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RESEARCH ARTICLE

The Utilization of Basic Oxygen Furnace Slag as Fine Aggregates in Concrete: Physical, Mechanical, and Durability Properties

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ABSTRACT

This study examines the feasibility of using basic oxygen furnace slag (BOFS) as an alternative to fine crushed limestone aggregate in concrete. BOFS is sourced from two steel production facilities in Türkiye, designated as I-BOFS and E-BOFS. The experimental results showed that as the E-BOFS aggregate replacement ratio increased, the water-to-cement (w/c) ratio increased to maintain the target workability. The concrete mixtures incorporating E-BOFS exhibited consistent reductions in the compressive strength with an increase in the BOFS ratio. At the same time, I-BOFS maintained higher compressive strength, with only minor losses up to 80% of the substitution ratio. Flexural strength was similarly affected, with notable reductions at higher BOFS levels, though I-BOFS performed better. Water penetration depth values remained similar to the reference concrete for both BOFS sources up to a 60% replacement ratio. Conversely, higher replacement levels led to increased water permeability. In summary, the study concludes that the inherent BOFS aggregate characteristics, such as mechanical strength, water absorption, and fines content, significantly affect the fresh and hardened concrete properties, which might limit their utilization ratio in concrete and require detailed testing before using such aggregates.

Keywords: Basic oxygen furnace slag, Mechanical properties, Water penetration depth, Alternative aggregate

1. Introduction

Concrete is a well-known and widely utilized material in the construction industry, mainly composed of cement, aggregate, and water [1]. The aggregates occupy the most significant volume of concrete [2] and have recently become quite expensive and scarce due to the increasing volume of the construction industry and high demand for concrete [3]. Therefore, several studies have been conducted to utilize industrial waste materials as alternative aggregate sources.

Converters, electric furnaces, open hearths, and crucible processes are the most used methods to produce steel [4]. Iron and steel production processes generate various types of slags [5], mainly including basic oxygen furnace slag (BOFS) and ground blast furnace slag [5, 6]. Steel slags are classified according to the steelmaking method employed in their production. The primary categories are BOFS, electric arc furnace slag, ladle furnace slag, induction furnace slag, and stainless steel slag [7, 8]. The application of these steel slags as an aggregate source in various construction applications has been previously documented. For instance, induction furnace slag has demonstrated the capacity to enhance the mechanical and durability characteristics of self-compacted concrete at reduced costs when applied at optimal rates while simultaneously decreasing flowability and drying shrinkage [9–13]. Steel slags, especially from basic oxygen furnaces, are also progressively employed as binders in cementitious and alkali-activated mixtures. Steel slag can partially substitute Portland cement in cementitious applications, enhancing wear resistance and diminishing carbon emissions [14].

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Nonetheless, its reactivity is typically reduced, requiring additions such as graphene oxide to augment initial strength [15]. Compared to steel slag types, BOFS stands out with elevated calcium oxide concentration, generally 40% to 60%, and a reduced aluminum or iron amount [16, 17]. In addition, BOFS is also distinguished by its potential extensive application in construction when it is properly modified [18, 19]. In contrast, electric arc furnace slag is esteemed for its hardness, and LF slag is recognized for its versatility in refining operations [20, 21]. Despite the vast potential of BOFS as a construction material, most BOFS is not utilized efficiently and is directly sent to disposal sites without any valorization, which causes significant environmental problems [22, 23]. The BOFS generally contains oxides such as SiO2, Fe2O3, Al2O3, CaO, and MgO, and their ratios change by the steel-making processes of raw materials and depending on the cooling and crushing methods [22]. Furthermore, some additions such as lime and dolomite incorporated to protect the alkalinity of the slag result in free MgO and CaO [24], which causes undesired expansion problems and may result in the cracking of concrete [25]. Using BOFS in concrete as a raw material is challenging due to the various issues it creates. On the other hand, recycling this by-product material is essential, as 100 to 200 kg of BOFS are generated per ton of steel [26]. It has been reported that BOFS has been used as an aggregate in concrete production [2, 6, 27], in asphalt for road construction [23], in clinker production [28], and as a supplementary binder in geopolymer concrete [24]. However, as previously stated, the characteristic properties of BOFS may significantly change depending on the applied processes.

