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Research paper

Mechanical Properties and Thermal Neutron Absorption of Heavyweight Hematite Aggregate Concrete for Radiation Shielding

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Abstract

Heavyweight aggregate concrete (HWAC) is the most widely used material as radiation shielding for nuclear reactors. The density of HWAC is increased through the use of heavy natural aggregates such as barites, hematite and magnetite. This study determines the density of HWAC with hematite aggregate replacing granite at 0%, 10%, 20%, 30%, 40% and 50%, its compressive strength and thermal neutron absorption of 1 MeV fast neutrons. The physical properties of hematite which include gradation, specific gravity, water absorption and loose unit weight are determined. The chemical composition of hematite is also determined using X-ray fluorescent (XRF) analysis. The slump, density, compressive strength and thermal neutron absorption of the heavyweight concrete containing different proportion of hematite as aggregate are also determined. Results show that the slumps of HWAC are between 77 mm – 84 mm, the density of HWAC increases between 0.3% - 1.18% by increasing the hematite content. HWAC with 10% hematite exhibits highest strength at 52.5 MPa and the highest thermal neutron absorption at 2085 count per second. The optimum amount of hematite to replace granite for best strength and neutron absorption is 10%.

Keywords: *Compressive strength; heavyweight aggregate concrete; hematite; nuclear reactors; thermal neutron absorption.*

1. Introduction

Concrete with specific gravity which is more than 2600 kg/m^3 is known as heavyweight concrete (HWC) and aggregate with specific gravity more than 3000 kg/m^3 is known as heavyweight aggregate [1].The properties of HWC depend on the aggregate types because aggregates have different densities depending on the materials used, hence the name heavyweight aggregate concrete (HWAC). HWAC has higher density compare to normal concrete. Heavy aggregate can be from natural materials. Examples of natural materials are barite, magnetite and hematite (the material used in the process of making iron, lead and etc.)

The density of concrete depends on the type of aggregate used in the construction sector. Barite is commonly used to produce HWAC with density of 3500 kg/m^3 which is 45% higher compare to normal concrete. Meanwhile, magnetite HWAC has density 3900 kg /m3 which 60% higher than normal concrete [2]. Researches have shown that the density of HWAC with iron and lead aggregate produce higher density HWACs which are 5900 kg/m^3 and 8900 kg/m^3 respectively [3].

HWAC is used for the construction of nuclear power plants, research reactors and particle acceleration and high-level radioactive research laboratories. HWAC is used as a radiation protective material because radiation contains substances that can harm human health and environment. The effects of radiation from nuclear reactor plant are very dangerous for the surrounding environment, including human beings, if exposed for some time. The effects are human disability for lifetime and the destruction of flora and fauna. HWAC is less expensive but has the required mechanical properties for radiation protection compared to metals. It is a more environmental friendly material as it is manageable and can be formed into various complex shapes [4].

HWAC is a mixture of hydrogen, light nuclei and nucleus that has high atomic number [5]. The compositions of the aggregate in the concrete containing various elements improve the characteristics of concrete as a radiation protector and protective properties to weaken photon and neutron [6]. Radiation can be classified into two types: ionizing radiation and non-ionizing radiation. Meanwhile, the thermal neutron absorption is a process that reduces the number of neutrons and will reduce radiation exposure to the environment.

Gamma radiation, also known as gamma ray (γ) refers to electromagnetic radiation having a very high frequency and consists of high-energy photons. It is biologically dangerous. To protect from gamma rays, the density of concrete is the most important parameter and it leads to the increase in the thickness of concrete. The properties of concrete cover can be adapted to various applications by changing the composition and density. When the radiation protective concrete is used to shrink the neutron, the mass of light atoms that produces hydrogen should be sufficient and included in the concrete mix [7]. Some aggregates are used because it has the ability to retain water of crystallization at high temperature, to ensure a source of hydrogen in the HWAC.

Thus, the heavyweight aggregate have an important role in the production of radiation protection concrete for a nuclear reactor plant. In this study, hematite is used as aggregate replacement of 0%, 10%, 20%, 30%, 40% and 50% natural granite aggregate. There are other factors that influence the absorption of thermal neutrons which are water per cement ratio, curing and also the quality of concrete produced, which is beyond the scope of this paper.

