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Utilization of Steel Aggregate and Iron Sand as Heavyweight Concrete for Gamma Radiation Shielding

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Abstract

This study aims to produce a homogenous and workable conventional heavyweight concrete (HWC) with similar performance as pre-placed HWC in attenuating radiation by increasing the concrete density with no risk of segregation. HWC was mixed using steel aggregate and iron sand with a specific gravity of 7.78 and 4.14, respectively. A w/c ratio of 0.5 was applied to obtain proper workability and viscosity modifying agent (VMA) was used to prevent segregation. The radiation tests were carried out using ^{133}Ba (356 keV), ^{137}Cs (662 keV), and ^{60}Co (1170 keV & 1330 keV) gamma sources. The results obtained a concrete density of 5133.07 kg/m^3 with no sign of segregation and a compressive strength of 18.61 MPa. Based on the radiation test, the conventional HWC was effective in reducing the shielding thickness by 50.41%. Our findings provide a workable conventional HWC with high gamma attenuation to replace an enormous dimension of normal concrete.

INTRODUCTION

Concrete is one of the composite materials that is frequently used as a radiation shield. The properties of concrete that are directly influenced by its constituent materials make concrete suitable as a radiation shield because it can be modified as required. A study conducted by Sarker et al. [1] using normal concrete with a density of 2350 kg/m3 as a radiation shield for a radiotherapy room revealed that the thickness of the concrete needed for primary protection is 2.1 m. This enormous dimension causes the concrete to be cast in mass and has common problems such as taking up a lot of space, being susceptible to thermal cracks that will become gaps for radiation leakage, and using a lot of cement that contributes to large amounts of CO_2 emissions. Therefore, it is essential to shrink the thickness by increasing the density, which is known as heavyweight concrete.

Heavyweight concrete (HWC) is one type of concrete that contains high specific gravity aggregate, has a higher density than normal concrete (>2600 kg/m^3), and is generally used as radiation shielding [2,3]. The utilization of high specific aggregate in concrete presents a major challenge, namely segregation that occurs when heavier aggregates separate from lighter materials such as cement paste, resulting in inhomogeneous concrete which prone to radiation leakage. Therefore, to properly produce homogeneous HWC, ACI 304.3R provides two mixing methods: the conventional method and the pre-placed aggregate method [4].

There are two things that distinguish between the conventional and the pre-placed method. First, in the conventional method, materials such as aggregates, cement, water, and admixture are mixed thoroughly before being poured into

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the formwork. On the other hand, in the pre-placed method, coarse aggregate is arranged in the formwork before the mortar grout is injected to fill the void left by the coarse aggregate as shown in Figure 1 [5,6]. Second, due to the respective producing method, pre-placed concrete has a higher coarse aggregate content of up to 60% of the total volume compared to conventional concrete which is only around 40% of the total volume [7]. According to ACI 304.3R, the highest density of conventional HWC is 4800 kg/m^3 by using metallic aggregates such as steel aggregate or iron shot. In contrast, by using the same aggregate, the pre-placed method proposes a higher density of around 5500 kg/m^3 resulting in better shielding against radiation. However, in practice, there is more demand for the conventional method as the pre-place method requires special skills and tools, making it difficult for workers who are unfamiliar with the standard practices of this method. Therefore, research is needed to modify the conventional HWC so it can achieve the same performance as pre-placed HWC in attenuating radiation.

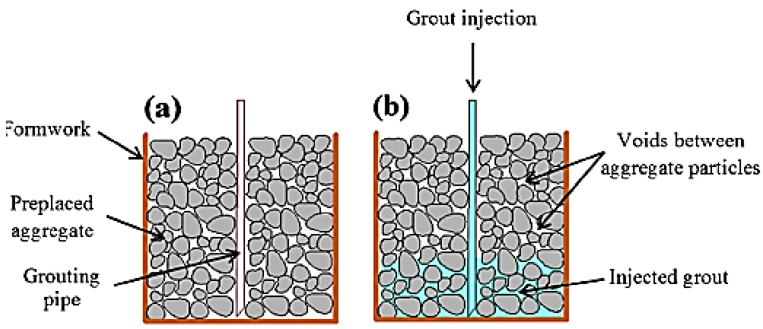

Figure 1. Concrete Casting with Pre-Placed Aggregate Method [6]

Several methods have been studied in order to increase the density of conventional HWC. ACI 304.3R suggests using type F or G admixtures (High-Range Water-Reducing Admixture) to reduce the amount of water by up to 30% without compromising concrete workability. Heavy aggregates will fill the void left by the lower water content increasing the density of concrete. A reduction in water will be followed by a loss in cement content, resulting in lesser binder material to prevent the heavy aggregate from segregation. Consequently, limiting the cement content is also required in producing a conventional HWC.

