Hindawi
Advances in Civil Engineering
Volume 2023, Article ID 7873637, 11 pages
https://doi.org/10.1155/2023/7873637

Research Article

Mechanical, Durability, and Gamma Ray Shielding Characteristics of Heavyweight Concrete Containing Serpentine Aggregates and Lead Waste Slag

Allahyar Sayyadi,[1] **Yaghoub Mohammadi**,[2] **and Mohammad Reza Adlparvar**[3]

[1]*Department of Civil Engineering, Qeshm Branch, Islamic Azad University, Qeshm, Iran*
[2]*Department of Civil Engineering, University of Mohaghegh Ardabili, Ardabil, Iran*
[3]*Department of Civil Engineering, University of Qom, Qom, Iran*

Correspondence should be addressed to Yaghoub Mohammadi; yaghoubmo@yahoo.com

Received 21 September 2022; Revised 4 December 2022; Accepted 27 December 2022; Published 11 January 2023

Academic Editor: Junqing Zuo

Heavyweight concrete is used to prevent harmful radiation for the construction of hospital, military, and nuclear power plants and also to increase the durability for the construction of marine concrete structures. In this research, using a combination of serpentine aggregates and lead slag, the mechanical, durability, impact resistance, and shielding properties of heavyweight concrete were examined. The variables included fine and coarse serpentine aggregates, which were replaced with normal fine and coarse aggregates in amounts of 0, 25, 50, and 100 percent, respectively. The lead slag in all samples was considered constant. Slump, compressive strength, flexural strength, water penetration depth, impact resistance (drop hammer), and gamma ray attenuation coefficient tests were conducted. The chemical composition of serpentine aggregates and lead slag were evaluated by X-ray powder diffraction. The results showed that the density and linear attenuation coefficient (LAC) increased with the increase of fine and coarse serpentine aggregates in heavyweight concrete containing lead slag. The highest density and LAC were obtained in a sample in which 100% fine serpentine aggregates and 100% coarse serpentine aggregates were used. Using 25% of serpentine fine aggregates and 25% of serpentine coarse aggregates in heavyweight concrete samples containing lead slag has achieved the highest compressive strength and flexural strength. But with the increase of fine and coarse serpentine aggregates to more than 25%, the upward trend of increasing compressive strength decreased. Silica constitutes a large part of the chemical structure of serpentine aggregates (about 42%). Increasing the amount of serpentine aggregates in concrete mixes leads to excessive release of calcium hydroxide in concrete. This issue can lead to the formation of a weak zone in concrete and decrease the compressive and impact resistance.

1. Introduction

Nuclear radiation protection is designed and built to absorb all the primary and secondary radiation emitted from a source [1, 2]. In the shielding design against photons, the attenuation efficiency is approximately proportional to the mass of the material. Therefore, different materials with the same mass in the path of the beam have the same protection against X-rays and gamma rays [3–5].

Concrete shields are widely used in nuclear reactors, megavoltage radiotherapy rooms, and nuclear waste centers [6, 7]. Concrete has different types for attenuation of gamma rays. The difference is due to the difference in the constituent elements of concrete, such as cement, aggregate, water, and additives [8]. If there is no space limitation in shielding, ordinary concrete will be a good shield for gamma rays; however, since the thickness of concrete has a direct relationship with the amount of beam attenuation and thick concrete walls are expensive and occupy a lot of space, it is preferred to use high-density concrete to reduce the thickness of the walls [9]. Heavyweight additives such as iron, steel, lead, and barite are used instead of sand in making heavyweight concrete. Heavyweight elements are large atoms with multiple layers of orbital electrons. The physical size, the number of orbital electrons, and the effect of the electrostatic field between charged particles significantly increase the possibility of attenuation of photon beams with these heavy elements. Depending on the aggregate used and their density, these types of concrete show different behaviors against different radiations, which are used according to the type of user's needs and the prevailing conditions of the system [9–11]. Aggregates in concrete make up about 60 to 75% of its volume. Hence, their physical, thermal, and sometimes chemical properties affect the performance of concrete [12, 13]. For the design of concrete shielding against gamma rays, the higher the density of concrete, the better the attenuation property. The use of heavyweight aggregates in concrete increases the density and reduces the thickness required for shielding [10, 14].