Using BOFS as an aggregate in the concrete industry is a promising and efficient way of consuming this byproduct material. Previous experimental studies have shown the positive and negative influence of BOFS aggregate (BOFSA) on concrete properties. Devi and Gnanavel [27] carried out mechanical and durability tests on concrete to observe the effect of BOFSA usage as a replacement for fine and coarse aggregate. The results showed that the BOFSA content increased the compressive strength. On the contrary, consistency and chloride-ion penetration decreased in all concrete mixtures, including BOFS. Mahieux et al. [9] reported that using BOFSA might cause a volume expansion of 5 to 10% in concrete, which may cause a decrease in mechanical strength and even disintegration. Therefore, the researchers have mostly suggested that BOFS must be treated before using concrete as an aggregate. Ding et al. [6] used BOFS as a fine aggregate in cement mortar after applying special treatment methods to remove the free lime. They further noted that the expansion value of the specimen was reduced to 0.16% after the treatment process, and the treated BOF slag improved the compressive and flexural strength of cement mortars. Van Tran et al. [29] reported that the compressive strength of concrete slightly increased up to 17% due to the replacement of basalt coarse aggregate by BOFS aggregate. Guo et al. [30] found that the concrete incorporating BOFS as a replacement of fine aggregate up to 20% yields comparable or better compression strength than the reference concrete. Bodor et al. [31] analyzed the utilization of BOFS in concrete as a replacement for fine sand to investigate the effect of particle size and the efficiency of the carbonation process as a treatment method. The researchers reported that 50% of BOFS usage as a replacement for sand decreased the flow significantly to 31%. Although the increase in particle size improved the fresh concrete properties (flow increased from 110 mm to 136 mm), the reference mortar showed superior performance with 161 mm of flow. Furthermore, the particle size played a significant role in compressive strength. Increasing the particle size to 0.5 mm positively impacted the mortar strength and showed comparable performance with the reference mortar regardless of the treatment process. Considering the tested properties, the carbonated BOFS with a particle size lower than 0.5 mm achieved the best results. Guo et al. [32] investigated the fresh and hardened properties of normal and high-strength concrete prepared with unprocessed BOFS fine aggregate. The results showed that using BOFS as an acceptable aggregate replacement in normal-strength concrete showed better performance than the high-strength concrete mixes. This was due to the high cement content and lower porosity in the high-strength concrete, which decreased the visible effects. Using BOFS up to 20% and between 60% and 100% increased the compressive strength. On the other hand, the increase in BOFS from 20% to 60% resulted in a gradual drop in the compressive strength of normal-strength concrete by up to 11.2%. Van Tran et al. [29] investigated the behavior of high-strength concrete using BOFS coarse aggregate (BOFSCA) to replace natural coarse aggregate (NCA). Results showed that the effect of BOFSCA on the development of concrete strength was insignificant. Nevertheless, the use of BOFSCA was found to improve the chloride penetration resistance and resistivity. Subathra and Gnanavel [27] studied the mechanical and durability properties of concrete incorporating BOFS aggregates as a partial substitution of natural coarse and fine aggregates. The authors noted drops in the workability and the compressive strength of concrete beyond an optimum replacement ratio for both aggregates. Lai et al. [33] performed a

Table 1. Properties of cement.

Component (%)	Test result
SiO_2	19.70
Al_2O_3	4.95
Fe_2O_3	3.50
CaO	63.50
MgO	1.50
SO_3	2.85
K_2O	0.60
Na_2O	0.25
Total eq. alkali	0.65
Cl^-	0.029
Loss on ignition	3.00
Compressive strength, 2 days (MPa)	28.5
Compressive strength, 28 days (MPa)	56.0

comprehensive study to investigate the effect of BOFS on concrete properties by replacing coarse and fine BOFS with natural aggregates. Based on the determined microstructural and mechanical properties, the authors suggested an optimum replacement ratio of 50% and 30% for BOFS coarse and fine aggregate, respectively. They further reported an improvement in the compressive strength of concrete up to 19.3% compared to the reference concrete.

The literature review shows that utilizing BOFS as an aggregate source in concrete has advantages and disadvantages depending on its intrinsic characteristics. Therefore, it is essential to validate the effect of locally manufactured BOFS on the properties of concrete. In the present study, the utilization of BOFS obtained from two different sources in Türkiye (designated as “E” and “I”) as a replacement for fine crushed aggregate in concrete has been comparatively studied by determining the compressive strength, flexural strength, and water penetration depth under pressure. The primary motivation of this experimental study is to compare the effect of BOFS obtained from two local steel producers on conventional concrete properties. The BOFS used in the experimental studies has stayed in the open stock area for a long time and has been exposed to outdoor conditions without further treatment.

