Properties and Durability of high performance heavy weight concrete in corporating black sand and different heavyweight aggregates types

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Abstract

The main objective of this research is to investigate the effect of utilizing steel slag as a coarse aggregate and black sand, ilmenite and magnetite as fine aggregate on the concrete behavior such as; compressive strength, resistance to sulfate attack, elevated temperatures and abrasion. Ferrosilicon was added by 10% of cement content, replacement percentages of black sand, ilmenite and magnetite equal 100%. Test specimens were subjected to elevated temperatures up to 750 °C for 2 hours. Specimens were exposed to sever sulfate attack through drying-wetting cycles in sodium sulfate solution with concentrations of 5%, 10% and 20% for 180 days. Exposure to 250 °C led to a notable increase in compressive strength. BS showed a significant effect on fire resistance properties for high performance heavyweight concrete (HWHPC) mixes, especially at 750 °C. The results indicated that utilizing 100% Ilmenite as fine aggregate replacement achieved the lowest water absorption, while black sand replacement enhanced abrasion resistance.

Keywords: Black sand, ferrosilicon,ilmenite, magnetite,water absorption, abrasion resistance, steel slag, HPHWC, durability.
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. Introduction

The properties of materials used in the concrete are affecting on the concrete properties such as strength, durability and serviceability. However, concrete is most of the times exposed to aggressive environments which may arise naturally such as seawaters, soils rich in sulfates or man-made such as chemical effluents from industries, waste water from drainage infrastructure, which affect the long-term performance of concrete. Some aggressive environments cause chemical processes reducing concrete properties due to the exchange of ions, these processes reducing the mechanical strength by the change in the binder matrix microstructure. Numerous investigations were conducted to ensure the effects of EAFS produced from electric arc furnace production on concrete.

High performance concrete prepared with steel slag and crystallized slag shows good physical and mechanical properties and can be used in construction as aggregates [1, 2].

The EAFS slag is detrimental for environmental so its use will reduce the harm for environmental [3]. Nowadays about 40% of global steel production in the world produced by Electric Arc Furnaces (EAF) plants [4], which, differ from older Basic Oxygen Furnace (BOF) plants, are used for scrap metal recycling to give more economical and sustainable production. demonstrated that the abrasion rate diminished by around 10% and 16%, respectively for the concrete mixtures with 5% and 10% silica fume, arranged at the water to cement ratio of 0.38 and 0.40, contrasted with the one of control concrete. Likewise, the concrete can resist abrasion by including silica fume[5]. Demonstrated that the compressive strength of concrete increased subsequent to heating up to 350oC for concrete with strength 170 MPa that containing 14-20% silica fume and afterwards reduced at higher temperatures[6]. demonstrated that the concrete strength and concrete weight reduced by sulfate attack because of the loss of the cement hydration products cohesiveness[7, 8]. Showed that the compressive strength of alkaline active slag concrete reduced by up to 17% and by 25% for ordinary Portland cement concrete in the case of 5% sodium sulfate solution[9]. The Rashid area in Egypt is considered a promising site with high abundance of black sand [10, 11]. The Egyptian black sands are derived from the River Nile tributaries in Ethiopia and Central Africa. These sediments are believed to be of Quaternary age [12]. (9)These black sands are derived from the upper reaches of the Nile, mostly from the Ethiopia Volcanic highland and Sudan, and are deposited at the river mouths where the flow velocity is reduced. For several years, various studies have been carried out by different investigators and organizations to assess the economic mineral constituent of these black sands in different areas [13].Ilmenite is the main constituent among the economic minerals in the areas investigated. Other economic minerals in decreasing order of abundance are magnetite, hematite, zircon, garnet, monazite and rutile[13, 14]. An isodynamic separator is used twice to concentrate all the heavy minerals in the magnetic fraction and to separate ilmenite from this fraction[15].

This research is the study of the compressive strength,modulus of elasticity,high elevated temperature, water absorption, abrasion resistance and sodium sulfate attack of the concrete containing black sand, ilmenite and magnetite as fine aggregate. Moreover, the effect of steel slag as coarse aggregate on these properties was studied. The importance of this study is to clarify the effect of enhancing the sustainability of HPHWC by using different types of environmentally friendly materials with so high contents, namely steel slag and ferrosilicon. No previous study has used this to investigate the effects of using black sand, ilmenite, and magnetite as fine aggregate onthe high elevated temperature, water absorption, abrasion resistance and sodium sulfate attack.

Objective of the investigation

In this framework, the present study aims to investigate the opportunity to replace the natural fine aggregates of concrete with black sand, ilmenite and magnetite by 100% beside the effect of steel slag. However, in this study, concrete is exposed to sodium sulfate attack for concentrations of 5, 10 and 20% Na_2SO_4 for 180 days and high temperatures up to 750°C for 2hours.

2. Experiment

2.1.Materials Properties

Raw materials containing CEM I 52.5 N (PC), ferrosilicon (FS); provided from Ferro-Silicon Alloys Company; Edfo-Aswan; Egypt. In this study, black sand (BS) was used as a raw material in the production of concrete mixtures, In addition to ilmenite (I) and magnetite (M) that were extracted (separated) from the black sand as shown in Fig.1. Coarse aggregates he was of size 4.75-10 mm and consisted of electric arc furnace steel slag (EAFSS) with a specific gravity of 3.5, normal sand (NS), and water were used in this paper. NS fineness modulus was 2.9 and the specific gravity was 2.55. The black sand was obtained from the Egyptian Black Sand Company, Rashid City, Egypt. With a particle size in the range between 0.15 to 0.3 mm and a specific gravity of 4, 4.5 and 4.7 for black sand, ilmenite, and magnetite, respectively. Fig. 2 shows the NS grading curve. All sand types were washed at the site to remove useless components. Chemical properties of BS, I and M are recorded in Table 1. A superplasticizer supported by a modified polycarboxylate ether was employed to get the highest durability and performance that are required for the various mixes. Its density at 20 °C is 1.1 gm/cm^3.

