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Research paper

Use of granulated lead-zinc slag as replacement of fine aggregate in structural concrete: compressive strength and radiation shielding study

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Abstract: In this study, the effects of replacing fine aggregate by granulated lead/zinc slag waste (GLZSW) on the thickness of concrete shields against X-ray radiation and on the compressive strength of concrete have been investigated. The fine aggregate was substituted by GLZSW in four percentages: 25%, 50%, 75%, and 100% (by weight). The first aim of the present study was to compare the thicknesses of concretes with GLZSW and control concrete using Lead Equivalent (LE). The second aim was to assess the effects of replacing fine aggregate by GLZSW on the compressive strength of concrete. Results of this study indicated that the compressive strength of mixed concretes increased significantly compared to the control upon replacing fine aggregate by GLZSW; the mixture containing 100% GLZSW had the greatest compressive strength. Further, the inclusion of GLZSW as a substitute for fine aggregate increased the radiation attenuation properties and consequently decreased the thickness of concrete shields in direct proportion to the mixing ratio of GLZSW. The results revealed that concrete mixes containing 100% GLZSW offered the greatest reduction in shield thickness. The study shows that there is a promising future for the use of GLZSW as substitute for fine aggregate in concrete used to shield against X-ray radiation.

Keywords: Compressive strength, granulated lead-zinc slag waste, X-ray radiation, concrete, concrete thickness, radiation attenuation

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1. Introduction

Widespread usage of X-ray radiation engineering makes it necessary to design and fabricate shields to protect various elements (e.g., structures, equipment, people) against the damaging effects of radiation. The most effective method of reducing harmful radiation can be achieved through the application of lead shields or special types of concrete characterized by high radiation attenuation [1,3,4,6,8,14,31].

Lead is heavy, expensive, has low mechanical and chemical stability, and it is inflexibility [13]. Concrete has ability to reduce radiation exposure without affecting the properties of a structure [37] and it is a very common and the most widely used construction material. Concrete is easy to manufacture, offers satisfactory mechanical properties, as well as it is cost-effective [10]. To improve the properties of concrete, various aggregates can be easily mixed with them according to a specific application (e.g., shielding engineering). Recently, various additives have been applied to enhance the shielding properties [33].

The most common aggregates are produced from natural sources, which are being depleted rapidly as a result of high consumption [20,36]. Therefore, finding new alternative materials to substitute for natural sand and gravel becomes crucial and necessary to decrease the consumption of natural resources.

In recent years, the amount of industrial waste and byproducts generated has increased because of population growth and economic development. For most of this waste, effective uses have not been found, causing environmental degradation and a waste disposal crisis. Therefore, incorporation of industrial waste into concrete as substitutes for natural aggregate counteracts the scarcity of natural materials and solves some of the problems of solid waste disposal and resource depletion.

GLZSW is one of the byproducts that may be incorporated into concrete as a replacement for fine aggregate. The conventional method of GLZSW disposal in landfills is a cause of negative impacts on health and the environment. Thus, minimizing the amount of GLZSW dumped into landfills by development of commercial applications (e.g., incorporation in concretes), can reduce environmental problems related to waste disposal and the recent growth in global demand for raw aggregates. Moreover, GLZSW concrete, because of its high density, can be used to reduce the thickness of shields against X-ray radiation.

A few authors have reported the effects on concrete and mortar properties of replacing fine aggregate by various types of slags such as iron slag [21], steel slag [12], zing slag [32], furnace and welding slag [28], granular slag [18], ferro-silicate slag [17], copper slag [5,19], copper tailing slag [34], industrial waste generated during extraction of zinc (imperial smelting furnace slag) [35], recycled coarse aggregates [9], micro- and nano-particles [15], amethyst ore [11], lead slag [29], barite-fluorspar mine waste [7], electric arc furnace slag [22]. These authors recommended various percentages for replacement of fine aggregates. There have been limited studies of the use of granulated lead-zinc slags in concrete.