2. Experimental scheme

2.1. Raw materials

Ordinary Portland cement (CEM I 42.5R) obtained from OYAK Cement Concrete and Paper Group (Bolu Factory) was used as the sole binder in the concrete mixes. The specific gravity and the Blaine fineness of the cement were 3.16 and 4000 cm2/g, respectively. The chemical composition and the physical and mechanical characteristics of the cement are presented in Table 1. The BOFSs acquired from two locations were used to replace crushed sand and prepare concrete mixes. The BOFS fines were supplied from the open stock areas, where they were exposed to outdoor conditions. The physical appearance of BOFS is shown in Fig. 1. The SEM micrographs of BOFS presented in Fig. 2 show the presence of iron particles within the microstructure. The X-ray fluorescence (XRF) test was conducted to characterize the oxide composition of the BOFSs, and the results are presented in Table 2. The main differences between the two BOFSs are the variations in their SiO2 and Fe2O3 contents. The SiO2 content of I-BOFS and E-BOFS was 17.77% and 10.62%, respectively. On the other hand, the Fe2O3 content of I-BOFS was 14.94% and significantly lower compared to E-BOFS, which has a Fe2O3 content of 23.38%. The X-ray diffractometry (XRD) analysis results of the BOFSs shown in Fig. 3 indicate significant variations in the detected crystalline phases. The major crystalline phases in the E-BOFS were srebrodolskite (Ca2Fe2O5), periclase, calcium manganese oxide, calcium iron oxide, magnesiowuestite, and quartz. The crystalline phases observed in the Iskenderun BOFS were brownmillerite, calcium iron oxide, calcium silicate, calcium manganese, and manganese oxide. Table 3 shows the physical, chemical, and mechanical properties of the aggregates used in the study. The limestone fine aggregate had a particle density of 2.69 g/cm3. On the other hand, the particle densities of the I-BOFSA and E-BOFSA were slightly higher compared to limestone aggregate and determined as 3.01 and 2.91 g/cm^3, respectively, due to their higher Fe2O3 content. One of the significant differences in the physical properties of the aggregates was their water absorption. The limestone fine aggregate had a significantly lower water absorption ratio of 0.9% compared to BOFSAs. The water absorption of E-BOFSA was found to be 5.3%, considerably higher than I-BOFSA’s (3.8%). The resistance of the aggregates to degradation was determined following the ASTM C131 standard, and the results are shown by percent loss after exposing the aggregates to impact and abrasion in the Los Angeles machine. Test results indicate that the Los Angeles abrasion was 26.9% and 17.4% for E-BOFSA and I-BOFSA, respectively, whereas the limestone aggregate had the highest value of 29.0%. The fine content of limestone fine aggregate and I-BOFSA was comparable and determined to be 9.0% and 9.7%, respectively. On the other hand, the E-BOFSA had a fine content of 17.3%, which might significantly affect the water demand for concrete. Fig. 4 further presents the grading curves of the aggregates, indicating that both BOFSAs present a finer gradation than limestone fine aggregate. To obtain the desired workability, Sika ViscoCrete Hi-Tech 2928 was used as a superplasticizer in the concrete mixes at a fixed ratio.

Fig. 1. (a) Stockpile of BOFS; (b) Cooling process; (c) Fine BOFS; (d) Coarse BOFS.

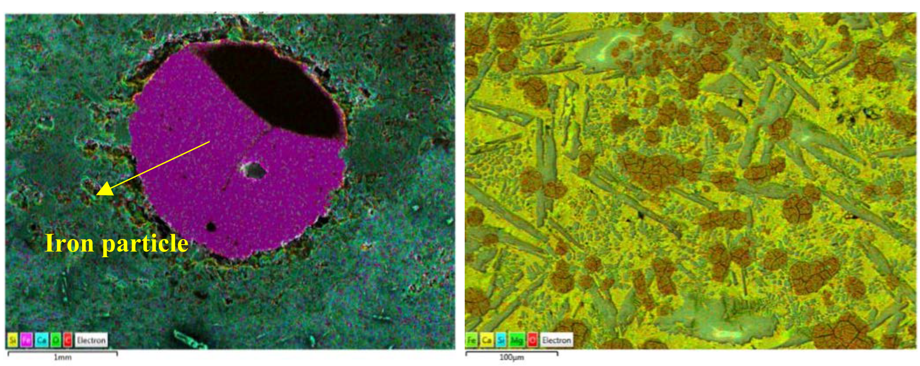

Fig. 2. The SEM micrographs of BOFS.

Table 2. Chemical composition of BOFS.