Rezaei-Ochbelagh and Azimkhani investigated the shielding properties of concrete containing different percentages of lead slag. Observations indicated that adding the lead powder to the amount of 46% of the weight of cement in the concrete mixture turns concrete into a suitable shield against gamma rays [15]. Nulk et al. investigated different combinations of basalt fiber concrete and concluded that basalt fiber is a relatively inexpensive material that can be used as reinforcement instead of steel fibers. Basalt fiber is approximately 56 times stronger than steel concrete. The linear attenuation coefficient (LAC) of gamma increases with the addition of basalt fiber. The results show that reinforced concrete containing basalt has shielding properties compared to normal concrete against gamma rays [16]. Ozen et al. investigated the structural and shielding characteristics of heavyweight concrete. They showed that the density is the most important factor in determining the LAC and its value does not depend on the type of heavyweight aggregate [17]. Ouda and Abdelgader evaluated the physical, mechanical, and shielding properties of heavyweight concrete. They showed that the use of 50 and 60% heavyweight fine aggregate leads to an increase in the LAC and the density of the specimens [18]. Nikbin et al. investigated the gamma ray shielding properties of heavyweight concrete containing nano TiO_2. The results showed that increasing the amount of TiO_2 nanoparticles from 0% to 8% leads to an increase in impact resistance and ultrasonic pulse velocity [19]. Massoud et al. investigated the effects of barite and hematite on the radiation shielding properties of serpentine concretes. It was found that the incorporation of barite and hematite has a negative effect on the physical properties of serpentine-based concretes [20]. Aslani et al. investigated heavyweight concrete containing fibers. The fibers improved the mechanical properties of heavyweight concrete, but the increase of fine heavyweight aggregates had a negative effect on the characteristics of heavyweight concrete [21]. Badarloo et al. investigated the mechanical characteristics and gamma radiation transmission of heavyweight concrete containing barite aggregates. The results showed that increasing the ratio of barite aggregates decreased compressive strength and tensile strength. Also, the reduction of the gamma transmission rate significantly depends on the density of concrete [22].

In previous studies on serpentine concrete, serpentine aggregates were used as coarse aggregates, and their mechanical and shielding properties were evaluated. This study used a combination of fine and coarse serpentine aggregates and lead slag to make heavyweight concrete. In addition to examining the mechanical and shielding properties, their durability and impact resistance properties were evaluated. According to the authors' knowledge, this issue was not investigated in past studies. The possibility of making heavyweight concrete was evaluated according to the serpentine mineral resources available in the Zakaria area of Mashhad in Iran. The best mode in the mass production of this product with the best performance was presented. For this purpose, several mixture designs containing different amounts of serpentine aggregates and lead slag were designed and built. According to the research [23, 24], the lead produced in the recycling process of spent batteries as aggregate in concrete mixes improved concrete compressive and flexural strength. Therefore, lead slag was combined with serpentine aggregates to produce heavyweight concrete.

2. Materials and Methods

2.1. Materials. The materials used in the construction of the examined heavyweight concrete samples include normal fine aggregates (sand), normal coarse aggregates (gravel), serpentine fine aggregates (as a replacement for all or part of the sand), normal coarse aggregates (as a replacement for all or part of gravel), lead waste slag as fine aggregates, cement, water, and superplasticizer. Gravel, sand, and normal aggregates were graded [25, 26]. Normal river sand and gravel were used in making heavyweight concrete samples. The grading curves of aggregates and the limits of regulations are presented in Figure 1.

As mentioned, serpentine aggregates were obtained from the Zakaria mine in Mashhad, Iran (Figure 2). These aggregates were crushed and used as fine and coarse aggregates. The chemical characteristics of the used serpentine aggregates are presented in Table 1 according to the XRD analysis. Type II Portland cement was used to make the samples (Table 1). Lead waste slag, known as a by-product of the pure lead production process from used batteries, was used as fine aggregates in the samples. The chemicals that makeup lead slag are presented in Table 1.

2.2. Mixed Design. The concrete mixture design was calculated using absolute volume method according to ACI 211.1-91 [27] (Table 2). In order to evaluate the effect of fine and coarse serpentine aggregates on the engineering characteristics of heavyweight concrete containing lead slag, 16 mixture designs were considered. In all the mixture, the water to cement ratio was considered constant and equal to 0.4 and the amount of cement equal to 400 kg/m^3. Also, the amount of lead slag was considered equal to 1350 kg/m^3. The air percentage of concrete was considered as 1%. To make the samples, at first the used cement was mixed with water

