Journal of Structural Engineering & Applied Mechanics (2023) 6(2):140-156
DOI 10.31462/jseam.2023.02140156

RESEARCH ARTICLE

Mechanical and durability characteristics of concrete containing induction furnace steel slag as an alternative to coarse aggregates

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Article History

Received 23 January 2023
Accepted 17 May 2023

Keywords

Concrete
Aggregate
Induction furnace slag
Compressive strength
Los Angeles abrasion test
Durability

Abstract

One of the greatest issues in today's world is the elimination of industrial disposal materials. To solve this problem, recycling waste has become a necessity in many countries according to regulations. Induction furnaces are systems where the heat is generated by induced currents by the electromagnetic field. Every production cycle, the system generates 15% of by-products as slag. In the present study, induction furnace steel slags are replaced with coarse aggregate at the ratios of 0, 50, and 100% in concrete samples with 150×150×150 mm size. The Los Angeles abrasion test, compressive strength test, and density calculations were made. Samples were also subjected to electronic and optical systems such as SEM, EDX, and XRD to determine the surface and microanalysis. This experimental study shows that utilizing induction furnace steel slag increased the physical and mechanical properties of concrete. The addition of these slags in concrete will allow the efficient usage of natural resources as well as the production of economical concrete. Due to their composition, the slags have high abrasion resistance and density compared to ordinary aggregates. For this reason, increasing the ratio of steel slags in concrete may result in the formation of heavy concrete.

1. Introduction

Civil engineers have done lots of remarkable research about the recycling of waste products in the past. Formerly, industrial waste materials (like silica fume and fly ash) were being disposed of. But with the help of accelerating studies and advancing technology, the researchers found out that these wastes were improving the durability and mechanical properties of concrete [1-4]. Recycling industrial wastes can minimize the damage they cause to nature and increase the properties of concrete at the same time [5]. This is an important scientific development in terms of civil engineering.

Aggregates obtained from natural resources constitute the biggest cost input in concrete production consisting of cement, aggregate, and water mixture. In addition, there are undeniable environmental effects in the process of obtaining natural aggregates [6]. For all these reasons, it has become a technological necessity to find a raw material that can be used instead of natural aggregates, has similar characteristics, cheap, and in which environmental negativities are minimized [7]. The use of slag, which is formed with steel production reaches 10 million tons per year on a European basis, seems to be the most suitable option instead of natural aggregate in concrete production [8].

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eISSN 2630-5763

In the last twenty years with developments of technology, induction furnaces gained significant progress in comparison to other systems owing to their great efficiency and pollution-free generation [9]. In the induction furnace process, heat is generated by induced currents due to the electromagnetic field created by a coil placed inside the furnace and surrounding it [10]. This electromagnetic field not only creates a voltage that heats the charged material; at the same time, it provides the best mixing of the metal bath by applying force to the molten metal [11-15] (Fig. 1).

In induction furnaces, steel is produced by using scrap steel and induction furnace slag is a by-product of this production. In every production cycle, the system generates 15% of by-products as slag [17-20]. As the amount of steel slag increases, the process of disposing and storing the slag becomes more difficult and creates additional costs. It is known that most of the slag obtained from iron and steel production has been kept in idle storage areas and more than 3 million tons of induction furnace slag is added to this heap every year [21-29] (Fig. 2).

Utilizing these slags in the construction industry will both reduce the cost of storage and enable more efficient use of natural resources [31]. Although slag has a high iron oxide content, it can't be used in cement production. The reason for this, the iron element is melted at a high temperature so there is no more reactive component left in the slag.

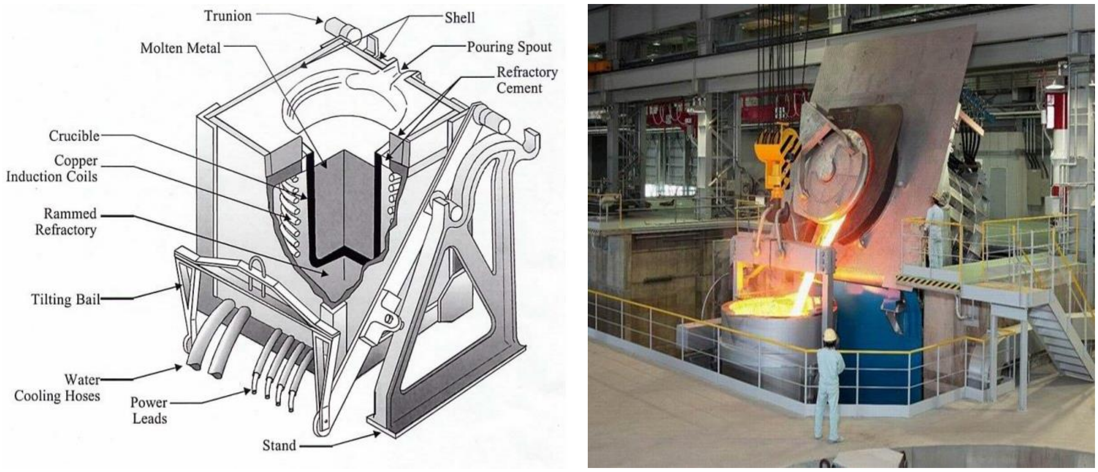

Fig. 1. Induction furnaces [16]

Fig. 2. Storing of induction furnaces slags [30]

The advantages of induction furnace slags are: high stability, high carrying ability, low deformation, high friction coefficient, high adherence with concrete mixture, low-cost aggregate can be produced, slag disposal costs of the facilities can be reduced, environmental pollution will be reduced by reducing the slag stockpile areas, conservation of natural resources to a certain extent will be provided [32,33].