However, to the best of our knowledge, there has been no previous research on the use of GLZSW as fine aggregate in concrete mixtures for X-ray radiation shielding. Therefore, our goals were (1) to assess the effect of GLZSW incorporation for a partial or full substitution of fine aggregate in concrete on the compressive strength properties, and (2) to evaluate the radiation-shielding thickness of mixed concretes for use against X-ray radiation.

2. Research program

Tests were performed to evaluate density, compressive strength, X-ray radiation attenuation, lead equivalent thickness of concrete, and concrete thickness. The properties of materials are presented in Table 1. Whereas the granulometric curves of the different aggregates are presented in Fig. 1.

Table 1. Chemical composition of the components used in the experimentation

Element	Portland cement (PC 35 type) [%]	Sand [%]	Water [%]	Granulated slag [%]
H	-	-	0.11	-
O	52.25	49.48	0.89	59.09
Al	2.55	6.04	-	6.19
Si	11.75	34.23	-	8.19
Mg	2.43	0.81	-	3.48
Fe	0.77	2.53	-	11.22
Na	-	4.03	-	-
C	-	0.46	-	-
S	1.34	-	-	1.58
Ca	23.66	2.42	-	8.90
Pb	-	-	-	0.56
Others	5.25	0.00	0.00	0.89

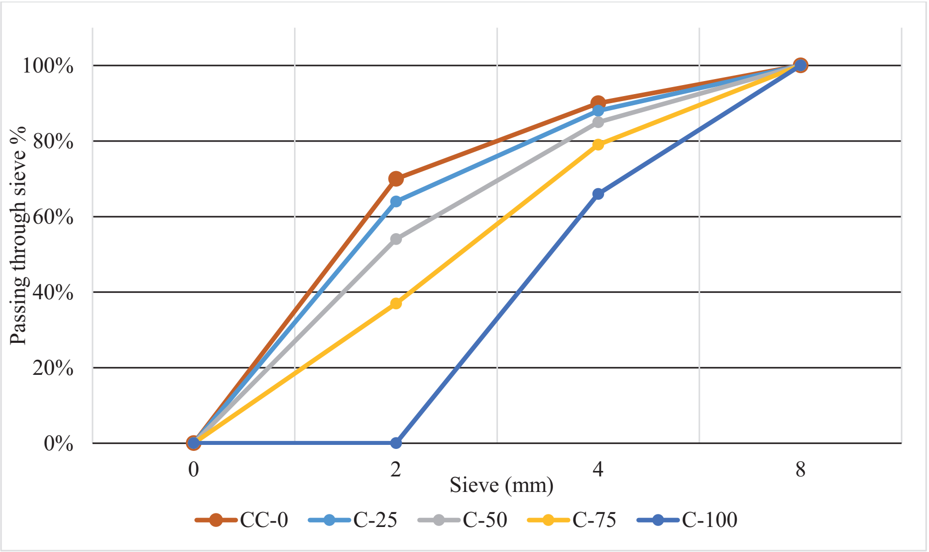

Fig.1.Granulometric curves of the different aggregates

2.1. Preparation of concrete mixes

Four mixes were prepared by replacing fine aggregate with GLZSW (25%, 50%, 75%, 100%) by mass and one control concrete was prepared with no additive.

Prepared concretes were classified as control concrete (CC-0), concrete incorporated 25% of Glzs (C-25), concrete incorporated 50% of Glzs (C-50), concrete incorporated 75% of Glzs (C-75), and concrete incorporated 100% of Glzs (C-100). Mixture proportions of mixed concretes is presented in Table 2. All concretes were manufactured according to [25,26,27].