Gökçe & Andiç-Çakır [8] compared the effect of limiting cement weight ranging from 350 kg/m^3 to 450 kg/m^3 in HWC with the water-cement ratio of 0.40; 0.48; and 0.56. The results showed concrete was free from segregation at a cement amount of 450 kg/m^3 and a water-cement ratio of 0.40. On the other hand, the cement content of 350 kg/m^3 produced concrete with the highest density as there was more aggregate compared to other variations. However, sign of segregation was visible suggesting the need to improve the cohesiveness of the cement paste by using Viscosity Modifying Admixture (VMA). Gyawali [9] also suggested that a heavyweight concrete mixture using a steel aggregate with a target density of more than 5 t/m^3 must be made viscous to prevent the aggregate from settling to the bottom of the formwork.

Research regarding conventional heavyweight concrete using steel aggregate and its performance in attenuating gamma radiation is still very limited. A previous study from Alhadi [10] investigated the radiation attenuation of a pre-placed heavyweight concrete made of steel aggregate with a diameter of 10 mm and a length of 20 mm as coarse aggregate, iron sand as fine aggregate, and superplasticizer. The findings proved that HWC exhibited a higher attenuation coefficient than normal concrete, which contributed to a 70% reduction in the concrete thickness.

Based on those aforementioned problems, this research aims to design a homogeneous conventionally cast HWC with a density of more than 4800 kg/m^3 using steel aggregate and iron sand. To achieve the target density as well as minimum segregation, type F admixture is used, and the total cement content is maintained to be not lower than 350 kg/m^3. VMA is also used to improve the cohesiveness of cement paste. Furthermore, the mechanical properties of HWC and the ability to attenuate radiation are examined using various gamma energy levels. The test results were then compared to the previous studies by Alhadi [10] and Sumarni [11] who examined the radiation attenuation of a pre-placed HWC.

METHOD

Materials

The primary materials for HWC consist of steel with a diameter of 10 mm that has been cut per 10 mm, iron sand from Kulon Progo, Yogyakarta, water, and Portland Composite Cement (PCC) as the main binder. The characteristics of steel aggregates as well as iron sand are shown in Table 1. In addition, the particle size distribution of iron sand and river sand is presented in Figure 2. It can be seen that iron sand has a very fine particle while river sand is moderately coarse which highly influences the properties of concrete in this research. A type F admixture named viscocrete-1003 from PT. Sika Indonesia was used by 1% of cement weight as a high-water reducer to enlarge the aggregate content thereby increasing the concrete density. Sika 4R VMA (Viscosity Modifying Admixture) is also added by 0.2% of cement weight to improve the cohesiveness of the mixture and to prevent segregation that may occur in conventional casting methods due to a very high specific gravity of steel aggregate. Figure 3 displays all of the materials used in this study.

Table 1. The Characteristics of Aggregate in this Study

No	Aggregate Properties	Unit	Value
1	Specific Gravity of Iron Sand	-	4.14
2	Specific Gravity of Steel Aggregate	-	7.78
3	Absorption of Iron Sand	%	0.02
4	Unit Weight of Iron Sand	kg/m^3	2491.75
5	Unit Weight of Steel Aggregate	kg/m^3	4633.60
6	Fineness Modulus of Iron Sand	-	0.26