2. Methodology

2.1. Materials

The aggregates are granite, hematite and natural sand. Coarse aggregate are sieved to obtain the well-graded distribution with maximum aggregate size of 12.5 mm, while the fine aggregate is sieved to obtain maximum size not exceeding 4.75 mm (ASTM C136-06) [8]. Hematite is sieved to divide into coarse and fine based on the standards of sand and coarse aggregates. The specific gravity of sand, granite, fine hematite and coarse hematite are 2.62, 2.7, 3.3 and 3.44 respectively. The percent absorptions of all aggregates are 0.84, 0.50, 2.04 and 1.12% respectively.

2.2. Grading of aggregates

The sieve analysis that determines the grade of an aggregate was done following ASTM C136-06 [9] and ASTM D422 [10] using the EFL 2000/2 sieve shaker. The maximum aggregate size should be specified in the mix calculation concrete to determine the workability.
In this study, coarse aggregates were sieved to get the required aggregate size of which cannot exceed 12.5 mm size openings of sieve, while the fine aggregates were sieved to obtain the size that is not exceeding 4.75 mm. Hematite aggregates were also sieved to separate them into two, coarse hematite and fine hematite to replace granite aggregate and sand, respectively.

2.3. Specific gravity test and water absorption

The specific gravity is the weight of aggregate particles relative to the volume of water equivalent. This test was carried out in accordance with ASTM C128 (2014) [11]. Water absorption of aggregates were determined to include in the calculation of free water in the mix.

2.4. Aggregate bulk density/ unit weight

This test was carried out to determine aggregate bulk density/ unit weight in accordance with ASTM C29- 09 (2014) [12].

2.5. Chemical composition analysis of hematite

X-ray fluorescence analysis (XRF) was carried out to determine the chemical content in hematite powder. XRP is able to analyze the grade up 100 ppm (parts per million).

2.6. Mix design proportion

The absolute volume method was applied in the mix design method of HWAC (ACI 211.1-91) [13]. The ratio of cement: sand: aggregate is 1:2:4 and the water: cement ratio is 1:0.42. The design strength is 40 MPa. The granite is replaced by 0%, 10%, 20%, 30%, 40% and 50% hematite aggregate (total of six mixtures). The control is where the granite replacement is 0%.

2.7. Mixing and Curing

The procedure for mixing heavyweight concrete is similar to that for conventional concrete. Slump test (BS EN 12350-2:2009) [14] of the fresh concrete was also performed for each mix. Then all concrete specimens were cast in molds and the molds were subjected to vibration. However, with the high specific gravity of hematite, excess compacting vibration which can cause segregation must be avoided. After 24 h, the specimens were demolded and then cured in lime-saturated water at 20 ºC ±2 ºC temperature for 28 days prior to testing.

2.8. Samples and testing

Samples includes (150×150×150) cm^3 specimens for density (BS EN 12390-7 2009) [15], compressive strength (BS EN 12390-3:2009) [16] and thermal neutron absorption (ASTM D6938 – 10) [17] tests. The thermal neutron test was done using MCM-2 Hydrotector to detect the thermal neutron absorption. The neutron source was 1.85 GBq Americium-241/Be with thermal neutron detector He-3, following the same configuration set up by [18].

3. Results and discussion

3.1 Grading of aggregates

Figure 1 and 2 show the grading of granite aggregates and sand while Figures 3 and 4 show the grading of fine and coarse hematite. All of the aggregates are well-graded because all of them are located within the upper boundary and the lower boundary specified by ASTM C33.

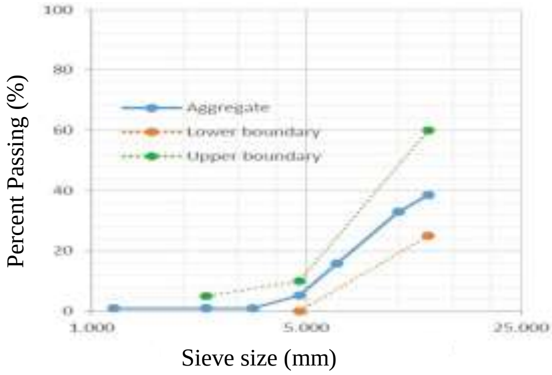


Fig. 1: Sieve analysis of aggregate.