Table 2. Mixture proportions of mixed concretes (kg/m^3)

Mixture	Cement	fine aggregate	GLZSW	Water	Gravel (grain coarseness2–4)	Gravel (grain coarseness 4–8)
CC-0	414	1122	-	214	319	162
C-25	4346	8841	2947	2123	335	170
C-50	5082	6893	6893	2336	391	199
C-75	4672	3167	9506	2229	360	183
C-100	4807	00	13039	2376	370	189

2.2. Testing method

This paper is a continuation of the previous work of the author pertaining to the use of selected industrial wastes as sand substitutes in concrete, which are relatively new materials with the potential for use in structural concrete applications. Hence, the measurement of attenuation capabilities for X-ray radiation and the determination of concrete thickness are based on [2].

Cubes (100 × 100 × 100 mm) were used to measure the compressive strength of the prepared concretes according to European standard [24]. Experiments were performed on all the specimens after 28 days of curing. Table 3 and Fig. 2 present results acquired for average tests of three measurements.

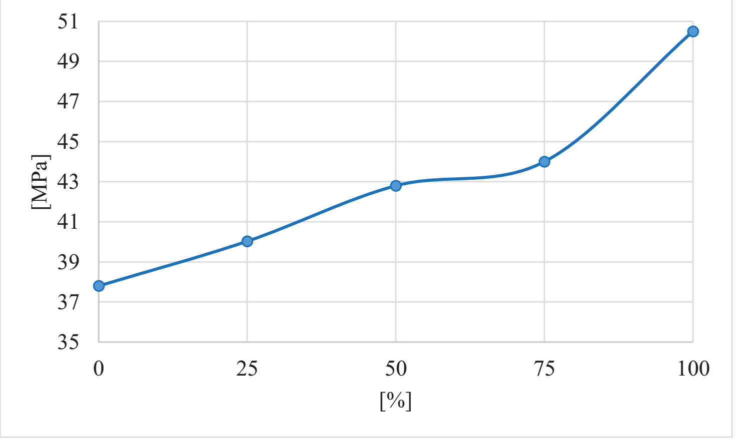

Figure 1. The Relationship between the granulated lead zing slag ratio and the compressive strength of concrete.

The thickness of concrete that absorbs radiation to the same extent as a given thickness of lead is the lead equivalent *(LE)*. The LE of CC-0 was compared to the concretes' thickness with admixtures at 100 kV and 150 kV in accordance with the standard tables [23].

To measure the lead equivalent of concrete, three specimens were made in slabs (dimensions: 250 mm × 250 mm with 26 mm thicknesses for each mixture proportion). We generated the X-ray beam by using a Röntgen apparatus (ERSECO 200 MF system). The selected X-ray tube voltage ranged from 100 kV for the 26 mm shield to 150 kV for 52 and 78 mm shields. The distance of the source from the first slab was 80 mm.

The LE was measured by locating the concrete slab and stepwedges of various heights (several lead foils, 0.05 mm thick) in the radiograph; then these elements were exposed to a primal broad X-ray beam. Then we added the second slab to increase the concrete shield thickness. We applied the same approach as above to make a measurement. Then the third slab was added and the procedure of measurement was analogical.

For lead equivalent calculation, the optical density (OD) of the concrete specimens and the OD of the stepwedge were compared in compliance with PN-EN ISO 17636-1:2013-06. WILSON- LCD 51 densitometer was used to measure the OD of the radiograph. The results of LE are presented in Tables 4, 5 and 6.

From the lead thickness equivalent based on the standard tables, we determined the shield thickness––composed of control concrete—equivalent to the tested shields' thickness (waste admixture at 100 and 150 kV) [23]; data are tabulated in Tables 4, 5 and 6.

3. Results and discussion

Fine aggregate replacement by GLZSW increased the compressive strength and the density depending on the replacement percentages. The results of density and compressive strength testing are presented in Table 3.

Table 3. Compressive strength and density of mixed concretes

Mixture	CC-0	C-25	C-50	C-75	C-100	Standard deviation	Coefficient of variation
Compressive strength (MPa)	37.80	40.03	42.80	44	50.50	4.83	0.11
Density (kg/m^3)	2160	2210	2380	2400	2560	0.16	0.07

Table 3 shows that 25% substitution fine aggregate by granulated lead zing slag waste has little to influence (marginal impact) on the density and on the compressive strength. Density and compressive strength of C-25 increased by 2.31% and 6%, respectively, compared to CC-0.