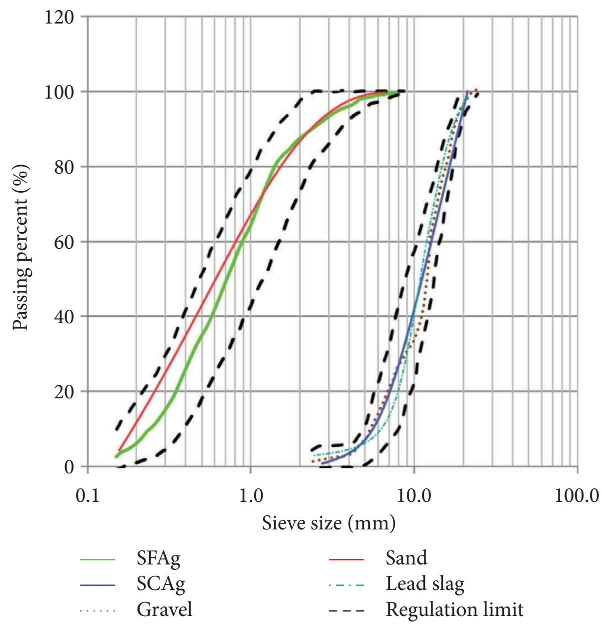
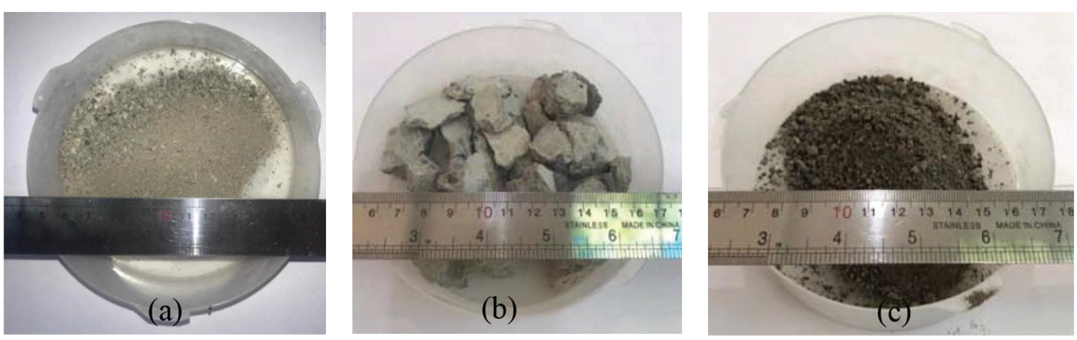


Figure 1: Grading curves of aggregates.



(a) (b) (c)

Figure 2: The materials used (a) fine serpentine aggregates, (b) coarse serpentine aggregates, and (c) lead slag.

for 2 minutes, then natural and serpentine coarse aggregates were added to the mixture, and finally natural fine aggregates, serpentine fine aggregates, and lead fine aggregates were added to the mixture. Fresh concrete according to the type of test was poured into moulds and kept for 24 hours at a temperature of 23 ± 2 degrees Celsius.

2.3. Methods. Compressive strength was measured using cube samples ($15 \times 15 \times 15$ cm) according to ASTM C39 [28]. Flexural strength was measured using prismatic samples with dimensions of $40 \times 40 \times 10$ cm according to ASTMC293 [29] (Figure 3). The water penetration depth was measured according to DIN1048 [30] on cubic samples of $10 \times 10 \times 10$ cm (Figure 4).

The impact resistance of the samples was determined using the recommendations of the ACI 544 2R [31] committee. The drop hammer device was used for testing the samples (Figure 5). A 4.45 kg mass has been used as an impact device. This mass falls from a height of 457 mm on a steel ball with a diameter of 635 mm. There is a holding chamber around the test. This chamber makes the test specimen not move after the weight hits it and remains stable. The whole set of the specimen and the holding chamber is located on a steel surface. After placing the test device on the samples, the weight is released. This process is repeated until the crack width of the concrete sample exceeds 2.5 cm. However, according to ACI 544 2R [31] recommendation, ultimate failure is when the pieces are completely separated. In this experiment, 16 mixed designs with different proportions of serpentine aggregates were predicted, and three samples of each mixed design were prepared for testing. The sample is a concrete disc with a diameter of 152 mm and a thickness of 63.5 mm. In this research, the first crack observed on the test specimen was considered the initial crack. When the specimen was completely separated, it was considered to be the ultimate

Table 1: The chemical attributes of the materials.

Components (wt. %)	Cement	Serpentine aggregate	Lead slag
Al_2O_3	4.95	0.79	2.1
CaO	62.95	0.27	5.1
SiO_2	21.27	41.98	11.8
Fe_2O_3	4.03	7.02	12.9
MgO	1.55	38.55	0
SO_3	2.26	0.03	0.05
K_2O	0.65	0.03	0.18
Na_2O	0.49	0	0.42
Mn_2O_3	—	0.05	—
TiO_2	—	0.04	—
P_2O_5	—	0.03	—
Cl	—	0.02	—
Cr_2O_3	—	0.32	—
NiO	—	0.38	—
CO_3O_4	—	0.04	—
PbO	—	—	48.8
LOI	—	10.45	18.65
Specific gravity	3.15	2.79	4.08

Table 2: Mixture design (kg/m^3).

Mix code	Cement	Serpentine fine aggregates	Serpentine coarse aggregates	W/C	Sand	Gravel	LS	SP
F0C0	400	0	0	0.4	430	275	1350	3
F0C25		0	68.75		430	230		
F0C50		0	137.5		430	185		
F0C100		0	275		430	90		
F25C0		107.5	0		360	275		
F25C25		107.5	68.75		360	230		
F25C50		107.5	137.5		360	185		
F25C100		107.5	275		360	95		
F50C0		215	0		300	275		
F50C25		215	68.75		300	220		
F50C50		215	137.5		300	180		
F50C100		215	275		300	85		
F100C0		430	0		160	275		
F100C25		430	68.75		120	275		
F100C50		430	137.5		70	275		
F100C100		684.87	402.064		0	0		

SP: superplasticizer; LS: lead slag; W: water; C: cement.