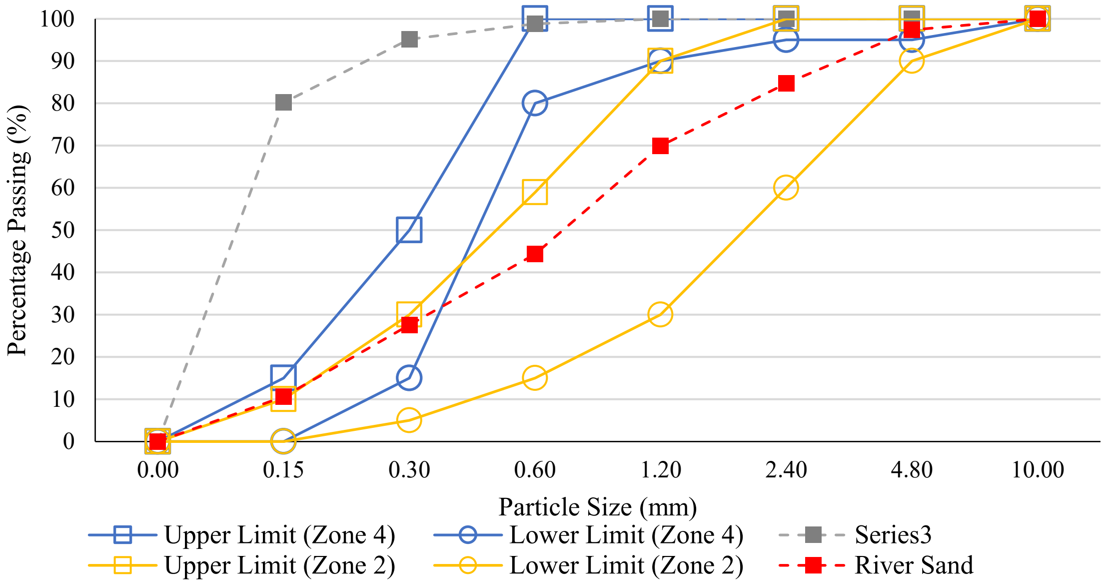

Figure 2. The Particle Size Distribution of Iron Sand

(a) (b) (c) (d)

Figure 3. Materials used in this Study: (a) Steel Aggregates, (b) Iron Sand, (c) PCC Cement, (d) Viscocrete-1003 and Sika 4R VMA

Mix Design and Specimens Production

In this research, concrete was designed to have a density of more than 4800 kg/m^3. Mix design followed the absolute volume method adapted from Satyarno et al. [12] using water cement ratio of 0.5. The amount of water was reduced by 30% to limit the cement content ranging from 350 kg/m^3 to 400 kg/m^3. This was done to minimize the risk of segregation and to reduce the CO_2 emissions from cement use. The specimens were divided into two, which are 100x200 mm concrete cylinders for the compressive test specimens and 150x150 mm cubicles for the radiation test specimens. The cube thickness was varied from 30 mm to 120 mm with increments of 10 mm. Both types of specimens can be seen in Figure 4.

(a) (b)

Figure 4. Specimens used in this Study: (a) Cylinder Specimen for Compressive Test, (b) Cubicle Specimen for Radiation Test

A concrete mixer with a capacity of 0.2 m^3 is used with the following mixing sequence: cement, iron sand, water, and steel aggregate. First, cement and iron sand were dry-mixed in the concrete mixer. Then, viscocrete-1003 and sika 4-R VMA that had been dissolved with water beforehand were poured into the properly mixed cement and iron sand. The materials were mixed for two minutes to produce mortar grout with good consistency so it could hold the steel aggregate that was poured last to prevent segregation. Normal concrete was also made using natural coarse and fine aggregate as a control specimen. The total number of concrete produced for this research can be seen in Table 2 and the materials required for making concrete per m^3 can be seen in Table 3. Heavyweight concretes were cured in dry air to reduce the risk of corrosion while normal concretes were cured by soaking for up to 28 days before testing.

Table 2. Total Number of Specimens for the Study

Tests	Concrete Ages (days)			
	Heavyweight Concrete			Normal Concrete
	3	7	28	28
Compressive Strength	3	3	3	3
Radioactive Counting			10	10
		Total	32	

Table 3. The Materials Required for Making Heavyweight Concrete per m^3

Materials	Heavyweight concrete (kg/m^3)	Normal concrete (kg/m^3)
PCC Cement	381.58	604.70
Water	190.79	302.35
Steel Aggregates	3421.97	-
Iron Sand	1009.73	-
Natural Coarse Aggregate	-	756.65
River Sand	-	556.66
Viscocrete-1003	3.82	-
Sika 4R	0.76	-
Total	5008.64	2220.36

Testing Procedure

The density and compressive strength of HWC were tested at the Building Materials Laboratory, Department of Civil and Environmental Engineering, Universitas Gadjah Mada after had been cured for 3, 7, and 28 days. The density of concrete was obtained by weighing a dry concrete and dividing it by the volume. Meanwhile, the compressive strength was obtained using a Universal Testing Machine by applying maximum load until the concrete reached failure.