The direct use of steel slags as filling material is the first method that comes to mind in the evaluation of such industrial wastes. On highways, it is getting harder to obtain the quality natural aggregates required for the construction of the lower layers of the road. Induction furnace slags are currently used in road construction as filling material under asphalt [34]. There are also currently Japanese standards for the use of slags as aggregates [35]

In experimental studies, the slag does not undergo any significant chemical or biological change, not dissolve, does not burn, does not react physically or chemically, does not undergo biological degradation, or affect the materials it comes into contact with in a way that will harm the environment or human life, and its total leakage ability and toxicity are insignificant. It has been determined that it is an inert waste that does not pose a particular risk of surface water and groundwater pollution. In addition, steel slags are currently used as ballast.

Another point to consider is, heavy concretes with high unit weight are used as protection against radiation in nuclear power plants, medical units, and experimental laboratories. In heavy concrete production, besides Portland cement with silica fume, aggregates with high unit weight such as barite and magnetite are used in the concrete composition. As a result of this research, it has been found that induction furnace slag can be used in heavy concrete production thanks to its high density. Baalamurugan et al. [36] studied using induction furnace slag in the concrete mix instead of coarse aggregate. They investigated the compressive strength, density, and Gamma attenuation factor of specimens. Their study shows that concrete mix with %50 induction furnace slag increases the compressive strength and density of the sample. Samples with %50 induction furnace slag samples have a higher Linear attenuation coefficient and Gama attenuation coefficient than normal concrete. Replacement of induction furnace steel slag as coarse aggregate in concrete is effective in gamma shielding.

Ahmad et al. [37] investigated the marble wastes used as fine aggregate in concrete production. The purpose of this study is to solve the disposal problems of marble waste and reduction of consumption for natural resources. They utilized the marble waste with different proportions in samples to examine the properties of concrete. After the experimental results, they observe that the slump value of concrete increased with the percentage of marble in the samples increase. Furthermore, concrete strength increases when up to 60% of marble waste is added. Since the strength decreased gradually after this rate, it was recommended by the authors that the marble waste should not be more than 60% in the concrete mix.

In this research, induction furnace slags are utilized at certain percentages in concrete samples instead of coarse aggregate. Specimens were subjected to laboratory experiments to investigate their mechanical and durability characteristics. Aggregates and induction furnace slags (IFC) were subjected to the Los Angeles abrasion test separately before being mixed in the concrete. With the help of SEM, EDX, and XRD analyses, the microstructures and surfaces of the samples were examined and the adherence between slags and the concrete mixture was evaluated.

The types of scrap metals melted in induction furnaces change, and the structure (porous/non-durable and non-porous/durable) of the slag that emerges as a by-product will also change. Since porous and weak slags cannot be used as concrete aggregate, some tests must be performed. As innovative aspects of this study, the strength of the slags using the Los Angeles abrasion test was measured and its effect on the workability of the concrete mixture was investigated with the help of the slump test. In addition, the unit weights of the concrete samples were measured and compared. The internal structures of the slags were examined, the voids were determined and which type of slag could be used as aggregate was interpreted.

2. Materials and measurements

2.1. Materials

Concrete samples were prepared with cement, water, aggregate, sand, and induction furnace slag. Eskişehir tap water was used as mixing water. The stone form of the induction furnace slags before shredding and sieved was shown in Fig. 3. In this research, CEM I 42.5 R cement was utilized conforming to the TS EN 197-1 [38]. Physical and chemical properties of Type I Portland cement are presented in Table 1 and Table 2.

Induction furnace slag utilized in concrete has been generated around 1300 °C and it was obtained from a steel factory. Induction furnace slags can have different chemical structures depending on the type of scrap steel melted in the furnace. In this study, the same type of metal slag was investigated. A close view of the induction furnace slag is given in Fig. 3.

Table 3 shows the sieve analysis and properties of aggregates. The size of the sand that is used in experiments is 1.25-5 mm. The maximum steel slags (IFS) and coarse aggregate size were 22.4 mm. The granulometry curve of induction furnace slag and limestone aggregate is shown in Fig. 4.