Figure 3: Flexural strength test.

failure state. The amount of energy absorption and the percentage increase in the number of blows after the initial break were calculated. The relationship provided to calculate the fracture energy is in the form of the following equation:

$$E = \text{nmgh}. \tag{1}$$

In this relationship, n is the number of blows, m is the mass of the drop hammer, g is the gravity acceleration, and h is the height of the fall.

Gamma ray attenuation test was performed using sodium iodide nal (TL) with a multichannel analyzer (Figure 6). cs137 radiation source was used in this experiment. The samples were placed in the water pool for 28 days. The samples with dimensions of 10×10 cm were placed in front of the rays of the gamma ray source. This

Figure 4: Water penetration test.

Figure 5: Drop hammer test.

Figure 6: Gamma ray attenuation.

test continued for 20 minutes for each sample. The LAC of gamma ray was measured by the fractional intensity of N_X-ray passing through the thickness x with N_0 source intensity. The linear damping coefficient is obtained from the following equation:

$$\mu = \frac{1}{X}\ln\frac{I}{I_0}, \quad (2)$$

where X represents thickness of concrete in centimeters, I represents the number of counts recorded in the detector in the absence of the sample, and I_0 represents the number of counts recorded in the presence of the concrete sample.

3. Results and Discussion

The workability results were obtained in the form of the slump of fresh concrete, and the results are presented in Table 3. According to the results, adding 25% serpentine fine aggregates to the samples improve the workability. The reason for this could be the roundness of these particles and the creation of tiny holes that have the same function as bullets. Adding coarse serpentine aggregates to the mixture reduced workability and slump. In higher percentages, the presence of this material reduced the slump by about 14.5%. The surface area of fine and coarse serpentine aggregates is more than normal aggregates. With the increase of serpentine aggregates, more water is needed, which causes the mixture to become dry.

In Figure 7, the density and compressive strength of the samples are compared with each other. As expected, the density of the samples increased with the increase of serpentine aggregates. The highest density was obtained in the F100C100 sample and was equal to 3003 kg/m^3. According to EN206-1 [32], heavyweight concretes have a specific gravity greater than 2600 kg/m^3. The density of the samples was obtained in the range of 2622 to 3003 kg/m^3. Therefore, all samples are of a heavyweight concrete type.

Contrary to density changes, the increase of serpentine aggregates does not lead to an increase in compressive strength. The greatest increase in compressive strength was obtained in a sample in which 25% of fine and coarse serpentine aggregates were obtained (sample F25C25). In this sample, the compressive strength of 46.9 MPa was obtained, which increased by 23.4% compared to the control sample. Serpentine fine aggregates can improve the microstructure and increase the compressive strength of

Table 3: Test results.

Mix code	Slump (mm)	Density (kg/m^3)	Compressive strength (MPa)	Flexural strength (MPa)
F0C0	69	2622	38	4.14
F0C25	71	2645	39.3	4.25
F0C50	65	2668	38.1	3.95
F0C100	62	2712	34.2	3.86
F25C0	73	2659	43.1	4.2
F25C25	74	2682	46.9	4.31
F25C50	67	2707	44.3	4.01
F25C100	66	2754	39.3	3.87
F50C0	68	2707	41.2	4.03
F50C25	69	2719	43.3	4.16
F50C50	65	2752	42.3	3.93
F50C100	64	2792	38.3	3.78
F100C0	62	2782	37.1	4
F100C25	63	2808	37	4.14
F100C50	60	2829	36.9	3.81
F100C100	59	3003	33.9	3.76

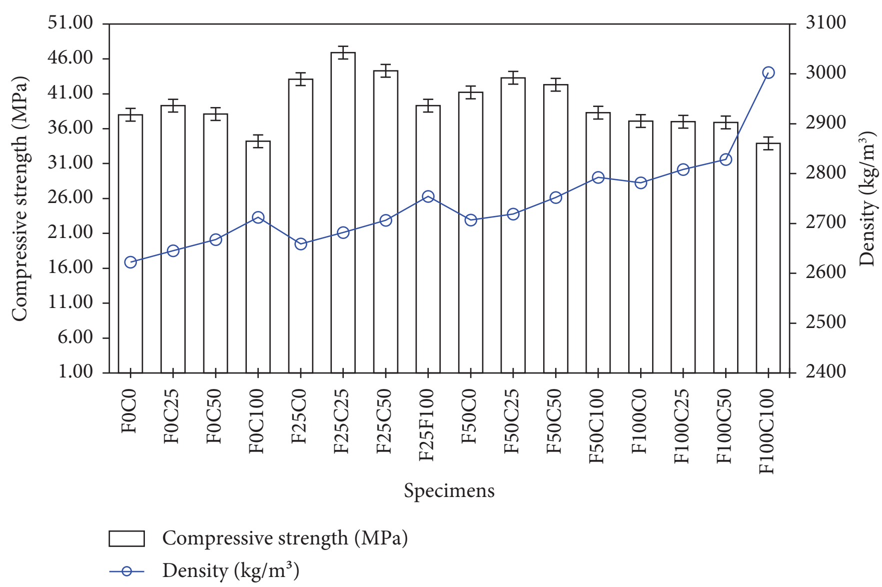


Figure 7: Compressive strength and density of concrete specimens containing different amount of serpentine aggregates.