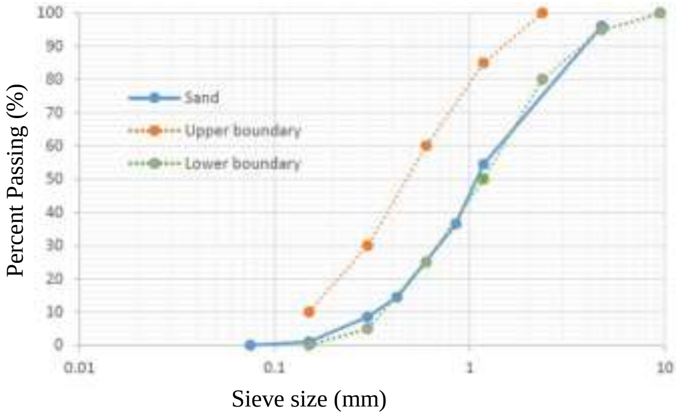


Fig. 2: Sieve analysis of sand.

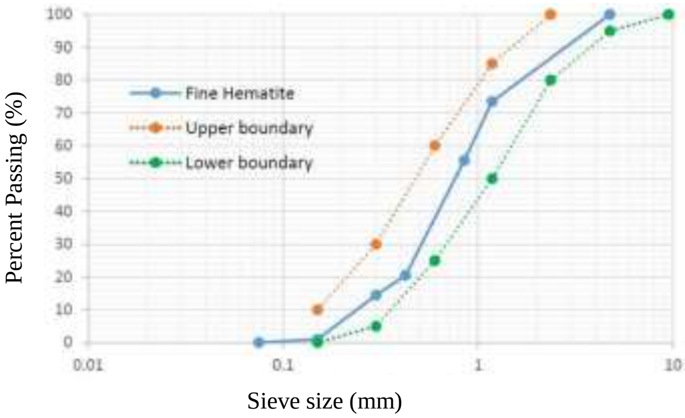


Fig. 3: Sieve analysis of fine hematite.

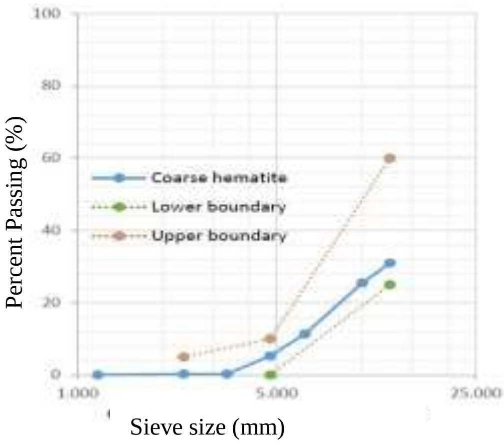


Fig. 4: Sieve analysis of coarse hematite.

3.2. Specific gravity and water absorption of aggregates

Specific gravity of granite aggregate and sand are normally between 2.55 - 2.75 g/cm^3. The specific gravity of the granite aggregate in this study is 2.70 g/cm^3 and 2.62 g/cm^3 for sand (Table 1). Previous researcher reported the specific gravity of coarse pure hematite to be between 4.9 g/cm^3 - 5.5 g/cm^3 (Gencel at al., 2011) [19], but varies with the types of source rock, location of the rock, chemical composition and the processes to get the final product. For hematite ore, the specific gravity is expected to be between 3.2 g/cm^3 - 4.3 g/cm^3. The specific gravity of the coarse hematite ore in this study is 3.44 g/cm^3 and 3.30 g/cm^3 for the fine hematite ore (Table 1), which falls under lower end of the classification of hematite ore. Figure 1 compares the specific gravity of aggregates in Gencel at al., (2011) for further comparison with other physical and mechanical properties and neutron absorption capacity later. Theirs values are 2.70 g/cm^3 2.63 g/cm^3 for granite and sand, respectively. For fine hematite and coarse hematite, their values are 3.75 g/cm^3 and 4.00 g/cm^3, respectively, which are higher than the hematite ore used in the current study. However, both hematite aggregates can be classified as heavyweight aggregate [1].

Table 1: Specific gravity of materials.

Material	Specific gravity (g/cm^3)
Coarse granite aggregate	2.70
Sand	2.62
Fine hematite aggregate	3.30
Coarse hematite aggregate	3.44