Fig. 3. Induction furnaces slags

Table 1. Physical and mechanical properties of Portland cement

	Chemical Composition (%)	CEM I 42.5 R
Physical Properties	Specific Weight	3.11
	Blaine Surface (cm^2/gr)	3501
	Residue on Sieve - 0.090 mm (%)	0.31
	Residue on Sieve - 0.045mm (%)	5.11
	Standard Consistency Water Amount (%)	28.3
	Setting Start Time (min)	180
	Setting Ending Time (min)	270
	Volume Expansion (mm)	1
Mechanical Properties	Compressive Strength - Day 2 (MPa)	23.1
	Compressive Strength - Day 28 (MPa)	49.5

Table 2. Chemical properties of Portland cement

Chemical Composition (%)		CEM I 42.5 R
Chemical Properties	SiO2	19.67
	Al2O3	5.21
	Fe2O3	2.68
	CaO	63.72
	MgO	3.01
	Na2O	0.92
	K2O	0.46
	SO3	2.13
	MnO	---
	S	---
	Cl-	0.006
	Loss of ignition	3.54
	Insoluble residue	0.5
	Free CaO	1.85

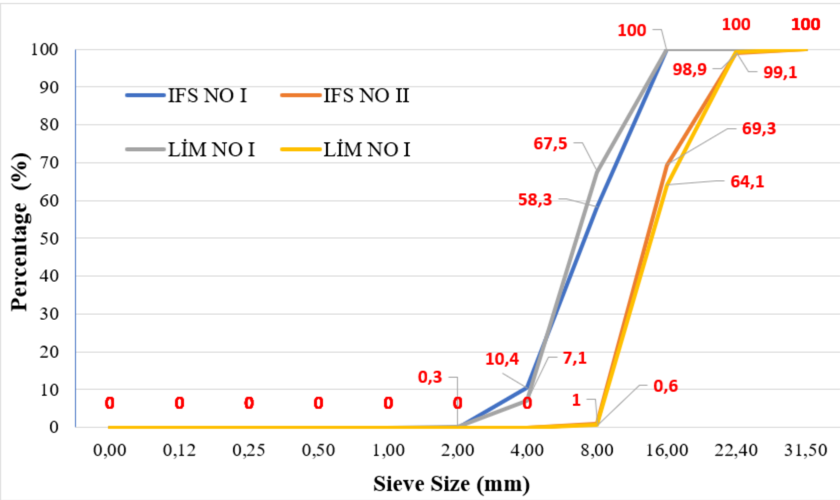

Fig. 4. Granulometry curve of induction furnace slag and limestone aggregate

2.2. Specimen preparation

Induction furnace slags were sieved through the sieves indicated in Table 4 to determine the sieve analysis. The materials passing through the sieves were weighed and the amount of material passed was determined as a percentage.

The reinforced concrete samples were prepared with a dosage of 350 kg/m^3 and a water/cement ratio is 0.50. In this study, the dimensions of the specimens were 150×150×150 mm. Unit weight and the mixing proportions of produced concrete samples are shown in Table 4. The sample was placed in the molds with the help of a vibrator. In addition, no chemical or mineral additives were used in any sample to observe the direct effect of induction furnace slag in terms of mechanical properties and workability. The prepared samples were cured in water in laboratory conditions for 28 days (Fig. 5).

Table 3. Sieve analysis of induction furnace slag and limestone aggregate

Sieve Size (mm)	Crushed Sand	Induction Furnace Slag		Limestone	
		No. I (4-11.2 mm)	No. II (11.2-22.4 mm)	No. I (4-11.2 mm)	No. II (11.2-22.4 mm)
31.5	100	100	100	100	100
22.4	100	100	98.9	100	99.1
16	100	100	69.3	100	64.1
8	100	58.3	1	67.5	0.6
4	100	10.4	0	7.1	0
2	62.4	0	0	0.3	0
1	39.6	0	0	0	0
0.5	29	0	0	0	0
0.25	16.4	0	0	0	0
0.125	0.4	0	0	0	0
Under sieve	0	0	0	0	0
Specific gravity (gr/cm^3)	2.66	3.11	3.11	2.71	2.71
Fineness modulus	2.37	5.38	6.42	7.25	8.36
Water absorption	1.35	0.51	0.40	0.71	0.53

Table 4. Mixing proportions

Mix Designation	Aggregate (%)	Induction Furnace Slag (%)	Unit Weight (kg/m3)	Slump (cm)
Control	100	0	2402	20.5
Mix 1 (IFS50)	50	50	2613	18.2
Mix 2 (IFS100)	0	100	2975	16.7