(a) Black sand (b) Ilmenite (c) Magnetite

Fig. 1. Fine and Coarse Aggregate used.

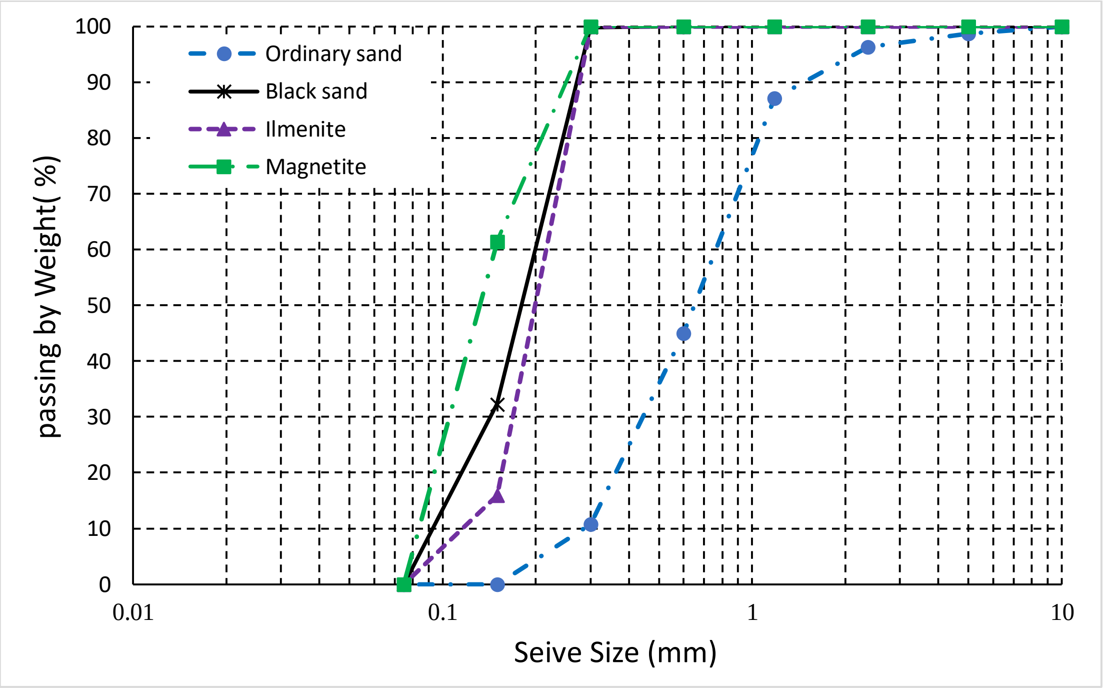

Fig. 2. Grading curve of Fine aggregate used.

Table 1. Chemical compositions of black sand, ilmenite and magnetite

Properties	Black Sand	Ilmenite	Magnetite
SiO_2	47.65	1.03	0.80
Al_2O_3	5.05	0.99	3.26
Fe_2O_3	4.97	40.42	87.29

CaO	20.60	-	-
MgO	15.42	2.77	0.61
TiO_2	2.02	53.07	5.61
Cr_2O_3	-	-	1.72
MnO	4.29	1.72	0.70
Loss on Ignition (LOI)	-	-	-

2.2.Mixing Procedures

Table 2 shows the mixtures proportions of HPHWC. Dry ingredients were blended in a laboratory drum rotary mixer with a capacity of 60 L for 1.5 min, followed by presenting the third mixing water for another 30 s. The remaining mixing water was blended with SP solution. Two steps were performed for the remaining solution separately:

- Half of the solution was added initially to wet the mixture to prevent binder flow. This progression required approximately 1 min.
- During mixing, another part of the solution, which was sufficient to wet components without performing binder, was added and left for 1 min.

After mixing, the concrete mixture was cast in the molding samples, compacted for 30 s by vibrating tables, and remained 24 h to cast. All samples were placed in a water curing tank until the test deadline. The fresh concrete pastes were thrown into the cube specimens that measured 100mm ×100mm ×100 mm and well compacted by a vibration table for 30 s. The curing specimens depended on restoring them in water until experimental time.

Mix no.	Cement	Coarse Aggregate	Fine Aggregate				FS	SP	W
		Steel Slag	Sand	Black Sand	Ilmenite	Magnetite			
MC	750	745.1	745.1	–	–	–	75	24.8	222.8
BS100	750	745.1	–	1129.0	–	–	75	24.8	222.8
I100	750	745.1	–	–	1270.1	–	75	24.8	222.8
M100	750	745.1	–	–	–	1326.5	75	24.8	222.8

Table 2. Mix proportions of heavyweight concrete kg per 1 m^3.

2.3. Methods

2.3.1. Compressive strength

The concrete was casted into a 100mm ×100mm ×100 mmcube mold and cured in saturated lime water for 7 and 28 days at 23 ±2 °C according to BS EN 12390–3[16].The compressive strength was tested by using Technotest compression machines.