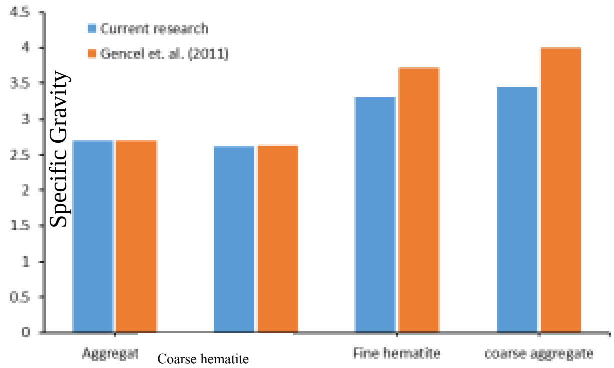
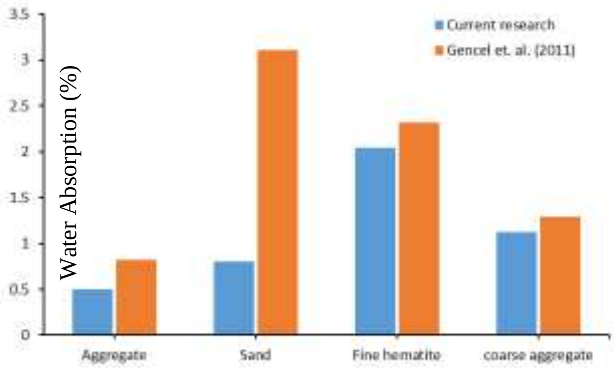


Fig. 5: Comparison of specific gravity of aggregates.

Table 2 shows the water absorption of the aggregates. Table 2 shows that granite aggregate has the lowest water absorption at 0.50 % while for sand it is 0.84 %. Fine hematite shows the highest water absorption at 2.04 % and coarse hematite at 1.12 %. This difference is influenced by the weather conditions and location of the stored aggregates, whether exposed to rain and shine, before laboratory experiments are carried out. Figure 6 shows the comparison of water permeability test with Gencel et al. (2011) [19], where their results show higher water absorption of all aggregates compared to this study; for granite aggregate, the difference is as much as 66 %, while for sand 272.62 %. But for hematite, the differences are lower with 15.20 % and 13.40 % for fine hematite and coarse hematite. These values may explain the differences in the mechanical properties of both studies.

Table 2: Water absorption of aggregates.

Material	Water permeability (%)
Granite aggregate	0.50
Sand	0.84
Fine hematite	2.04
Coarse hematite aggregate	1.12



Coarse hematite

Fig.6: Comparison of water absorption of aggregates.

3.3. Aggregate bulk density/ unit weight

Based on the ASTM C29-09 (2014) [12] standard in conducting this experiment, the result obtained is shown in Table 3**.** The bulk weight for the aggregate is 1450 kg/m^3 while for sand is 1600 kg/m^3. For fine hematite and gravel hematite respectively, the unit weights are 1962 kg/m^3 and 1743 kg/m^3. The results of this study were compared with Gencel at al. (2011) and the differences are: coarse granite (-15.58 %), sand (-14.37 %), fine hematite (+0.31 %) and hematite (+0.57 %) of weight, respectively. Figure 7 shows the difference between this study and the study of Gencel at al. (2011) graphically. The factor that has influenced the difference in the bulk density is due to the different maximum sizes of aggregates. In this study, the maximum size of the coarse granite aggregate is 12.5 mm while, in Gencel at al. (2011), the maximum size is 20 mm. For hematite, the bulk density is influenced by processing method of crushing the hematite to produce the fine hematite and coarse hematite.

Table 3: Aggregate bulk weight

Material	Bulk Weight (kg / m^3)
Coarse granite aggregate	1450
Sand	1600
Fine hematite	1962
coarse aggregate	1743

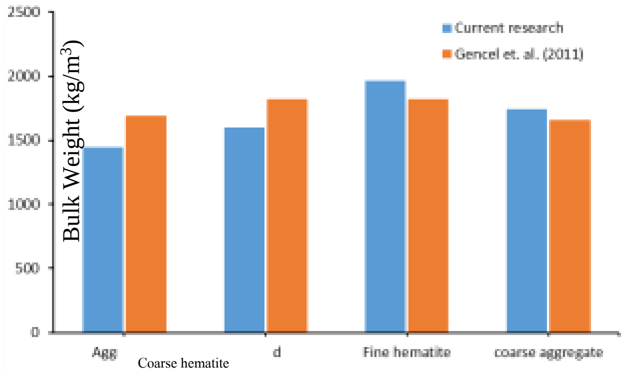


Fig.7: Comparison of aggregate bulk weight

3.4. Chemical composition of hematite

Table 4 shows the chemical properties of hematite. It can be seen that the composition is different from the hematite used by other researcher (Gencel et al. 2010) [4]. Fe_2O_3 composition is very low compare with Gencel et al. 2010, but the value of Al_2O_3 and SiO_2 is much higher than that of Gencel et al. 2010, which affects the density and the neutron absorption capability of hematite HWAC.

Table 4: The chemical composition of hematite (%).