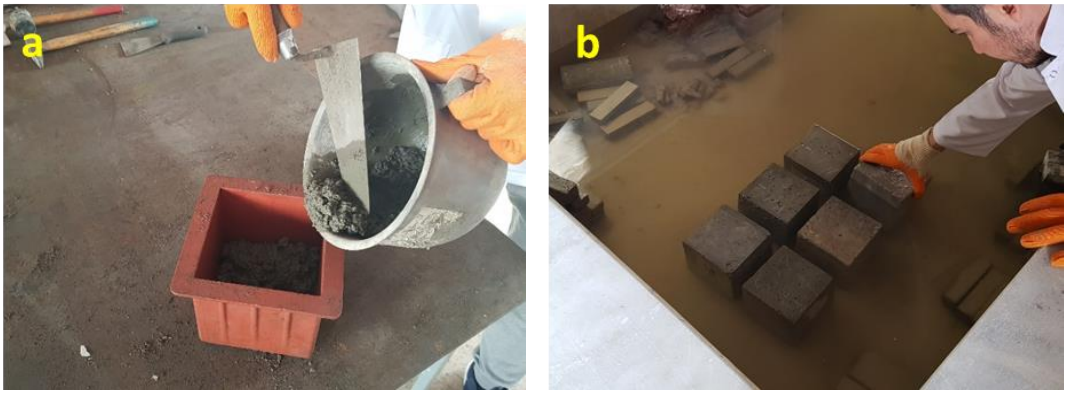

Fig. 5. (a) Preparation of samples, (b) Curing the samples

In this study, the durability properties of concrete cubes with induction furnace slags, which are replaced with limestone aggregate, were investigated. Except for the aggregate ratios, other ingredients were used at the same rate and in the same sample size. The slags were added to the concrete mix in different proportions (0%, 50%, and 100%) instead of coarse aggregate (Fig. 6).

2.3. Measurements

2.3.1. Density and consistency

The concrete design is depending on the type and properties of the materials. The density of the aggregates used in concrete mix was a major parameter and it must be within the boundaries mentioned in standards. Otherwise, their use can't be suitable for concrete production. In this research, the density of both traditional aggregates (limestone) and induction furnace slags were measured (Fig. 7).

After the density of the slag was measured, the prepared concrete mixture was poured into 15 cm cube sample molds. The unit weights were calculated and compared with conventional concrete. In this study, we perform a slump test to obtain an idea about the workability of the concrete series. This is because induction furnace slags with hard corners and rough surfaces might reduce the workability of concrete.

2.3.2. Los Angeles abrasion test

Reinforced concrete aggregate should have sufficient physical properties (geometry, water absorption, specific gravity, mechanical resistance to fragmentation, surface abrasion) for suitable use. Los Angeles abrasion test is suggested in many various applications (such as asphalt concrete, recycled aggregate concrete, and backfilling materials) to find the resistance to fragmentation of reinforced concrete aggregate. The mechanical behavior of concrete is raised when increasing the resistance of induction furnace slag due to Los Angeles abrasion test results.

Fig. 6. Concrete samples with different slag proportions

Fig. 7. Measurement of density

If the material remaining on this screen is P_U weight, the abrasion percentage U is found as:

$$: U = \frac{P - P_U}{P} x\,100 \quad (1)$$

where lower the calculated abrasion percentage (U) results in higher abrasion resistance of the aggregate. According to ASTM C131 standards [39], this loss percentage is required not to exceed 30% for concrete aggregate.

The Los Angeles test is an experiment to measure the deterioration of the standard gradation of the aggregate as a result of abrasion and impact effects. The test was carried out according to the ASTM C 131 test standard. The experiment was conducted with 2500 g of aggregates with a particle diameter of No I (4-8 mm) and 2500 g of aggregates with a particle diameter of No II (8-22 mm). A total of 5000 g aggregates were washed and dried in an oven at 110 ± 5 °C and weighed. Balls and oven-dried aggregates were placed in the drum, which rotates at a constant speed of 31-33 revolutions per minute.

The slags and aggregates were shredded with the weights and dynamic effect of the metal balls and particles obtained at the end of the experiment were sieved through a 1.7 mm mesh sieve and the remaining particles on the sieve were weighed. The Los Angeles abrasion test was performed under different conditions by changing the number of revolutions and balls. The test was carried out separately with 12, 18, and 24 balls for 500, 1000, 1500 and 2000 revolutions, respectively.

To investigate the abrasion strength of the induction furnace steel slags, the Los Angeles abrasion test was applied in this study according to ASTM C131 standard (Fig. 8). In the present experimental study, it is seen that the LA results of the induction furnace slag fulfill the boundary conditions in standards.

2.3.3. Compressive strength

Concrete samples containing induction furnace slag were poured into 150 mm cube molds and subjected to compressive strength tests in the laboratory. For every concrete mix, three samples were tested and all samples were cured during the 28th and 90th days in laboratory conditions (Fig. 9).

2.3.4. Micro-analyzes

The sample of Induction furnace slag (IFS) was manually cracked with a hammer and all pieces are milled. The obtained powder was collected and sent for micro-analysis to the laboratory. In this paper, Chemical compounds of induction furnace slags were analyzed by using the XRD test and to examine the microstructure of induction furnace slag, a scanning electron microscopy (SEM) test was carried out. The EDX analysis used in this study aims to make a quantitative chemical analysis by using the energies of the elements.