Further increases in percentage replacement had considerable impact on the density and on the compressive strength. For 50%, 75%, and 100% GLZSW substitution, the density values were 10.19%, 11.11% and 18.52%, respectively higher than the control specimen value.

Compared to the control concrete, for the 50%, 75%, and 100% GLZSW substitutions the compressive strength values increased to 42.80 MPa, 44 MPa, 50.50 MPa, respectively, compared to the CC-0 strength of 37.80 MPa.

From the results it suggested that mixture containing 100% GLZSW provided the best density and compressive strength performance among other mixes.

The influence of GLZSW addition on the thickness of lead equivalent (*TLE*) at 100 kV for 26 mm can be seen in Table 4. thickness of lead equivalent increases with an increase in the granulated lead zinc slag waste contents.

Table 4. Comparison of the values of the lead equivalent of control concrete and mixed concretes shields and the control concrete shields' thicknesses matching the mixed concrete shields' thickness of 26 mm at 100 kV

Mixture		CC-0	C-25	C-50	C-75	C-100
Lead equivalent thickness (mm)		0.25	0.35	0.45	0.53	0.60
Control concrete thickness (mm)		26				
Thicknesses of control concrete shields corresponding to the thickness of mixed concrete shields (mm)		-	45.02	51.08	66.04	70.07
Obtained difference (mm)	Lead equivalent thickness (mm)	-	0.10	0.20	0.28	0.35
	Concrete thickness (mm)		19.02	25.08	40.04	44.07

Compared to the control concrete, incorporating 25% of GLZSW as fine aggregate results in a 0.10 mm increase in the *TLE*. By using 50% GLZSW the *TLE* increased by 0.20 mm. The presence of 75% and 100% of GLZSW leads to 0.28, and 0.35 mm increase in the TLE of the mixed concretes.

Table 5 presents the influence of fine aggregate replacement on the *TLE* of concrete (52 mm thick at 150 kV).

Table 5. Comparison of the values of the lead equivalent of control concrete and mixed concretes shields and the control concrete shields' thicknesses matching the mixed concrete shields' thickness of 52 mm at 150 kV

Mixture identification		CC-0	C-25	C-50	C-75	C-100
Lead equivalent thickness (mm)		0.45	0.65	0.75	0.90	0.95
Control concrete thickness (mm)		52				
Thicknesses of control concrete shields corresponding to the thickness of mixed concrete shields (mm)		-	76.01	84.90	89.50	95.01
Obtained difference (mm)	Lead equivalent thickness (mm)	-	0.20	0.30	0.45	0.50
	Concrete thickness (mm)		24.01	32.90	37.50	43.01

Based on these data, there is an increase of *TLE* (composed of mixed concrete) with an increase in the amount of GLZS applied as an alternative for fine aggregate. The *TLE* of C-25, C-50, C-75, C-100 was, respectively, 0.20, 0.30, 0.45, 0.50 mm—higher compared to control concrete.

Table 6 presents the results of the impact of GLZSW addition at 150 kV—78 mm concrete thickness.

Table 6. Comparison of the values of the lead equivalent of control concrete and mixed concretes shields and the control concrete shields' thicknesses matching the mixed concrete shields' thickness of 78 mm at 150 kV

Mixture		CC-0	C-25	C-50	C-75	C-100
Lead equivalent thickness (mm)		0.60	1.09	1.17	1.25	1.33
Control concrete thickness (mm)		78				
Thicknesses of control concrete shields corresponding to the thickness of mixed concrete shields (mm)		-	125.8	137.01	141	154.3
Obtained difference (mm)	Lead equivalent thickness (mm)	-	0.49	0.75	0.65	0.73
	Concrete thickness (mm)		47.8	59.01	63	76.3

An increase of fine aggregate replacement by GLZSW led to an increase in the *TLE*. The lead thickness equivalent of concrete with 25%, 50%, 75%, and 100% GLZSW were 1.09, 1.17, 1.25, and 1.33 mm, with respect to concrete with GLZSW admixture thickness of 0.60 mm.