Radioactive counting tests were carried out at the Nuclear Energy Technology Laboratory, Department of Nuclear Engineering and Physics Engineering, Universitas Gadjah Mada, using a set of gamma radiation spectroscopy systems with NaI(Tl) detector. The radiation sources used are Barium-133, Cesium-137, and Cobalt-60 with energy levels of 356 keV, 662 keV, 1170 keV, and 1330 keV respectively. In order to measure the number of gamma rays that penetrated through the concrete, the intensity count per second of gamma rays was first recorded without any concrete for each energy source (I_0). Afterward, the concrete was placed between the radiation source and detector to measure the attenuated intensity count per second (I), subsequently for each thickness from 30 mm to 120 mm. For more accurate measurement, the attenuated intensity (I) was averaged from five points for each specimen as shown in Figure 5. The counting time was kept constant at 4 seconds and was measured 100 times for each point.

Subsequently, the linear attenuation coefficient (μ, cm^{-1}) was obtained using Beer-Lambert's law as presented in Equation 1 which follows a linear regression equation where μ is the slope of a straight line associating $\ln\frac{I}{I_0}$ and thickness (x, cm).

$$\frac{I}{I_0} = e^{-\mu x}, \text{ or } \ln\frac{I}{I_0} = -\mu x \quad (1)$$

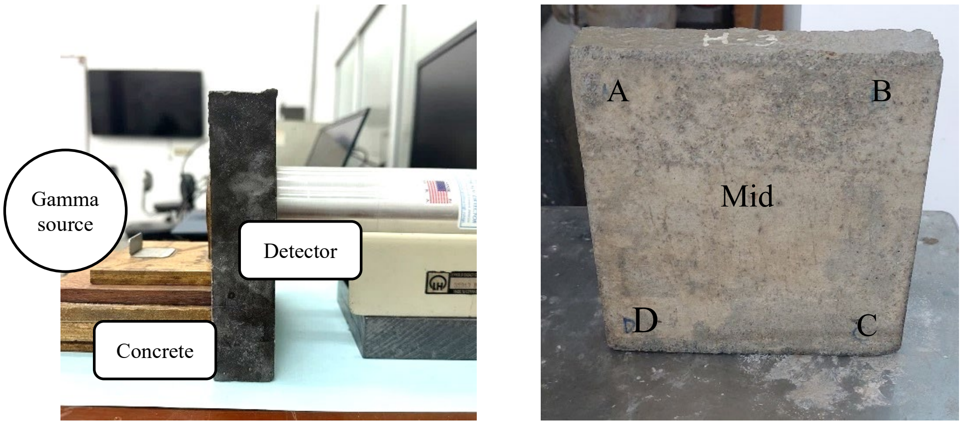

Figure 5. Radioactive Intensity Counting Test: Setup Preparation and Five Points Measurement

RESULTS AND DISCUSSION

Density

Table 4. Density of Heavyweight Concrete (HWC) and Normal Concrete (NC)

	Design density (kg/m^3)	Actual density (kg/m^3)	Correction factor
Heavyweight concrete (HWC)	5008.64	5133.07	1.02
Normal concrete (NC)	2220.36	2366.28	1.07

The density of heavyweight concrete (HWC) and normal concrete (NC) is shown in Table 4. It can be seen that the average actual density of HWC is 5133.07 kg/m^3 which was 116.93% higher than NC using natural aggregates. The high density of concrete is due to the utilization of high specific gravity steel aggregate and iron sand, respectively at 7.78 and 4.14 [13,14]. This is because materials with high specific gravity are generally made up of heavier atoms, and are more tightly packed, resulting in greater mass per unit volume. A similar study from Kazjonovs et al. [15] replaced natural aggregates with steel aggregates. The HWC was cast using conventional method with w/c ratio of 0.47, cement content of 470 kg/m^3, and water reducer admixture 1.5% by cement weight. The results showed that the density of concrete was 4640 kg/m^3. It was evident from our study that lowering cement content increased the density as there were more heavy aggregates in the concrete.

(a) (b)

Figure 6. (a) HWC Specimen Tested in this Study, (b) Honeycomb Surface in HWC with Cement Content Lower than 350 kg/m^3

However, the pre-placed HWC from the study conducted by Alhadi [10] using the same steel aggregate with a cement content of 330 kg/m^3 has a density of 5700 kg/m^3 which was higher than the conventional HWC in this study.