Fig. 8. Application of Los Angeles abrasion test

Fig. 9. Compressive strength test

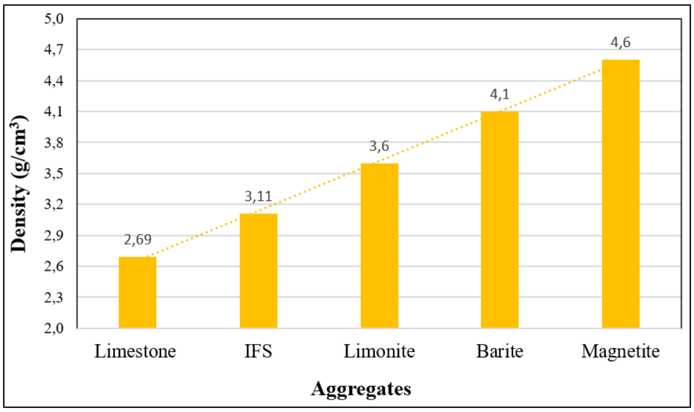

Fig. 10. Density of IFS and some other aggregates [40]

3. Results and discussions

3.1. Density and consistency

According to experimental findings, induction furnace steel slags have high specific gravity because of their metallic (iron) and dense internal structure so it is increasing the unit weight of all the concrete samples (Table 4). Furthermore, induction furnace slag has a higher density than limestone aggregate, which is most commonly used in concrete. In Fig. 10, the density of some stone examples used in concrete mixture as aggregate was represented [40].

The density of IFS was found 3.11 gr/cm^3. Control samples with no IFS have a unit weight of 2402 kg/m^3. It was observed that concrete samples that have 50% IFS have a unit weight of 2613 kg/m^3. Lastly, concrete samples that have 100% IFS have a unit weight of 2975 kg/m^3. According to the results, induction furnace slag has greater specific gravity than limestone aggregates because of the higher iron ingredient. In concrete design, the increasing unit weight has to be considered otherwise induction furnace slag may be caused in heavy-weight concrete.

Table 4 shows that Slump values (consistency-workability) decrease with increasing IFC ratio in concrete samples. The reason for this is that rough and angular slags increase the adherence forces between cement paste and aggregate. With the increase of these forces, the workability of concrete decreases. Super and hyper plasticizers can be used to increase workability. The formation of reinforcements in reinforced concrete structures can be complex and frequent. Therefore, this may result in the concrete mix not reaching deep parts of the mold. The increase in workability is a key factor for the complete and proper placement of the concrete into the mold. This problem can be avoided by using some chemical additives.

3.2. Los Angeles abrasion test

To evaluate the Los Angeles abrasion values in intense situations, the experiment was conducted with both increasing the number of balls and revolutions. As a result of the laboratory tests, resistance to abrasion of slags and limestones declined with the increasing number of revolutions and balls, which means LA percentages also decreased. The highest LA value was obtained with 12 balls of 500 revolutions, while the lowest LA value was obtained with 24 balls of 2000 revolutions.

Fig. 11 shows the comparison between limestone aggregates and IFC aggregates. It is seen that the induction furnace slag gives a lower LA abrasion percentage for each revolution Fig. 11-b. However, especially in the phases where 500 and 1000 revolutions were applied, the induction furnace slag shows %50 more resistance to abrasion than limestone aggregate (Fig. 11-a). According to obtained LA results, approximately %90 abrasion was calculated for both limestone aggregate and induction furnace slags after the 2000 revolution with 24 balls. It is seen from the figures almost linear changes have occurred in LA percentages with incrementing the revolution and balls. The best abrasion resistance was obtained from the induction furnace slag tests conducted for 12 balls and 500 revolutions. As a result of laboratory tests, Induction furnace slags gave about 14.5% LA abrasion value. This is proof that the resistance of the induction furnace slags is below the critical limits, complies with the abrasion boundary limits specified in the standards, and can be used as concrete aggregate.

As a result of experimental studies, the abrasion resistance of the induction furnace slag is close to that of the conventional limestone aggregate. Although the density of the induction furnace slag is high, because of its porous structure its abrasion percentage is slightly higher. Also, another reason for the high percentage of abrasion is the rough and uneven corners and edges. During the experiment, these corners and edges can be easily divided. However, these uneven surfaces increase the adherence between concrete paste and aggregate.

3.3. Compressive strength test

The effect of induction furnace slag on concrete compressive strength is shown in Fig. 12. The prepared concrete samples were cured in laboratory conditions for the 28th and 90th days. As a result of the compressive strength test, it has been observed that IF steel slag, which is used instead of aggregate in concrete, increases the compressive strength for all series.

Despite the high porosity of the induction furnace slag, its high specific gravity with metallic content increased the compressive strength and the unit weight of the concrete series. It has been observed that as the rate of induction furnace slag in concrete series increases, also the compressive strength increases. Another issue that should be mentioned here is that induction furnace slag, which has a higher adherence than limestone aggregate, also positively affects compressive strength.

The 28th- and 90th-day compressive strength values of the IFS50 sample are 42,8 MPa and 44,7 MPa, respectively, and these values are 12% higher than the control sample without any slag. The 28th-day and 90th-day compressive strength values of the IFS100 sample are 44,1 MPa and 46,2 MPa, respectively. This sample, which contains full of induction furnace steel slag instead of aggregate, is the highest compressive strength value obtained in this study. The compressive strength value of the IFS100 sample has increased by 16,1% compared to conventional concrete. It was seen that replacing the induction steel slag with aggregate significantly increases the compressive strength of concrete specimens.