2.3.2. Modulus of elasticity

Modulus of elasticity testing at 28 days was carried out using 150 mm × 300 mm cylinder complying with ASTM C469[17].

2.3.3. High elevated temperature

After curing for 28 days, 3 cubes per mixture were transferred to an electrical oven for drying at 105°C for 24 hours, after drying; the concrete specimens were exposed to high elevated temperature using an electric furnace up to 250, 550, and 750°C at a heating rate of 4°C/min and held at each temperature for a period of 2 hours. After exposure to elevated temperatures, the specimens were cooled naturally inside the oven to room temperature so as to avoid any temperature shock [18, 19].

2.3.4. Water absorption

Water absorption tested according to ASTM C 642 [20] for hardened concrete.The concrete specimens were dried at 105 °C for at least 24 h until the mass change does not exceed 0.5%. The dried specimens were immersed in water for at least 48 h until the mass change of the specimens does not exceed 0.5%. The immersed specimens were boiled for 5 h then cooled the specimens by a natural loss of heat to 20 to 25 °C. After finishing the whole step A and B were used to calculate the water absorption using the Eq. 1.

$$\text{Absorption after immersion } (\%) = \frac{\mathrm{B} - \mathrm{A}}{\mathrm{A}} * 100 \tag{1}$$

Where:

A is the mass of dried concretes.

B is the mass of surface dry concretes after immersion.

2.3.5. Abrasion resistance

Abrasion resistance was determined in accordance with the ESS 269/2005 standard procedures [21]. According to this method, the surface of the concrete is pressed onto a rotating steel plate via a constant load (600 gm/cm^2). Seven hundred grams of abrasive sand is put between the concrete and the steel plate. The concrete specimen’s surface was 70 mm × 70 mm and its thickness was 40 mm. Later, the plate is rotated 352 times with speed of 60 m/min for 9 min. Thus, the difference between the initial and final thickness of the specimen expressed the amount of abrasion resistance, decreasing the amount of thickness loss, increasing the abrasion resistance. Thickness losses of all test specimens were estimated as Eq. 2.

$$\mathrm{TL(mm)} = \frac{\mathrm{Wb} - \mathrm{Wa}}{\mathrm{D} \times \mathrm{L} \times \mathrm{B}} \tag{2}$$

Where:

TL= Thickness loss of the test specimen

W_b= Specimen weight before test

W_a= Specimen weight after test

D= Density of the test specimen

L= Length of the specimen face = 70 mm

B= breadth of the specimen face = 70 mm

2.3.6. Sodium sulfate attack

The resistance of concrete specimens exposed to sodium sulfate solution (Na_2SO_4) with concentrations of 50 g/l, 100 g/l and 200 g/l were determined by immersing concrete cubes in plastic containers for 28, 60, 90 and 180days until the test. The concrete specimens were exposed to sulfate solution under drying-wetting cycles in order to accelerate the sulfates attack, where even cycle includes drying specimens in the air for 10 days and 20 days immersed in the sulfates solution. The chemical attack tests were carried out according to ASTM C1012 [22].

3. Results and discussion

3.1. Unit weight

The unit weight of HWHSC made with (BS, I and M) as replacement from fine aggregate in Fig. 3. Unit weight of all mixes varied from 2635 kg/m^3 to 3110 kg/m^3 at 28 days. Concrete is considered high-density if its unit weight is more than 2,600 kg/m^3, as stated in BS EN 206-1[23]. The weight of heavy-weight concrete is due to the high weight of the components and their properties. Usually, minerals used as aggregates in concrete are magnetite, ilmenite, limonite, barite and some artificial materials such as perforated steel and iron shot[24].The unit weight increases with the high substitution ratio of (BS, I and M) of fine aggregate. For instance, unit weights are 2898, 3065 and 3110 kg/m^3 for 100% of black sand, ilmenite and magnetite, respectively whereas the unit weight of conventional concrete is 2635 kg/m^3.

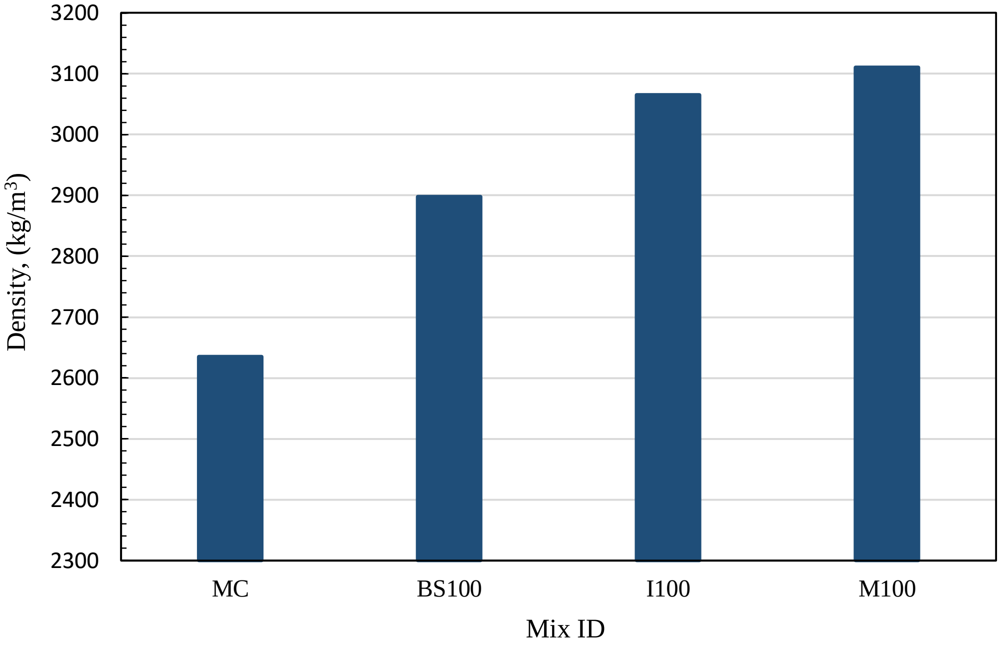

Fig. 3. Effect of fine aggregate type replacement on unit weight at 28 days.