Increasing the density of conventional HWC to the same as pre-placed HWC is essential to achieve similar radiation shielding performance. Therefore, a conventional HWC was cast with a lower cement content of 330 kg/m^3 and the density reached 5550.45 kg/m^3. However, it was found that the concrete was less workable, was susceptible to honeycomb, and there was a risk of segregation as it reduced the cement paste to fill and bind heavy aggregate, thus creating an inhomogeneous concrete that was unfavorable as a radiation shield. The conventional HWC specimen used in this study (5133.07 kg/m^3) with a smooth surface is shown in Figure 6a, while Figure 6b shows the denser HWC (5550.45 kg/m^3) with a honeycomb surface. Based on these findings, it was highly suggested not to make conventional HWC with a cement content below 350 kg/m^3.

Compressive Strength

The results for compressive strength of HWC at 3, 7, and 28 days are illustrated in Figure 7. It can be seen that the strength gradually grew from 3 to 28 days with the highest strength of HWC achieved at 18.61 MPa which is lower than the compressive strength of NC with the same w/c ratio. This could be due to the ultra-fine particle size of iron sand which increased the total surface area that needed to be covered by cement paste. Previous studies reported that finer particles demand more water thus leading to a more porous microstructure potentially decreasing the concrete strength [16–18]. Moreover, in this study steel aggregate has a uniform size particle which typically results in lower compressive strength compared to well-graded aggregates due to poor particle interlock and increased susceptibility to cracking. The smooth surface morphology of steel aggregate also negatively affected the interfacial transition zone (ITZ) propagation, since there is less area of contact between the aggregate and the cement mortar compared to rough surfaces of natural aggregate, thus decreasing adhesion and having a significant impact on the mechanical behavior of concrete [19–23].

Based on these compressive strength results, further research is needed to increase the compressive strength of conventional HWC before it is applied in the fieldwork. First, it is highly suggested to add a well-distributed size heavy aggregate to enhance the interlocking effect between particles, reduce voids, thus contributing to higher compressive strength. The loss in strength could also be prevented by adjusting lower water-cement ratio and increasing the cement content in the concrete. However, this approach should be applied carefully since it will decrease the heavy aggregate content and lower the concrete density which has a more vital role than concrete strength in blocking radiation.

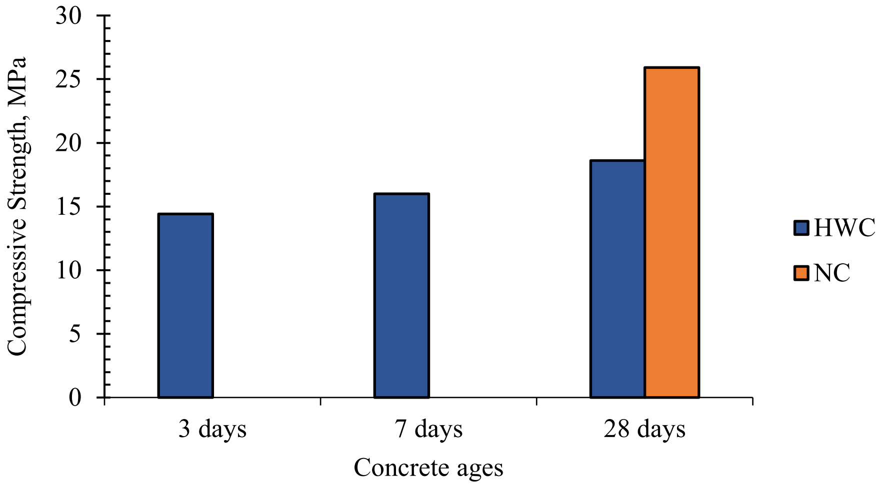

Figure 7. Compressive Strength of Heavyweight Concrete (HWC) and Normal Concrete (NC)

Gamma Radiation Shielding

Radiation shielding ability is primarily influenced by three factors: the density of the shielding material, the atomic number of the shielding material, and the radiation energy that penetrates the shielding [24]. The performance of radiation shielding for both HWC and NC was measured using ^{133}Barium (356 keV), ^{137}Cesium (662 keV), and ^{60}Cobalt (1170 keV & 1330 keV) gamma energy sources. The abilities of HWC and NC to block the gamma penetration are presented in Figure 8 represented by the reduction rate (%) for each thickness increment. It can be seen that for every gamma source, the increment of thickness will increase the reduction rate meaning more radiation intensity that can be blocked for both HWC and NC. However, for the same thickness, HWC has better performance in blocking gamma radiation due to the higher density of HWC at 5133.07 kg/m^3 which was twice more than the NC density that only 2366.28 kg/m^3. This is because denser materials have more electrons and atomic nuclei that can collide with the incoming gamma rays to absorb their energy. Similar results were also reported that the radiation shielding was primarily affected by the dry density of the concrete rather than the concrete strength [13,25].