concrete. Very fine serpentine particles improve concrete density by filling the holes in the cement paste and reacting with the calcium hydrates in the paste. With the increase of serpentine aggregates to more than 25%, the compressive strength of concrete has decreased. According to the observations, the reason for this decrease in strength is the weak hydration of cement paste and insufficient adhesion of cement paste with serpentine aggregates in concrete.

The concrete structure consists of phases: paste, aggregates, and interfacial transition zone (ITZ). After mixing the materials, the aggregates are surrounded by water and cement. Due to the high ratio of water to cement and limited space, the large hydrated crystals around the aggregates start to grow and create a soft structural network around them. As a result, the ITZ has more holes than cement mortar. When this area has many holes, the crystals in this area are easily broken and cracked. Therefore, the density and porosity of ITZ can significantly affect the compressive strength. Due to the high surface energy, the serpentine aggregates fill the pores during the formation of the C-S-H gel and increase ITZ's density. Also, fine serpentine aggregates, in combination with lead slag, cause a higher hardness for concrete.

Figure 8 shows the results of flexural strength with different percentages of replacing serpentine aggregates. The flexural strength of mixtures containing 25% of serpentine fine aggregates increased compared to other samples. The 28-day flexural strength of F25C0, F25C25, F25C50, and F25C100 samples is 4.25, 4.31, 4.16, and 4.14 MPa, respectively. The flexural strength of these samples increased by 2.6 to 3.3% compared to the control sample. By increasing the use of serpentine aggregates to more than 25%, the flexural strength decreased. This decreasing trend can be related to the fact that concrete samples containing serpentine aggregates absorb more water and the porosity

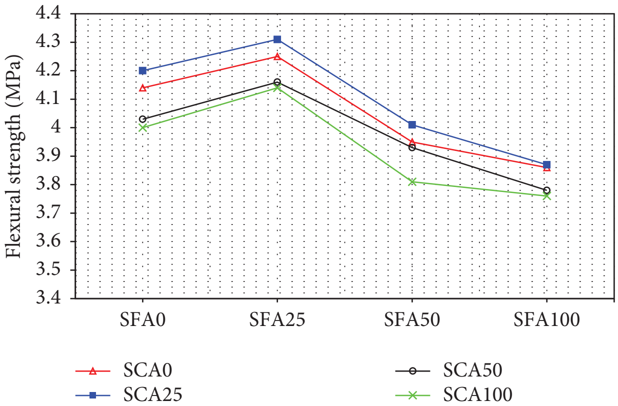


Figure 8: Flexural strength of concrete specimens containing different amount of serpentine aggregates.

around the aggregates increases and the quality of the ITZ decreases. Since the tensile strength is strongly affected, it can be concluded that the flexural strength decreases with the increase of serpentine aggregates.

The water penetration depth of the samples is presented in Figure 9. The highest depth of water penetration was observed in the F100C100 mixing design, which is 48.3 mm, and also the lowest water penetration depth is related to the F25C0 sample, which is 43.7 mm. The use of serpentine fine aggregates has led to a decrease in the depth of water penetration by 25%. Serpentine fine aggregates fill the holes of concrete and reduce its permeability of concrete. Neville divided concrete into three categories according to penetration depth [33]. Therefore, concretes with a depth of penetration between 0 and 30 mm are impenetrable concrete against a corrosive environment, concretes with a depth of 30 to 50 mm are impenetrable concrete, and concretes with a penetration depth of more than 50 mm are permeable concrete. All samples are in the category of impermeable concrete. Serpentine coarse aggregates did not have much effect on water penetration depth. This can be attributed to the presence of microcracks in heavyweight concrete containing serpentine coarse aggregates.