3.2. Mechanical properties

3.2.1. Compressive strength

Fig. 4 shows the results of the compressive strength test of concrete samples containing black sand, ilmenite and magnetite as fine aggregate and containing 10% FS, 750 kg/m^3 and cured in water for 7 and 28 days. The Results of concrete compressive strengths are mean values of three test specimens in each mixture. The compressive strength after 28 days for mixture BS100 was found to be 18% less than the control mix MC and more decreases of 23% for mixture I100 that contains 100% ilmenite replacement level. Moreover, the use of 100% magnetite as fine aggregates decreased the compressive strength with a value of 29% at 28 days respectively, compared with Mc. Although BS, I and M contain metallic elements (Si, Ti and Fe), but due to the smoothness of the surface the cohesion was poor. BS, I, and M replacement at 100% showed unusual strength decay. These results are consistent with the results of previous research [25].

3.2.2. Modulus of elasticity

Modulus of elasticity of concrete is an important test to achieve the structural concrete requirements according to the American Concrete Institute [26]. Fig. 5 shows the results of the modulus of elasticity test of concrete samples containing black sand, ilmenite and magnetite as fine aggregate and containing 10% FS, 750 kg/m3 at 28 days. The modulus of elasticity results of MC, BS100, I100 and M100 were 45.56, 41.52, 40.15and 39.03 GPa, respectively. The results obtained are in agreement with the results of compressive strength