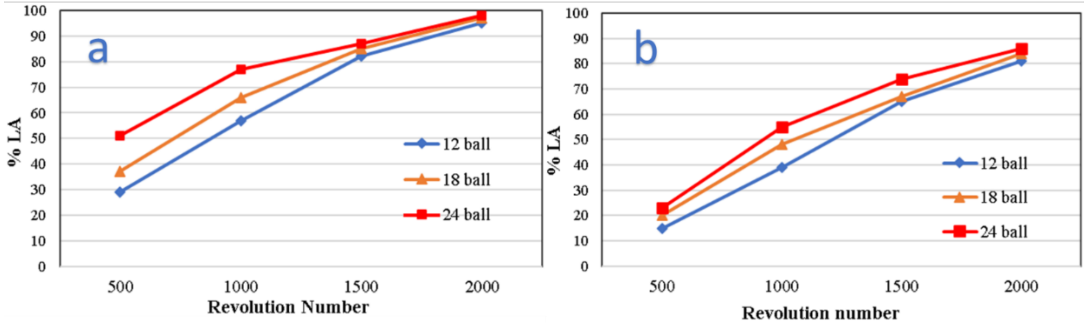

Fig. 11. Los Angeles abrasion percentages limestone aggregates and IFC

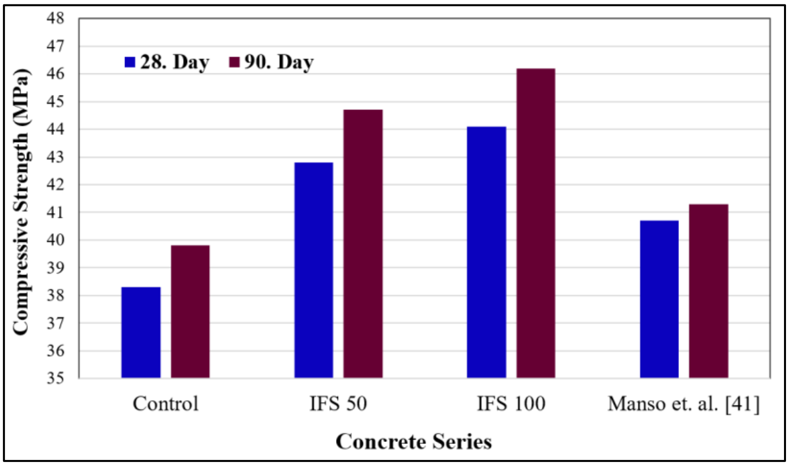

Fig. 12. Compressive strength test results

According to the results of a study conducted by Manso et. al. [41], cement concrete mixtures produced from natural aggregate and aggregates obtained from steel slags show exceptionally good mechanical and physical properties. This study includes various tests applied to slag aggregate cement concrete samples. A number of tests were carried out examining the interactions of cement components with slag aggregate and the behavior of cement concrete against environmental influences such as freezing and moisture. In mixtures made with natural aggregate, acceptable results were obtained in terms of both environmental resistance and mechanical properties. According to the results, slag-based aggregates are useful in terms of mechanical properties. They found the compressive strength as 40.7 MPa for the 28th day and 41.3 MPa for the 90th day (Fig. 12). In addition, positive results were obtained in the aging tests of the samples. The toxicity tests of the steel slag were also within acceptable limits.

3.4. Micro-analyzes

The chemical structure of a material to be used as a building material should be known. For this purpose, some micro-analyses have been performed on induction furnace slag. Induction furnace slag was characterized by using XRD analysis and major compounds are given in Table 5.

In the XRD analysis shown in Fig. 13, the two highest peaks were in Fe and Si elements, and these two points are approximate to each other. Two other components with high peaks in induction furnace slag are Al, Mn, and Ca. The remaining components are Cr, Ti, and Mg and are present in small amounts in the slag.

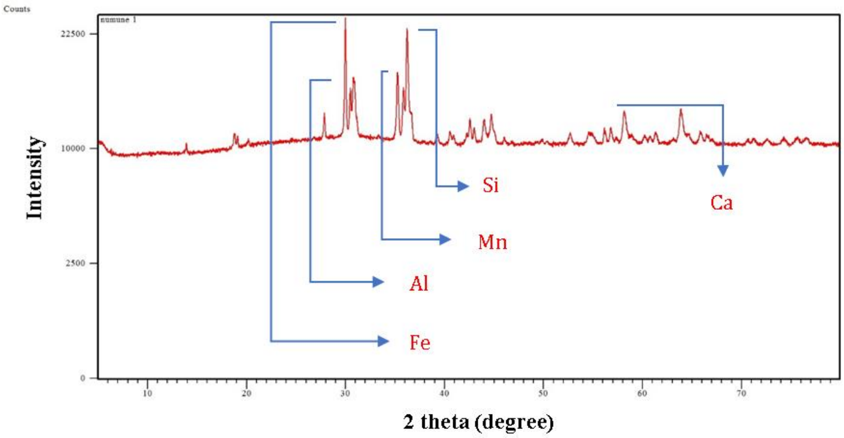

Fig. 13. XRD analysis of induction furnace steel slag

Table 5. Major compounds present in induction furnace steel slag

Chemical Compounds	Concentration (%)
Fe	21,48
Si	19,34
Mn	15,73
Al	14,21
Ca	14,09
Cr	9,52
Mg	4,97
Ti	0,66

As a result of the experiments, many metal and metal alloys were found in induction furnace slag. These metal contents give the slag high specific gravity and strength. Moreover, since they are in the form of an alloy, they do not react with water and do not cause corrosion reactions.