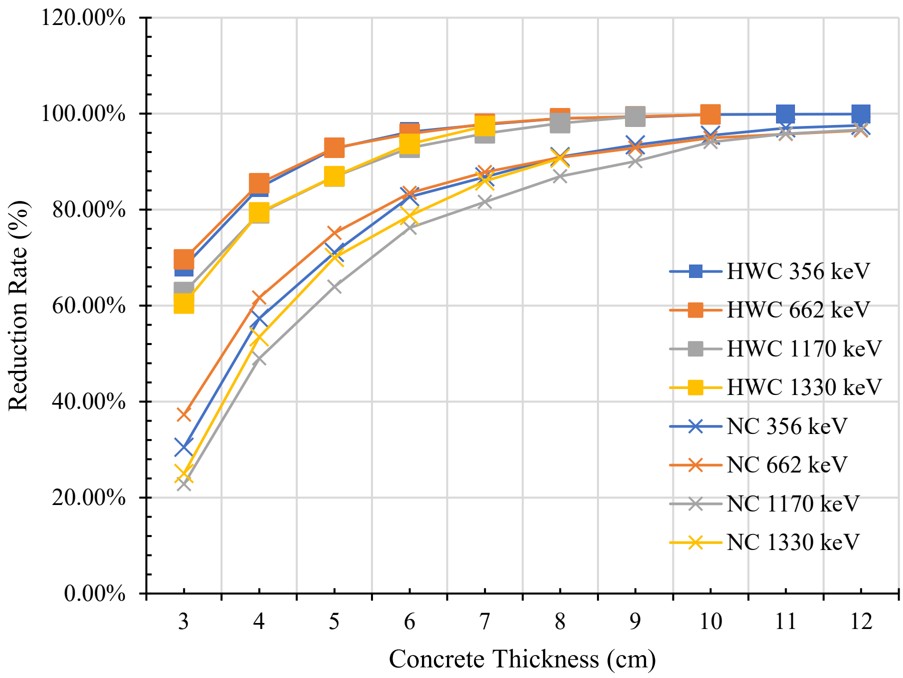

Figure 8. The Reduction Rate of Gamma Radiation Intensity of HWC and NC for Each Thickness Increment

Furthermore, it was shown that gamma energy level has an inverse effect on the absorption ability of material with the highest reduction rate displayed at ^{133}Ba (356 keV) which has the lowest energy compared to other gamma sources. This was because on the higher energy the photons from gamma are dominantly scattered rather than fully absorbed, requiring thicker or denser shields to weaken the energy. However, we can see from Figure 8, that the reduction of gamma radiation intensity follows an exponential trend of Beer-Lambert's law as presented in Equation 1. This trend concluded that there will always be a small fraction of photons that pass through matter. It also implies that to reduce gamma radiation by nearly 100%, extremely thick shielding would be required, which may be impractical due to size, weight, and cost constraints. Instead of aiming for 100% blocking, the effective shielding design focuses on reducing gamma radiation to an acceptable level provided by the International Commission on Radiological Protection (ICRP) which is 20 mSv per year for workers and 1 mSv per year for the public [26].

Linear Attenuation Coefficient (μ)

The linear attenuation coefficient (μ) is the probability of radiation interaction with a material per unit path length. A higher probability of interaction means more radiation photons will be absorbed or scattered, thus the radiation intensity decreases more significantly as it passes through a matter. Finding μ is important to design an effective minimum thickness of radiation shielding. It was obtained through Beer-Lambert's law (Equation 1) by graphically plotting the concrete thickness as the X-axis and ln(I_0/I) value as the Y-axis. Following a linear regression ($y = mx$), μ was acquired from the slope value as shown in Figure 9. From the graph, it can be seen that HWC has higher μ than NC for every gamma energy level since a denser material has more electrons per unit volume thus increasing the probability of radiation to be absorbed or scattered [27–29]. Furthermore, μ decreased with the increasing gamma energy both for HWC and NC [30]. Based on this finding, utilizing heavy steel aggregate and iron sand in HWC increased the ability to block radiation compared to natural aggregate in NC.