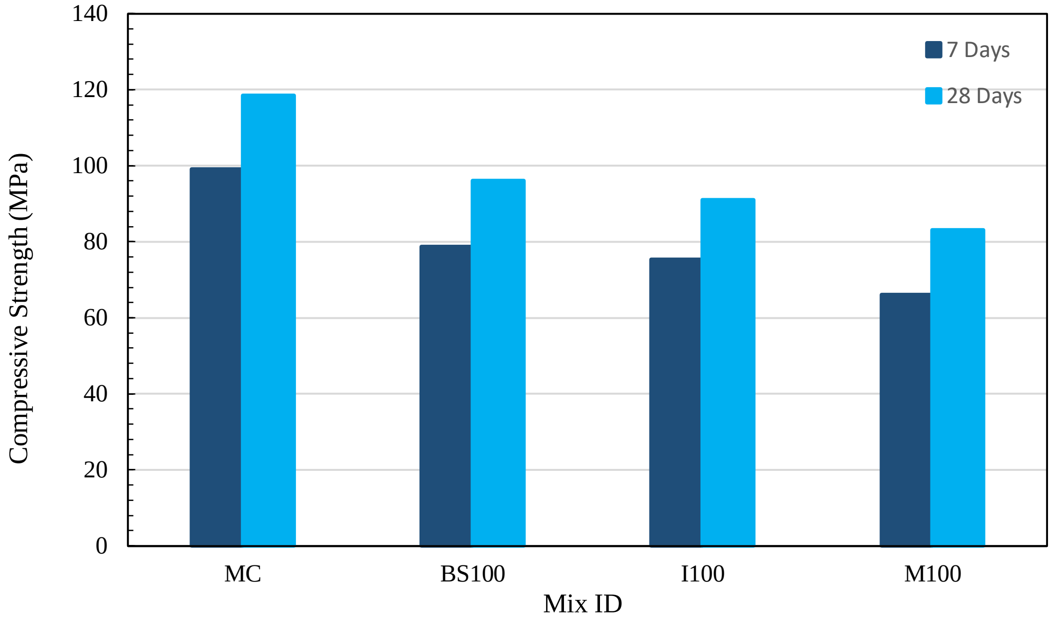

Fig. 4. Compressive strength at 28 days

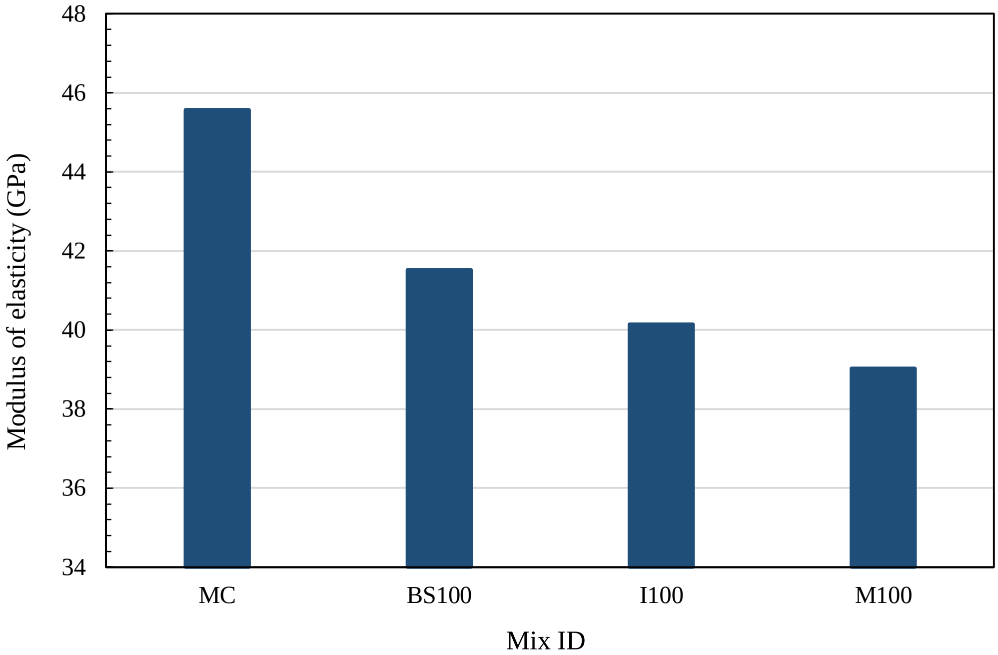

Fig. 5. Modulus of elasticity at 28 days

3.3. Durability of concrete

3.3.1. High elevated temperature

Fig. 6shows the effect of high temperature on the compressive strength of heavyweight concrete at 28 days. Fig. 6shows that exposing concrete samples to high temperatures of 250°C, 550°C and 750°C period of 2 hours is sufficient to reduce the compressive strength in varying proportions. In addition, the results showed that the exposure of concrete containing black sand, ilmenite and magnetite with a 100% substitution ratio to a temperature of 250°C improves the compressive strength by 5.4%, 4.2% and 6.0%, respectively, compared to the control concrete at 22°C and 28 days. This result may be due to the increased density of heavyweight concrete which enhances compressive strength. The loss in compressive strength as a result of exposure to high temperature has a direct, important relationship with the type of fine aggregate used in the production of heavyweight concrete in addition to its ratio of substitution with ordinary sand. Compressive strength losses of 29.6%, 34.9% and 29.8% were reported at 550 °C for BS100, I100 and M100, respectively. Also, compressive strength losses of 57.8%, 68.1% and 51.9% were reported at 750 °C for IBS100, I100 and M100, respectively compared to the control concrete at 22°C and 28 days. These results are consistent with the results of previous research [25, 27].

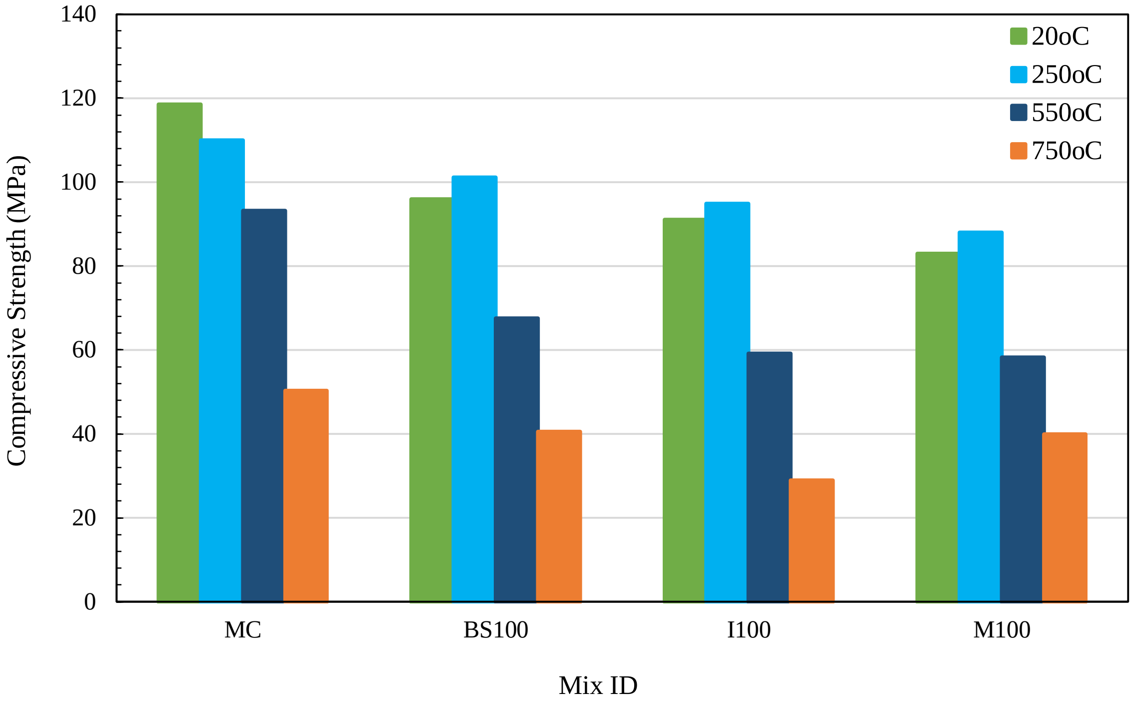

Fig. 6. Compressive strengths of heated (2 hours) and unheated concrete specimens after 28 days.

3.3.2. Water absorption

The absorption test was performed on HPHWC cubes and the results are shown in fig. 7. According to previous studies, the water absorption process inside concrete can be divided into a slow absorption phase and a fast adsorption phase [28, 29].The rapid absorption stage is generally considered to be the capillary absorption process of porous media[30-35]. Once the concrete contacts with water, the pore walls are infiltrated by water and the meniscuses are formed. The I100 mix has the lowest water absorption, Which indicates that the replacement of natural sand with black sand, ilmenite and magnetite densify the UHPC matrix and decrease the internal pores so the absorption ratio decreased from 5.1% in case of MC to 4.5% at 100% black sand, 2.9% in case of 100% ilmenite and 3.6% at 100% magnetite.

