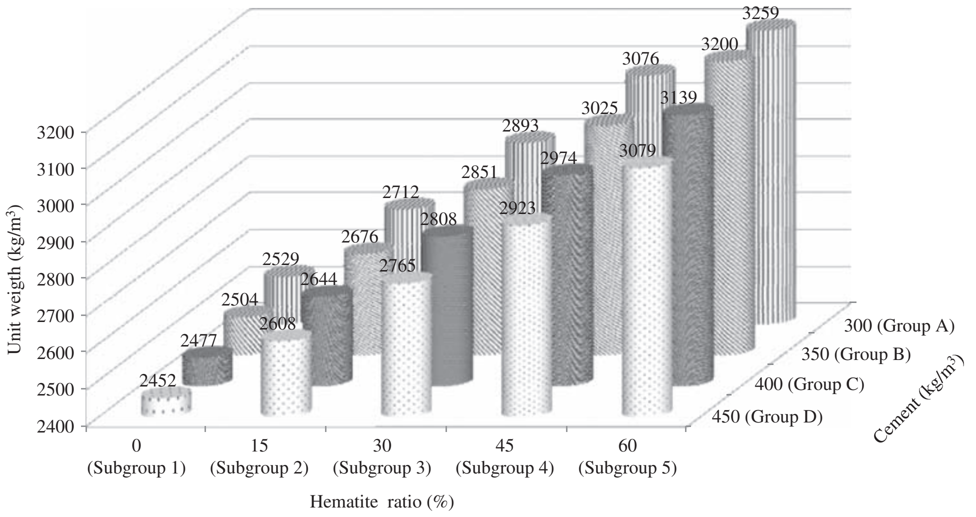

Figure 9 Unit weights of concretes.

4.5 km/s or greater, 3.5–4.5, 3.0–3.5, 2.0–3.0 and 2.0 km/s, respectively. Thus, all our concretes produced are excellent according to the Whitehurst classification.

3.2.4. Schmidt hardness The results of the rebound hammer measurements are presented in Figure 8. It is well known that rebound hammer measurements correlate strongly with concrete hardness. Thus, it was to be expected that the higher hardness of hematite aggregates would exhibit higher rebound hammer test values. As seen in Figure 8, the hardness of concrete is increased depending on hematite and cement content. Also, there is a connection between compressive strength and Schmidt hardness. When Figures 5 and 8 are considered together, it can be concluded that compressive strength and hardness coincide with each other.

Multiple regression analysis was applied to obtain the following equation:

$$S_h=0.0484\ C+0.195\ H+19.35;\ (R^2=0.935) \qquad (4)$$

where S_h is the Schmidt hardness of concrete; C is cement content (kg/m^3); H is hematite content (%). As can be seen from the high R^2 correlation coefficients, there is a strong agreement between the experimental and calculated values.

3.2.5. Unit weight One of the most important properties with regards to shielding is the unit weight of concrete; the greater the density, the more effective the shielding. The results of the unit weight measurements are presented in Figure 9. The Figure is reverse in the scale to see the unit weights of concretes. As seen from Figure 9, the unit weight increased with increase of the hematite content in the mixture.

However, the increment in cement content decreased the unit weight. This is a result of when the w/c is kept constant and the cement content is increased, the water content in the mixture increases. So, the aggregate volume in the mixture decreases, causing a reduction in the unit weight. Aggregate volumes were 0.78, 0.75, 0.71 and 0.68 for groups A, B, C and D, respectively. The maximum value of unit weight was 3259 kg/m^3, which belonged to A5.

4. Conclusion

The influence of hematite and cement content on the physical and mechanical properties of concrete was studied in this work. The following conclusions can be drawn:

1. The incorporation of hematite into concrete and the increase of cement content in the mixture significantly increased the slump and workability of concrete. However, increasing the water content of mixtures should be watched carefully, since concrete tends to segregate due to high density of hematite aggregates. The maximum slump measured was 22 cm.
2. Hematite aggregates exhibited a good adhesion with cement paste.
3. In general, addition of hematite and increased cement content in the mixture increased the compressive strength. However, it was observed that cement content greater than 450 kg/m^3 may cause segregation.
4. The pulse velocity and hardness of concrete containing hematite increased as hematite content increased. The result was consistent with the trend that unit weight increases with hematite content in concrete.
5. The unit weight of concrete increased dependent on hematite content. However, increase in cement content decreased aggregate volume in the mixture, causing a decrease in unit weight.
6. The mixture of D5 can be the optimum mixture with regards to shielding, since the D5 mixture has the highest unit weight and fairly high compressive strength.

The major outcome of this research, from the point of view of applications, was that hematite concrete has a high potential to be an excellent high performance concrete that can be used for structures where radiation impermeability is required.

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