The minimum shielding thickness required to reduce gamma intensity is calculated using Equation 1 and μ that has been obtained for each gamma source. For instance, if HWC in this study is built as a shield in a radiotherapy room that uses a ^{137}Cs (662 keV) source with emitted dose of 360,000 mSv/hour (I_0) [31], the minimum thickness (x, cm) to lower the dose into allowable level regulated by ICRP, which is below 0.00228 mSv/hour (I) [26], can be calculated using corresponding μ of HWC for ^{137}Cs (662 keV) as follows:

$$\ln\frac{I}{I_0} = -\mu x$$

$$\ln\frac{0.00228}{360000} = -0.5701x$$

$$x = 33.11 \text{ cm}$$

The same calculation can be done to obtain the minimum thickness of NC for blocking the exact ^{137}Cs (662 keV) gamma source and the result is 65.68 cm. Based on this finding, HWC with steel aggregate and iron sand can reduce the radiation shielding thickness by 50.41%. According to Stabin [32], μ is constant for an identical material with the same composition, density, and gamma energy. Therefore, μ values that have been obtained in this study can be used as a reference in designing the thickness of HWC to shield against ^{133}Ba (356 keV), ^{137}Cs (662 keV), and ^{60}Co (1170 keV & 1330 keV) gamma energy sources.

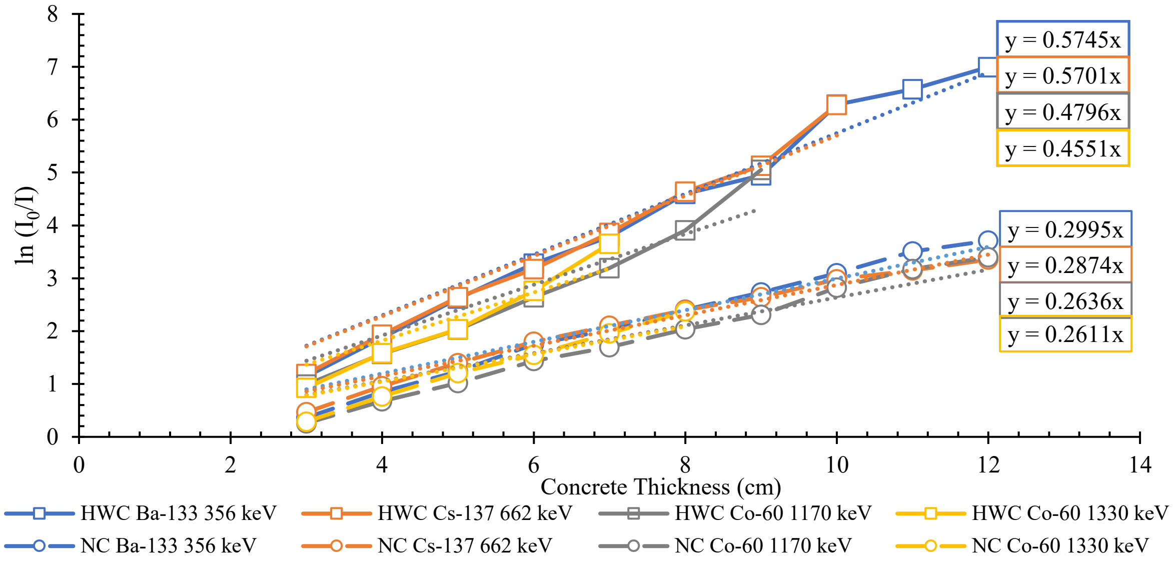

Figure 9. The Correlation between Concrete Thickness and Ln(I_0/I) of HWC and NC for Each Gamma Energy Sources