3.3.3. Abrasion resistance

The abrasion resistance results according to sand blasting test on different concrete specimens are listed in Table 3. The concrete specimen's loss in thickness decreased from 1.82 mm for mixture MC to 0.9 mm for mixture BS100 after 28 days when black sand percentage was 100% as shown in Fig. 8. Full replacement of ilmenite as mixture I100 decreased the thickness loss to 0.79 mm as seen in Fig. 8, this is due to the high hardness of ilmenite as fine aggregate. On the other hands replacement 100% magnetite indicated thickness losses 0.44 mm, compared with Mc.

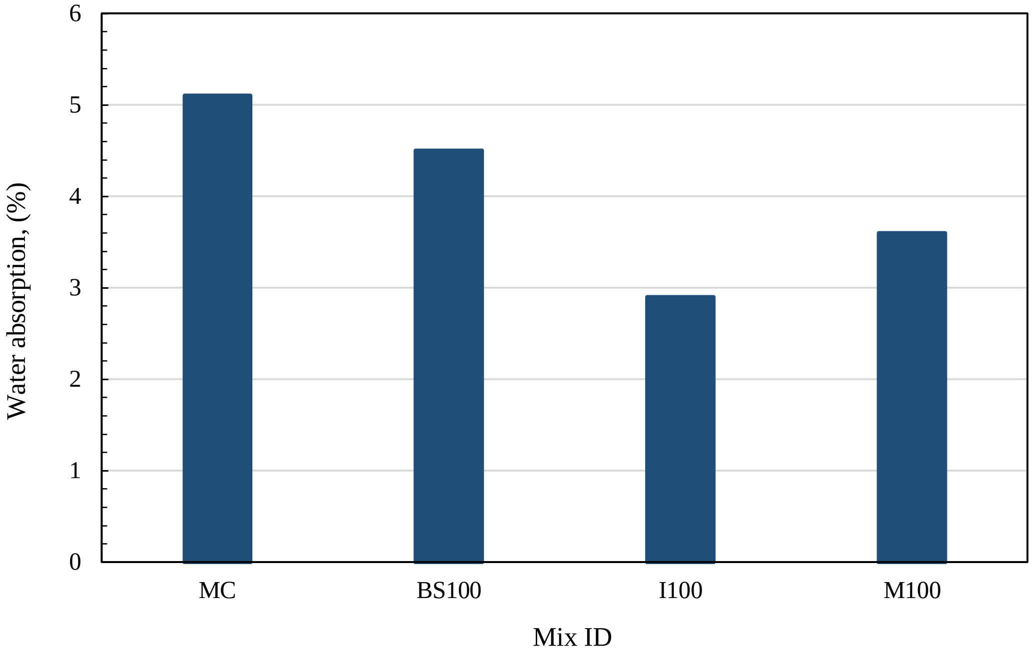

Fig. 7. Water absorption of concrete specimens after 28 days.

Table 3. Abrasion Resistance of the Test Concrete Mixtures after 28 Days.

Mixture	Weight before test (gm)	Weight after test (gm)	Density (gm/cm^3)	Thickness loss (mm)
MC	498.7	475.3	2.62	1.82
BS100	543.7	530.9	2.89	0.90
I100	548.7	536.9	3.05	0.79
M100	556.7	550.0	3.10	0.44

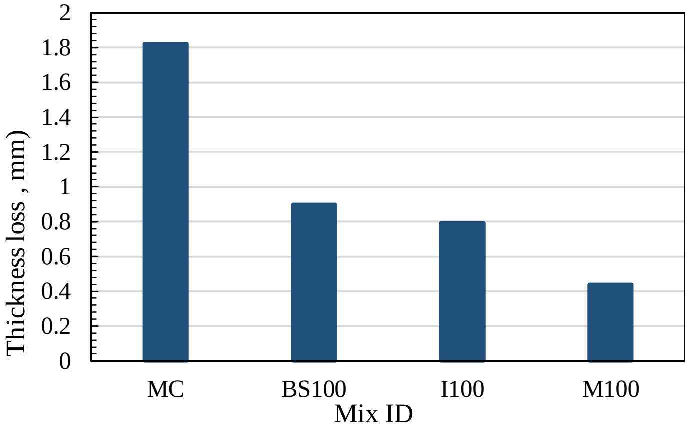

Fig. 8. Abrasion resistance of concrete specimens after 28 days.