In Figure 10, the impact energy of the samples is presented. The impact energy at the initial crack level of the control sample was 780 joules. Using 25 and 50% serpentine coarse aggregates increased the impact energy at the initial crack level by 1.9 and 1.3%, respectively. But using 100% serpentine coarse aggregates reduced the impact energy at the initial crack level by about 0.4%. The addition of 25, 50, and 100% serpentine fine aggregates increased the impact energy at the initial crack level by 13.4, 8.4, and 3.7%, respectively. In samples containing 25% serpentine fine aggregates, a higher impact energy at the initial crack level was obtained than in other samples. The impact energy at an initial crack level in F25C0, F25C25, F25C50, and F25C100 samples increased by 13.4, 26.5, 25.4, and 16%, respectively, compared to the control sample. By increasing the amount of serpentine fine aggregates to a value greater than 25%, the percentage increase in impact energy at the initial crack level decreased. The cracking load corresponding to F50C0, F50C25, F50C50, and F50C100 samples increased by 8.4, 19.6, 16.8, and 13%, respectively, compared to the control sample. Also, the percentage increase in impact energy at the initial crack level of F100C0, F100C25, and F100C50 samples increased by 3.7, 11.3, and 7.8%, respectively, compared to the control sample. Also, the impact energy the percentage increase in impact energy at the initial crack level of a sample containing 100% fine serpentine aggregates and 100% coarse serpentine aggregates decreased by about 0.5% compared to the control sample.

The highest impact energy corresponding to the ultimate crack level was obtained in F25C25 sample. In this sample, the impact energy corresponding to the ultimate crack level increased by about 23.4%. One factor that increases the impact energy is the failure of the aggregate in loading at a higher speed. Under slow rate loading, cracks grow in weak cement paste and aggregate areas. But at a high loading speed, a large number of microcracks in concrete begin to grow, and due to lack of sufficient time, they pass through areas with high resistance and increase the apparent resistance to crack propagation. In samples containing 25% serpentine fine aggregates, less microcracks were created in the concrete, and the impact energy was higher than in other samples. In samples with more than 25% of serpentine aggregates, the percentage of increase in impact energy corresponding to the ultimate crack level decreased. But with the increase of fine and coarse serpentine aggregates to more than 25%, the upward trend of increasing compressive strength decreased. Silica constitutes a large part of the chemical structure of serpentine aggregates (about 42%). The highest impact energy corresponding to the ultimate crack level was obtained in F25C25 sample. In this sample, the impact energy corresponding to the ultimate crack level increased by about 23.4%. One of the factors that increase the impact of energy is the failure of the aggregate to load at a higher speed. Under slow rate loading, cracks grow in weak cement paste and aggregate areas. But at a high loading speed, a large number of micro cracks in concrete begin to grow, and due to lack of sufficient time, they pass through areas with high resistance and increase the apparent resistance to crack propagation. In the samples containing 25% serpentine fine aggregates, less microcracks were created in the concrete and the impact energy was higher than that in other samples. In samples with more than 25% of serpentine aggregates, the percentage of increase in impact energy corresponding to the ultimate crack level decreased.

In Figure 11 the LAC of the samples is presented against the density. Replacing serpentine aggregates instead of ordinary aggregates in heavyweight concrete increased the value of the LAC. The reason for this is that serpentine aggregates are more capable of absorbing radiation than ordinary aggregates. By replacing 100% fine and coarse serpentine aggregates, the LAC has increased by 42%. In general, the results of the gamma ray test show that the pores in concrete have a significant effect on the shielding properties of concrete. In cases where the pores are empty, the radiation easily passes through the pores. But in cases where the pores are filled with serpentine fine aggregates, the LAC increases and this means that the protective properties

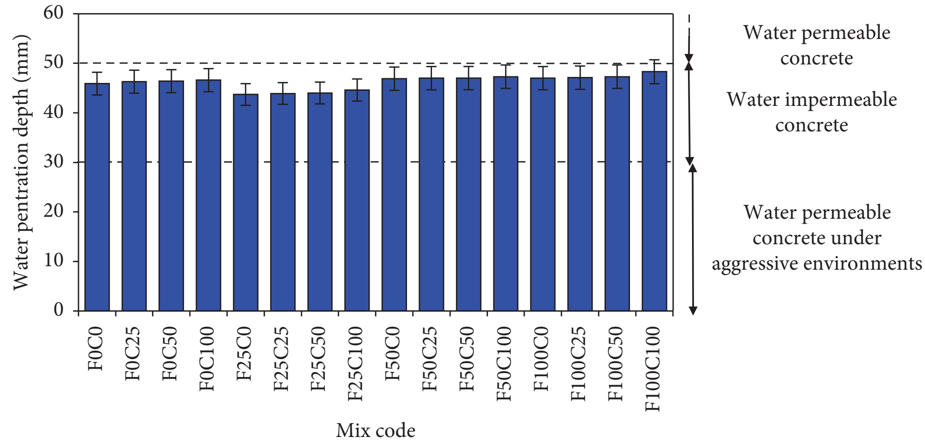


Figure 9: Water penetration depth.