Induction furnace slag has good freeze and corrosion resistance. Caijun and Jueshi [39] show that the strength of the steel slag did not change after the freezing test, which was repeated 100 times between -15 and +20°C. In their study they immersed the slag in seawater, the surface does not deteriorate, and even after 1% H_2SO_4 and 20% NaOH and sulfate solutions are used for 1 year, an increase in strength has been observed. They figure out that the strength develops with the effect of CO_2.

From Table 5, we can observe the presence of dominant components such as manganese, iron, and silica. These metallic parts are related to scrap metals entering the molten mix according to the steel production process. As a result of the literature research, it has been understood that the chemical content of induction furnace slag has differed in many studies. This is because the scrap metals entering the induction furnace have different structures. Slags obtained from scraps containing aluminum or iron also have a different structure.

EDX and SEM micro-analyzer are used to investigate the microstructure of induction furnace slags. The various metal oxides with different shapes and sizes were observed in the induction furnace slag SEM analysis. According to the induction furnace steel slags surface morphology, it has been seen that there are so many dissimilar particles present in the elementary structure of slags. Different magnification of the SEM images of steel slag is represented in Fig. 14.

In the scanning electron microscopy image in Fig. 14, the Fe element is observed. The crystal structures around it are Si and Al elements. When we closely examine the microstructure of the induction furnace slag on SEM and EDX analyses, it is observed that a slightly porous structure. Pores may increase the water requirement of concrete. However, these pores have not reduced the durability of the steel-containing induction furnace slag. Even, the Los Angeles abrasion test results of induction furnace slag converge with those of conventional concrete aggregate. In addition to the durability of the slag, the rough surface seen in the figures provides good clamping, increasing adherence, and a higher friction coefficient.

In Fig. 15, when the EDX analyses taken from different points are examined, after the reactions that occurred inside the induction furnace, high amounts of calcium and carbon compounds were found. The high amount of oxygen is due to its porous structure as seen in the pictures.

Induction furnace slag is a heterogeneous material but does not consist of a completely porous structure, contrarily the density is high in some regions. Even in slags taken from the same bundle, it can be found that materials with different colors and shapes.