Composition	Contents (%) (current research)	Gencel et al. 2010
Fe_2O_3	39.6	81.13
MnO	0.2	0.14
MgO	0.3	1.55
TiO_2	0.5	0.03
Al_2O_3	23.6	0.57
CaO	0.7	4.80
SiO_2	31.6	4.20

3.5. Slump test

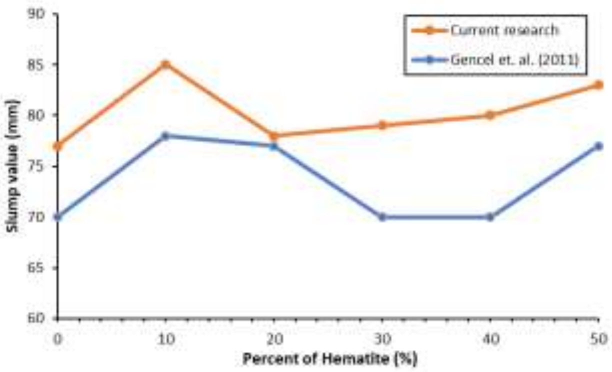


Fig. 8: Slump values of hematite concrete.

Figure 8 shows the result of slump test of this current research and comparison with Gencel et al. (2011) [19]. When granite is replaced by hematite, the slump increased at all percentages of replacements. As the percent absorption of all aggregates (sand, granite, fine hematite and coarse hematite = 0.84, 0.50, 2.04 and 1.12% respectively) are included in the calculation of free water, it can be said that texture of the hematite is smoother that natural sand and granite to have increase the slump of their mixes

3.6. Density

Table 5 shows the density of hematite concrete. It can be seen that the densities of all hematite replacement concrete only increase at a minimal amount even though results of specific gravity of hematite is higher than sand and granite (specific gravity of sand, granite, fine hematite and coarse hematite are 2.62, 2.7, 3.3 and 3.44 respectively). The lowest density of the HWAC is 2324kg/m^3 for 0 % hematite (standard concrete density) [20] and the highest with 50% replacement of hematite only achieved density of 2406 kg/m^3. It can be concluded that with only 50% replacement of granite with hematite, heavyweight concrete with specific gravity which is more than 2600 kg/m^3 could not be achieved. However, results by Gencel at al. (2011) [19] show better improvement in density as shown Figure 9, with density more than 2600 kg/m^3 at 30 % and more replacement of granite with hematite due to the higher specific gravity of the hematite that they used.

Table 5: Density of hematite concrete.

Percent of Hematite (%)	Density (kg/m^3)
0	2328
10	2340
20	2356
30	2365
40	2393
50	2406

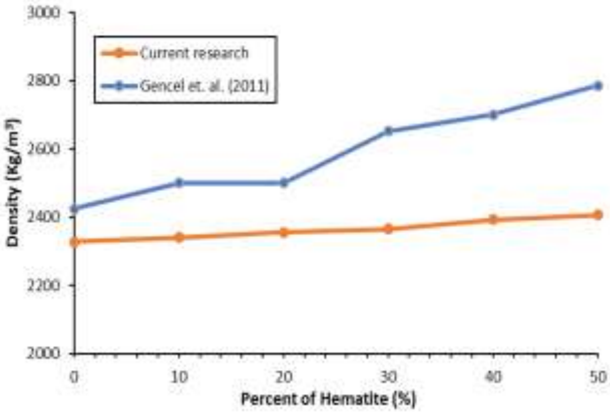


Fig. 9: Density of hematite concrete.

3.7. Compressive strength

Table 6 shows the compressive strength of all mixes. The control concrete is at 44.42 MPa. The strength increases at all hematite replacement levels. However, there is no specific trend in the results. The compressive strength of 10% hematite concrete is the highest at 52.54 MPa. Replacement of more than 10% hematite shows a decline but still the strengths are higher than control. Comparison with Gencel at al. (2011) [19] shows the pattern resembles this current results (Figure 10). The replacement of granite with hematite has increased the strength due to the increased of density of aggregate, but surface texture, maximum size and cleanliness of aggregate may also affect the strength of concrete [19, 21]. Visual inspection had shown that the hematite is not as clean as the granite.

Table 6: Compressive strength of hematite concrete.