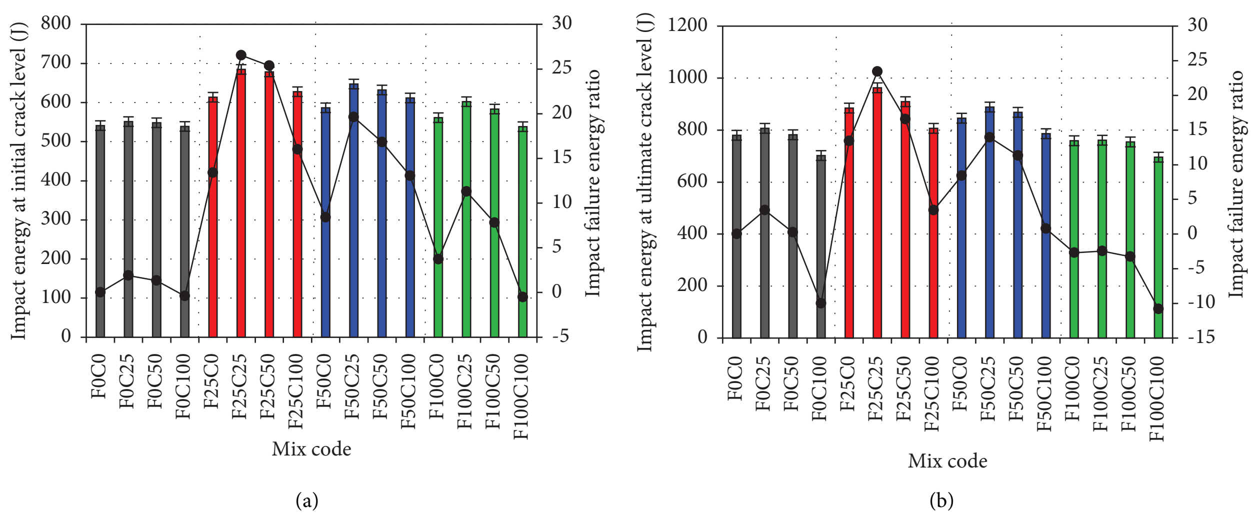


Figure 10: The impact energy (a) at initial crack level and (b) at ultimate crack level.

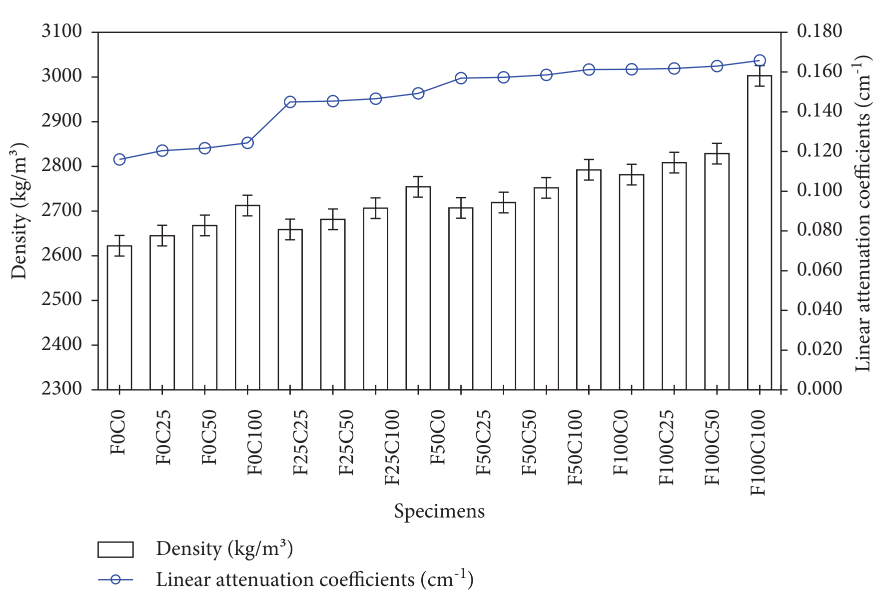


Figure 11: LAC and density of the specimens.

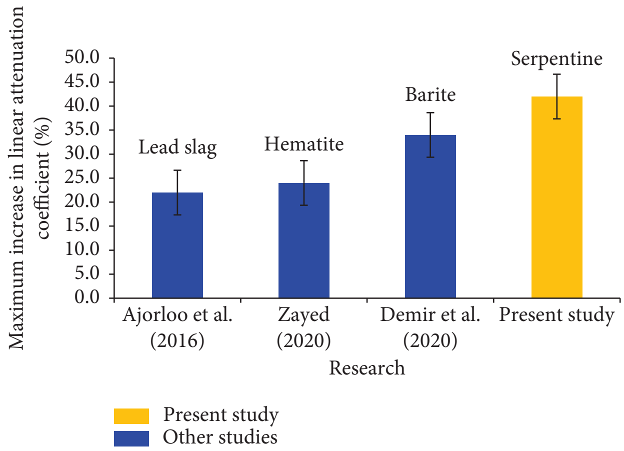


Figure 12: Comparison of the maximum LAC with other studies.

are improved. The results showed that 25% of coarse serpentine aggregates and 25% of fine serpentine aggregates is the optimal amount to improve the shielding features against gamma rays; because the mentioned values, in addition to improving the shielding characteristics of heavyweight concrete, also lead to the improvement of the mechanical characteristics of concrete.