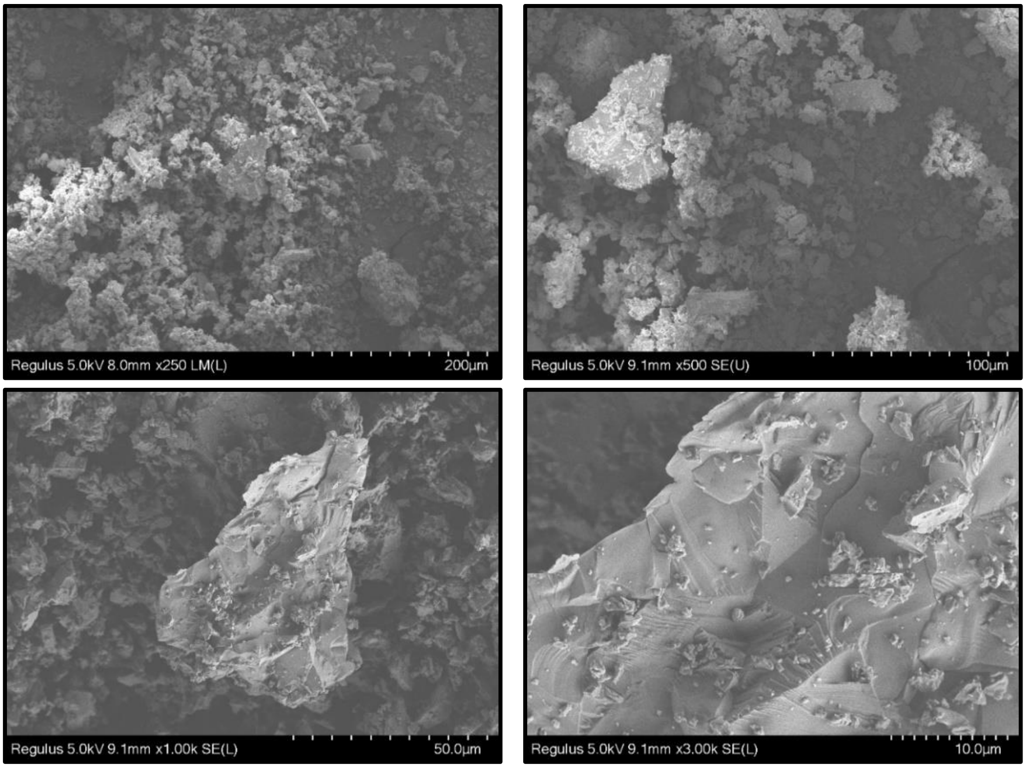

Fig. 14. SEM images of induction furnace slag

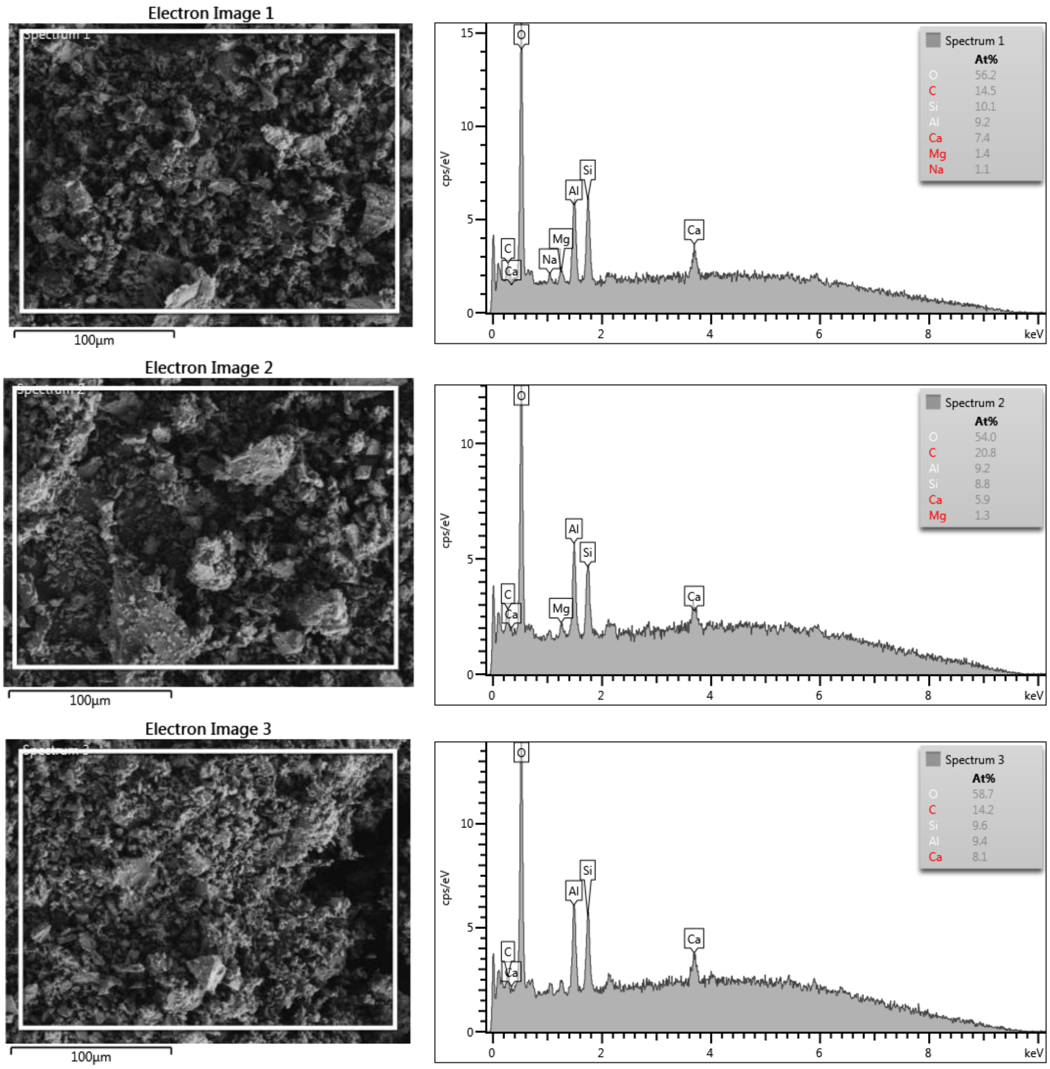

Fig. 15. EDX analyses for induction furnace slag

4. Conclusion

In the present experimental study, it is seen that the LA results of the induction furnace slag fulfill the boundary conditions in standards. It was observed that replacing the induction steel slag with aggregate significantly increases the compressive strength of concrete specimens. This is due to the jagged surfaces and edges of the induction steel slags. These edges have contributed to the compressive strength by increasing the adherence of cement paste and slags. According to the analysis, it was concluded that the induction furnace slag is at least as stable as the other aggregates. Considering the savings in resource and energy costs, it has been determined that the cost of obtaining the slag is 30% lower than the cost of natural aggregate production.

This research indicates that the durability of the superstructure material obtained from slag is equivalent to those obtained naturally. Slag is a very dense and hard material. Due to their high stability, slags can be used safely instead of aggregate in concrete. The fact that the slag aggregates have an angular structure and thus the materials can be clamped to each other more tightly provides an advantage in terms of strength in concrete and road structures.

Conflict of interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

This research received no external funding.

Data availability statement

No new data were created or analyzed in this study.

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