3.3.4. Sodium sulfate attack

The concrete exposed to wetting-drying cycle's sulfates environments was investigated in order to provide experimental data for subsequent specification of concrete performance. The compressive strength of concrete specimens that were exposed to sodium sulfate solution at the concentration of 5%, 10 and 20% Na_2SO_4 is presented in Table 4 respectively; the mentioned data is also shown in Figs. 9, 10 and 11. The residual strength was calculated as the percentage of strength retained by control samples after 28 days without exposure to Na_2SO_4. From the figures, it may be observed that all the concrete mixtures exhibited gradual strength loss at the end of 180 days after immersion in severing sodium sulfate solution. There is an initial increase in the compressive strength, indicating the formation of gypsum and ettringite in the pore spaces, this followed by a steady drop after 60 days. The sulfate attack products are poorly cohesive, which causes instability in binder system and thus reduces the mechanical performance[36].Exposure to (50 g/l Na_2SO_4) for 180 days, exhibited 77.3% residual strength of the control mixture however the residual strength for mixture BS100 that containing 100% black sand replacement was 83.1% on the other hands, adding 100% ilmenite replacement (I100) represented 92.6% residual strength, In addition to a 90.1% residual strength to mixture M100. also, exposure to (100 g/l Na_2SO_4) for 180 days, exhibited 68.8% residual strength of the control mixture however the residual strength for mixture BS100 that containing 100% black sand replacement was 79.9% on the other hands, adding 100% ilmenite replacement (I100) represented 83.4% residual strength, In addition to a 81% residual strength to mixture M100. On the other hands, exposure to (200 g/l Na_2SO_4) for 180 days, exhibited 65.2% residual strength of the control mixture however the residual strength for mixture BS100 that containing 100% black sand replacement was 68.2% on the other hands, adding 100% ilmenite replacement (I100) represented 77.7% residual strength, In addition to a 71.6% residual strength to mixture M100. The resistance of concrete specimens exposed to sodium sulfate solution of HPHWC was similar to the developments of water absorption. In general, the replacement percentage of the used black sand, ilmenite and magnetite fine aggregate increased the impermeability of the concrete. These differences in strength improvements are credited to the nearness of the fine particles of fine aggregate that fill in as brilliant fillers. In addition, it can be noticed that the concrete specimens utilizing 100% black sand, ilmenite and magnetite showed a high resistance to the sulfate at-tack due to its low permeability.

Mixture	C kg/m^3	S. Slag %	Sand %	BS %	I %	M %	Compressive Strength, (MPa)				
							Control Mix 28 d	50 g/l (Na_2So_4)			
								28 Daye	60 Daye	90 Daye	180 Daye
MC	750	100	100	–	–	–	118.5	122.0	123.3	98.5	91.6
BS100	750	100	–	100	–	–	96.0	98.6	99.6	83.8	79.8
I100	750	100	–	–	100	–	91.0	92.8	94.1	87.6	84.2
M100	750	100	–	–	–	100	83.0	84.2	85.5	75.7	74.8
							Control Mix 28 d	100 g/l (Na_2So_4)			
MC	750	100	100	–	–	–	118.5	124.0	126.2	88.5	81.5
BS100	750	100	–	100	–	–	96.0	100.2	101.8	77.1	76.7
I100	750	100	–	–	100	–	91.0	94.0	96.1	83.9	75.9
M100	750	100	–	–	–	100	83.0	85.4	87.2	69.1	67.2
							Control Mix 28 d	200 g/l (Na_2So_4)			
MC	750	100	100	–	–	–	118.5	124.5	127.2	81.5	77.3
BS100	750	100	–	100	–	–	96.0	100.6	102.8	72.3	65.5
I100	750	100	–	–	100	–	91.0	95.0	97.2	77.7	70.7
M100	750	100	–	–	–	100	83.0	86.3	88.4	65.7	59.4

Table 4. Compressive Strengths of the Concrete Mixtures at (5%, 10% and 20% Na_2So_4).

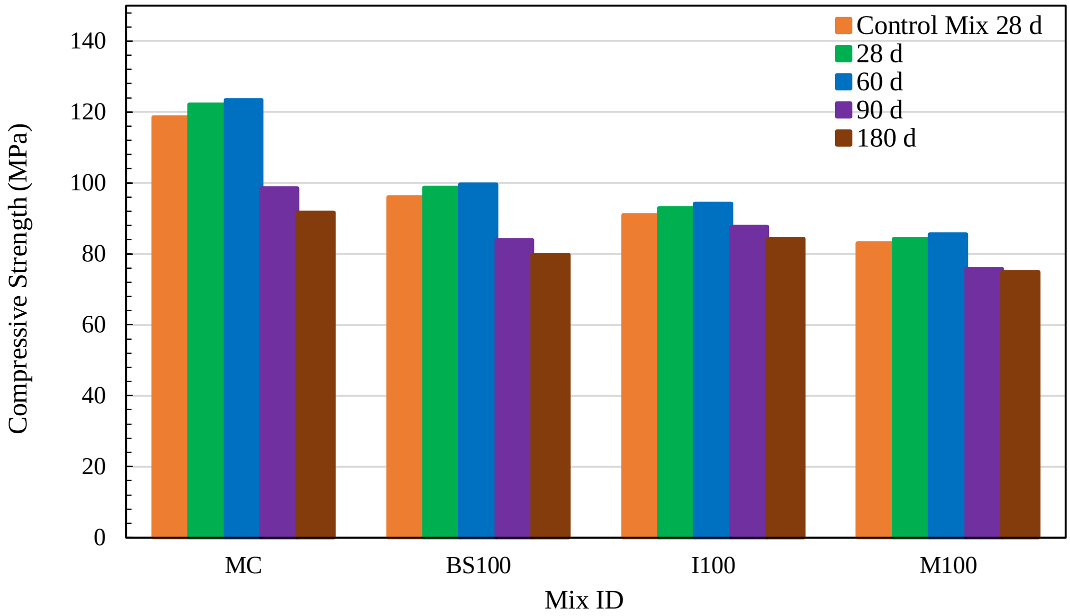

Fig. 9. Effect of Mix ID on the compressive strength of the specimens exposed to sulfate attack (5% Na_2SO_4).