Relationship between μ and Gamma Energy

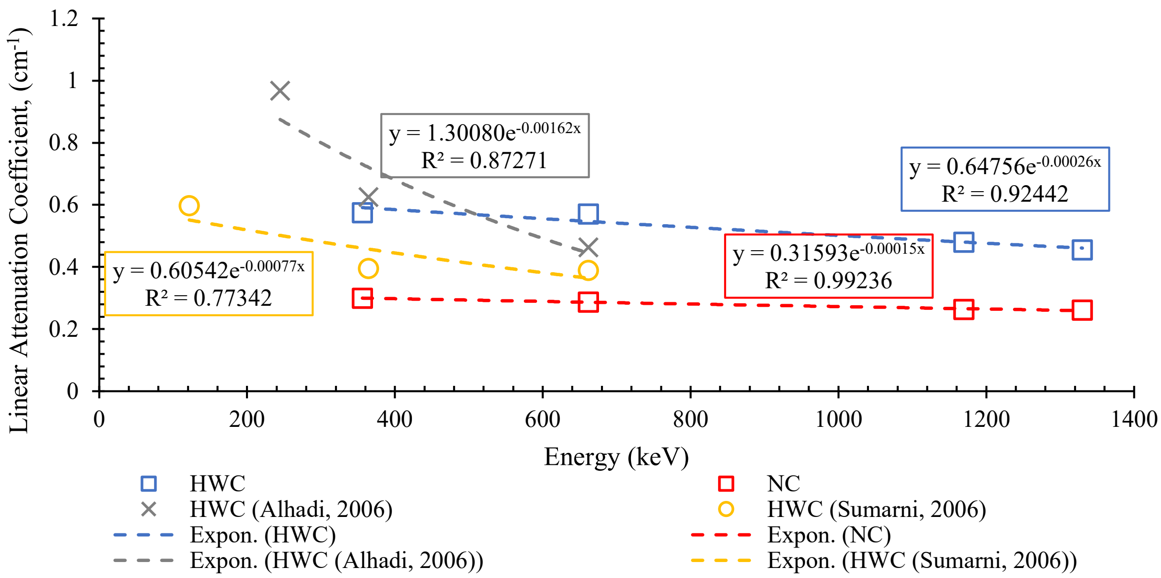

Figure 10. The Correlation between Energy (keV) and μ (cm^{-1}) for HWC and NC Compared to [10] and [11]

In this study, the relationship between μ and gamma energy is graphically plotted in an exponential regression model of form $y = \alpha e^{\beta x}$ to provide an equation that can be used for future study as illustrated in Figure 10**.** This equation means to quickly predict the value of μ when other gamma radioactive sources aside from this study were applied against an identical HWC. In addition, the predicted μ value then can be used to find the required minimum thickness. For example, the predicted μ of HWC to attenuate radiation from ^{54}Mn (834.8 keV) can be determined using the equation obtained, $y = 0.64702e^{-0.00025x}$, which is 0.5212 cm^{-1}. In comparison with previous studies, for particular gamma energy the μ of conventional HWC in this study is slightly lower than the pre-placed HWC from Alhadi [10] but far higher than barite concrete from Sumarni [11] since the pre-placed HWC has the highest density compared to others. Future studies using other gamma radiation sources are necessary to obtain more data and able to more accurately predict the thickness required for various gamma energies.

CONCLUSIONS

Based on the research that was done, to produce a homogenous and workable conventional HWC with similar performance as pre-placed HWC in attenuating radiation, essential modifications have to be followed such as: reducing the water content by 30%, limiting the cement content not below 350 kg/m^3, using admixture type F by 1% of cement weight, and VMA by 0.2% of cement weight. A concrete density of 5133.07 kg/m^3 was obtained with no sign of segregation and a compressive strength of 18.61 MPa. Based on the gamma radiation test, the conventional HWC was effective in reducing the shielding thickness by 50.41%, slightly lower than the pre-placed HWC from Alhadi [10] which can reduce the thickness up to 70%. Considering there is more demand for the conventional method than the pre-placed method in the practice field to cast HWC, our findings provide a solution to produce a workable HWC with high gamma attenuation properties to replace an enormous dimension of normal concrete that is usually used as a gamma shielding. This study also offered an empirical equation that can be used in future studies to quickly predict the value of μ and the HWC thickness if applied to block other gamma radioactive sources aside from this study. However, further improvements are required before applying the conventional HWC in the field, primarily to increase its compressive strength. Our suggestion for future work consists but is not limited to: lowering the water-to-cement ratio and using a well-graded heavy aggregate. It is also necessary to test the consistency of the mixture, the optimum free-fall height, and the loss-of-slump to obtain the technical specifications for casting in the field.

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