Based on the studies, density has a direct relationship with linear and mass damping coefficient. As the density of the concrete sample increases, the damping coefficient should also increase. The relationship between the damping coefficient and the density is expressed as a linear regression relationship [34, 35]. In the present study, the reason for the increase in density is the substitution of lead slag and serpentine aggregates. Lead slag and serpentine aggregates improve the performance of concrete against gamma rays by improving damping and reducing radiation penetration.

The LAC of the sample containing 100% coarse serpentine and 100% fine serpentine has increased significantly compared to the control concrete, and it means that serpentine aggregates can also be effective in reducing the gamma ray transmission flux. The presence of serpentine aggregates in the samples increases the LAC of the samples. The interaction of serpentine aggregates, ordinary aggregates, and lead slag has created a compound resistant to gamma radiation. Serpentine aggregates play an effective role in increasing the resistance to gamma rays due to their inherent fragility and the locking of aggregates.

Figure 12 compares the results of the gamma ray test with similar studies. In the selected studies, the authors tried to use heavyweight materials to produce suitable concretes to deal with gamma rays. Ajorloo et al. [36] increased the LAC of concrete by about 22% by using lead aggregates. Zayed et al. [37] increased the LAC by about 24% by using hematite aggregates. Also, Demir et al. [38] showed that the use of barite aggregates can increase the LAC by 34%. In the present study, the use of serpentine aggregates increased the LAC by 42% compared to the control sample.

4. Conclusions

This study evaluated the shielding, mechanical, and durability properties of heavyweight concrete containing serpentine aggregates and lead waste slag. For this purpose, tests such as slump, XRD, compressive strength, flexural strength, water penetration depth, drop hammer, and gamma rays were performed. A summary of the most important results is presented below:

(i) Adding 25% of serpentine fine aggregates to the samples improves the workability. The reason for this could be the roundness of these particles and the creation of tiny holes. Adding coarse serpentine aggregates to the mixture has reduced workability and slump. In higher percentages, the presence of this material reduced the workability by about 14.5%. The surface area of fine and coarse serpentine aggregates is more than normal aggregates; with the increase of serpentine aggregates, more water is needed, which causes the mixture to become dry.

(ii) Serpentine fine aggregates can improve the microstructure and increase the mechanical strength of concrete. Very fine serpentine particles improve concrete compaction by filling the cavities of cement paste and reacting with calcium hydrates.

(iii) The density of concrete samples containing serpentine aggregates and lead waste slag was obtained in the range of 2622 to 3003 kg/m^3. According to EN206-1, such concretes are considered heavyweight concretes.

(iv) The degree of compaction and porosity of ITZ can significantly affect the compressive strength of concrete. Due to the high surface energy, the serpentine aggregates fill the pores during the formation of C-S-H gel and increase ITZ's density. Also, serpentine fine aggregates, in combination with lead waste slag, cause a higher stiffness for concrete.

(v) The flexural strength of mixtures containing 25% serpentine fine aggregates increased by 2.6 to 3.3% compared to the control sample. The flexural strength decreased by increasing the use of serpentine aggregates to more than 25%. The reason is that concrete samples containing more serpentine aggregates absorb more water, the porosity around the aggregates increases, and the quality of the transition zone (ITZ) decreases. Since ITZ strongly influences tensile strength, it can be concluded that flexural strength decreases with the increase of serpentine aggregates.

(vi) The use of fine serpentine aggregates up to 25% in combination with coarse serpentine aggregates up to 0, 25, 50, and 100% reduced the water penetration depth by 4.8, 4.3, 4.1, and 2.8%, respectively. In other samples (serpentine fine aggregates more than 25%), the use of serpentine aggregates increased the water penetration depth, and serpentine coarse aggregates did not have much effect on reducing the water penetration depth. This can be attributed to the presence of microcracks in heavyweight concrete containing serpentine coarse aggregates.

(vii) The highest impact energy at the ultimate crack level was obtained in the sample containing 25% coarse serpentine aggregates and 25% fine serpentine aggregates. In this sample, the impact energy increased by 23.4%. In samples with more than 25% serpentine, the increasing percentage in impact resistance decreased.

(viii) The replacement of serpentine aggregates instead of ordinary aggregates in heavyweight concrete increased the LAC. This is because serpentine aggregates are more capable of absorbing radiation than ordinary aggregates. By replacing 100% fine and coarse serpentine aggregates, the LAC increased by 42%.

(ix) Serpentine fine aggregates significantly affect gamma ray damping due to their properties that reduce the pores in concrete, especially when these materials are made from high-density minerals.

Data Availability

All data generated or analyzed during this study are included in the manuscript.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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