Tables 4–6 present the results of the effect of fine aggregate replacement by GLZSW on the control concrete thickness corresponding to the concrete thickness with admixture tests. The control concrete thickness matching the concrete with GLZSW admixtures follows the same pattern as TLE, in that the control concrete thickness corresponding to the mixed concrete increases when the percentage replacement increases.

Data included in Table 4 show that with an increase in the amount of granulated lead zinc slag waste used as an alternative for fine aggregate, we observe an increase in the control concrete thickness shield matching the tested shield thickness with granulated lead zinc slag waste admixture (26 mm thickness, 100 kV). The control concrete shield thickness matching the tested shield thickness with 25%, 50%, 75%, and 100% increased by 19.02 mm, 25.08 mm, 40.04 mm, and 44.07 mm respectively, compared to concretes with granulated lead zinc slag waste admixture.

Table 5 shows increases in the control concrete thickness matching the concretes' thickness with admixture (52 mm thickness, 150 kV) with an increase of GLZSW content. The increase in *CC-0* thickness up to 76.01, 84.90, 89.50, and 95.01 mm was recorded in comparison with 52 mm thickness of C-25, C-50, C-75, C-100, respectively.

For concretes with GLZSW admixture with a 78 mm thickness at 150 kV, the data presented in Table 6 also show an increase in the control concrete thickness corresponding to the mixed concrete. The control specimen thickness corresponding to the mixed concrete was 125.8 mm, 137.01 mm, 141 mm, and 154.3 mm with respect to concrete with GLZSW admixture thickness 78 mm.

In other words, the outcome indicate that we obtained thinner concrete than concrete with no additive. Concretes with 25%, 50%, 75%, and 100% with a thickness of 26 mm were thinner than control concrete by 19.02 mm, 25.08 mm, 40.04 mm, and 44.07 mm respectively. In comparison with CC-0, the mixed concretes with 52 mm and 78 mm thickness were thinner by 24.01, 32.90, 37.50, and 43.01 mm and 47.8 mm, 59.01 mm, 63 mm, and 76.3 mm, respectively.

4. Discussion

The following observations can be made based on the acquired results:

- Density and compressive strength of GLZSW concrete mixes are high as compared to control concrete with no additives. This effect had a positive impact on the absorption of X-ray radiation. The highest density and compressive strength were that of the concrete specimens containing 100% granulated lead-zinc slag waste aggregate, which were 18.52% and 33.60% higher than the control concrete.
- The thickness of lead equivalent increases with the increment of GLZSW filler loading.
- The control concrete thickness corresponding to the concrete thickness containing lead-zinc slag waste as a substitute for fine aggregate increases with the increment of GLZSW.
- The concrete with GLZSW displayed a notable influence in reducing the thickness of concretes for radiation shielding. Using GLZSW as a replacement of fine aggregate in concrete shields reduces its thickness by 19.02 mm, 25.08 mm, 40.04 mm, and 44.07 mm for concretes with a 26 mm thickness and by 24.01, 32.90, 37.50, and 43.01 mm and 47.8 mm for the mixed concretes with the 52 mm thickness, and by 47.8 mm, 59.01 mm, 63 mm, and 76.3 mm for concrete shields with a 78 mm thickness dependence on the percentages replacement.

5. Conclusions

The results obtained in this study may be useful in development of radiation shielding applications to reduce the harmful effects of X-ray radiation to acceptable levels (e.g., in nuclear engineering, medicine, industry, and nuclear reactors). All concretes with GLZSW exhibited higher density, compressive strength, and less equivalent thickness than control concrete. The results support the conclusion that GLZSW has potential to be used as an fine aggregate substitute to enhance the radiation shielding properties of concrete, to reduce environmental impacts, and to compensate for scarce natural resources.

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