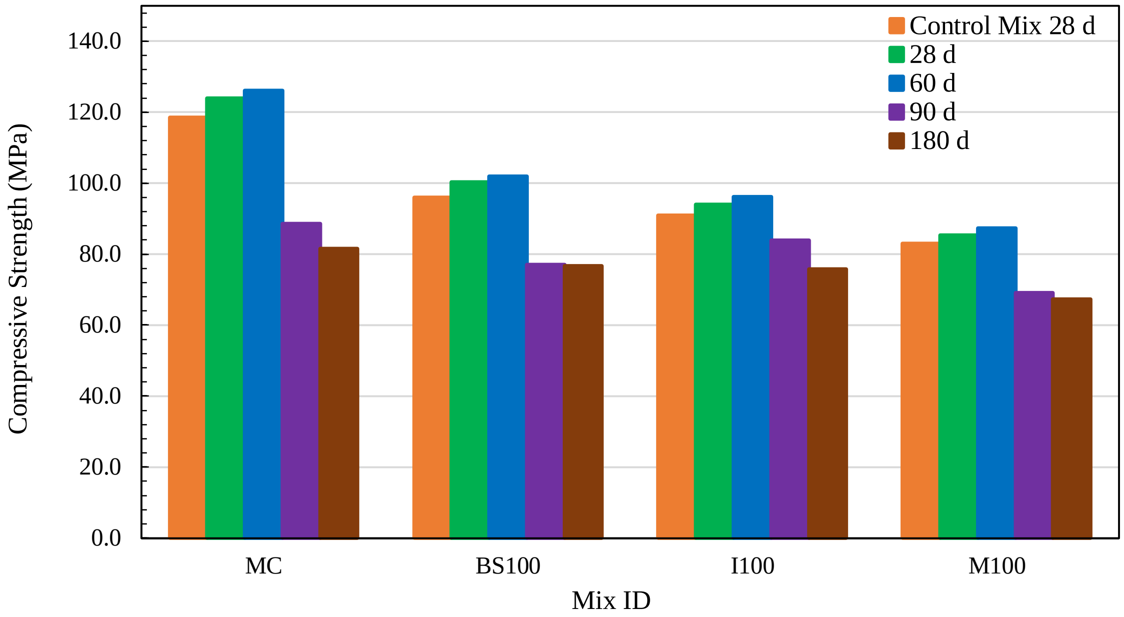

Fig. 10. Effect of Mix ID on the compressive strength of the specimens exposed to sulfate attack (10% Na_2SO_4).

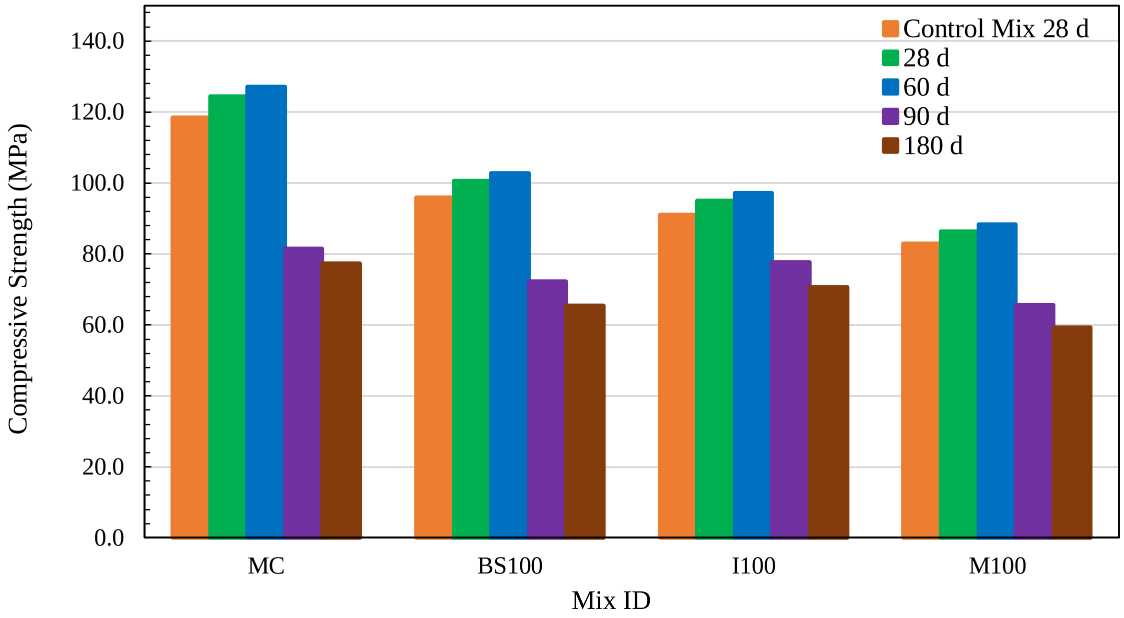

Fig. 11. Effect of Mix ID on the compressive strength of the specimens exposed to sulfate attack (20% Na_2SO_4).

4. Conclusions

In this study, durability properties of mixes with and without black sand, ilmenite and magnetite as a fine aggregates were evaluated. The following conclusions could be drawn as follows:

1. The highest density of HPHWC mixtures is 3110 kg/m3 for mix M100.

2. The compressive strength of HPHWC ranged from 83 to 118.5 MPa at 28 days.
3. The results showed that using black sand as fine aggregate for HPHWC production has a good effect on modulus of elasticity compared ilmenite and magnetite.
4. The compressive strength of HPHWC increases as the temperature rises from 22 to 250°C at 28 days.
5. Sever sulfate attack can be resisted for reliable levels especially when BS, I and M was used by 100% replacement in the presence of 10% ferrosilicon.
6. Mixtures that incorporating 100% magnetite exhibited optimal resistance of abrasion that exhibited minimum thickness losses.

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