Percent of Hematite (%)	Compressive strength (MPa)
0	44.4
10	52.5
20	48.3
30	47.2
40	45.9
50	46.3

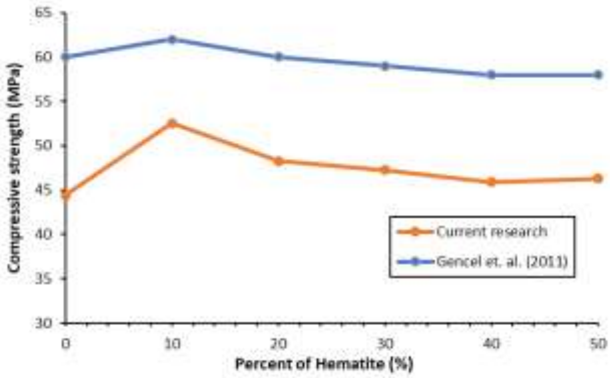


Fig. 10: Compressive strength of hematite concrete.

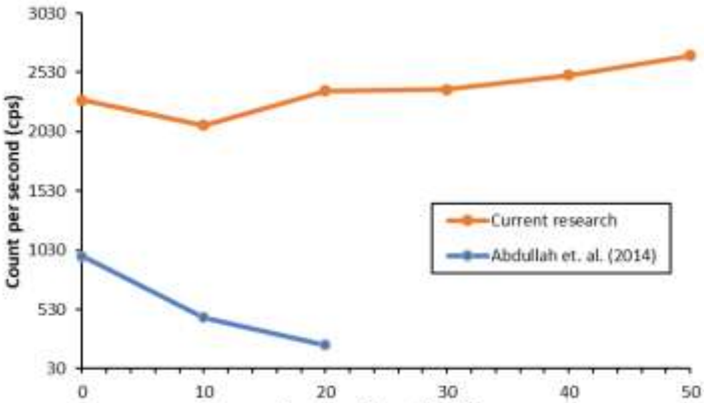
3.8. Thermal neutron absorption

Table 7 shows that 10% of hematite in concrete exhibits the lowest counts per second of neutron compares to 0 %, 20 %, 30 %, 40 % and 50 % concretes. The neutron reacted with hydrogen atoms that exist in concrete. Some of the thermal neutrons are absorbed by the hematite particles whereas the remaining thermal neutrons dissipate to the He-3 detector. MCM-2 hydrotector device emits fast neutron Am/Be of 25000 counts per second (cps) and after passing the concrete block, the He-3 detector detects reduced amount up to 2085 cps. Concrete with 10 % hematite has captured the most neutrons through the least number of neutrons detected. Replacing more amount of hematite has reduced the capability of concrete to capture the thermal neutrons, which indicates that less hydrogen exist in concrete when more than 10 % granite is replaced with hematite. Further tests need to be done to confirm these results. Also, the high water absorption of hematite compares to granite may have contributed in the reduced strength and thermal neutron absorption.

Figure 11 compares the thermal neutron absorption of hematite aggregates concrete with concrete with addition of boron carbide powder [22]. This result shows that boron carbide powder captures more thermal neutrons with much less number of neutrons detected. Boron carbide addition is more effective in capturing thermal neutrons compares with hematite aggregates.

Table 7: Thermal neutron absorption of hematite concrete.

Percent of Hematite (%)	Count per second (cps)
0	2295
10	2085
20	2373
30	2388
40	2508
50	2673



Percent of hematite aggregate replacement and % boron carbide addition

Fig. 11: Thermal neutron absorption of hematite concrete.

4. Conclusion

The chemical composition of the hematite used in this research is very low in Fe_2O_3 but the value of Al_2O_3 and SiO_2 is much higher than previous research, which affects inversely the density and the neutron absorption capability of hematite HWAC. The slump increased at all percentages of replacements. It can be said that texture of the hematite is smoother than natural sand and granite to have increased the slump of their mixes. The densities of all hematite replacement concrete only increase at a minimal amount even though results of specific gravity of hematite is higher than sand and granite. It can be concluded that 50% replacement of hematite could not produce HWAC. The compressive strength increase at all hematite replacement levels with the strength of 10% hematite concrete is the highest at 52.54 MPa. Replacement of more than 10% hematite shows a decline but still the strengths are higher than control. The replacement of granite with hematite has increased strength due to increase in density of aggregate, but surface texture, maximum size, cleanliness and aggregate also affect the strength of concrete. Concrete with 10% hematite has captured the most neutrons through the least number of neutrons detected. Replacing more amount of hematite has reduced the capability of concrete to capture the thermal neutrons. Comparison with boron carbide powder addition concrete shows that boron carbide addition is more effective in capturing thermal neutrons compares with hematite aggregates.

Acknowledgments

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