Component (%)	E-BOFS	I-BOFS
SiO_2	10.62	17.77
Al_2O_3	2.51	3.03
Fe_2O_3	23.28	14.94
CaO	52.18	51.43
MgO	2.96	3.05
SO_3	1.74	2.04
K_2O	0.04	0.01
Na_2O	0.07	0.053
TiO_2	0.85	0.45
P_2O_5	1.57	1.58
Cr_2O_3	0.27	0.16
Mn_2O_3	2.85	3.97
ZnO	0.01	0.01
SrO	0.04	0.863
V_2O_5	0.93	0.135

2.2. Design and production of the concrete mixes

A total of 11 concrete mixes (one being the reference concrete) were produced following the design rules specified in the TS 802 standard. The BOFS fine aggregate was incorporated as a replacement for the crushed limestone sand in 0, 20, 40, 60, 80, and 100% ratios. The Portland cement and the superplasticizer content were taken as constant for all mixes as 300 kg/m3 and 3.9 kg/m3, respectively. To evaluate the effect of BOFS fine aggregates on the water demand of concrete, the amount of water is increased to achieve a target slump value between 180 and 210 mm.

The concrete mix details are presented in Table 4. The origin of BOFS and the replacement ratio coded the concrete mixes. The 'Ref' mix is the reference concrete manufactured with fine limestone and coarse

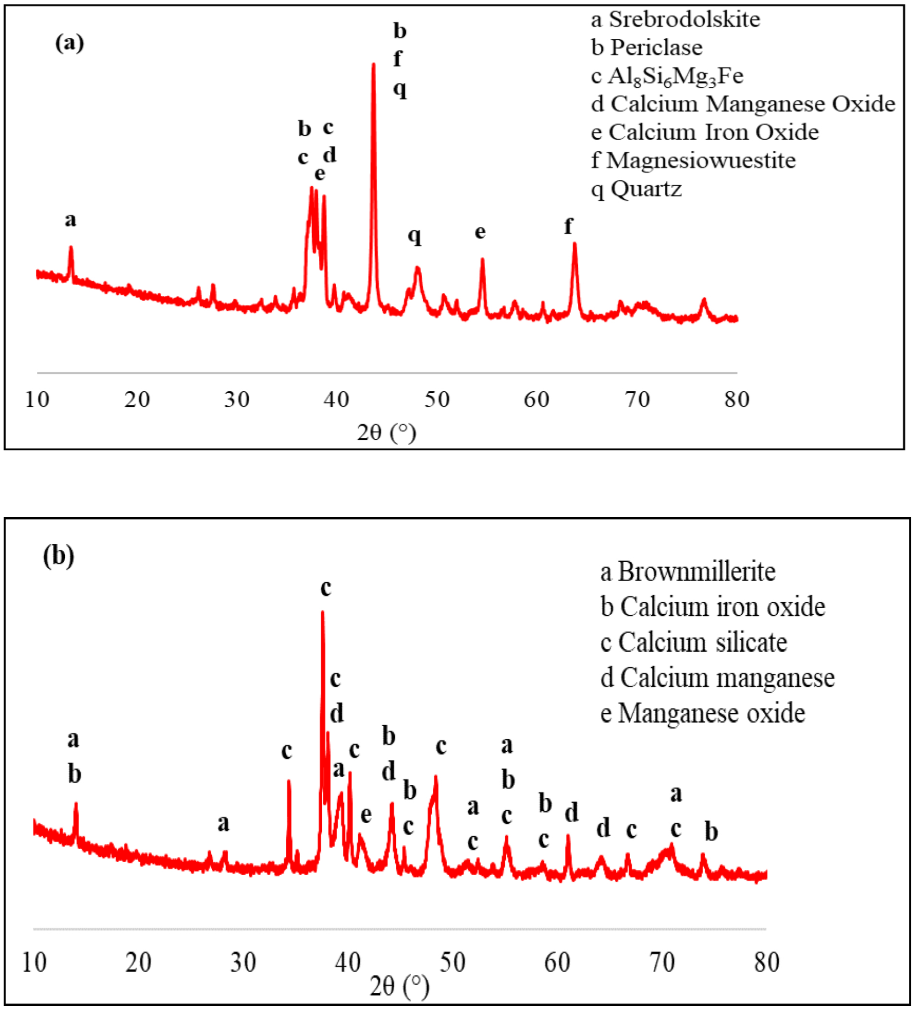

Fig. 3. XRD patterns of (a) E-BOFS and (b) I-BOFS

Table 3. The physical, chemical, and mechanical properties of aggregates.

	Limestone aggregates				
Property	0–4 mm	5–12 mm	12–22 mm	E-BOFS	I-BOFS
Water absorption (%)	0.9	0.4	0.3	5.3	3.8
Particle density (g/cm^3)	2.69	2.71	2.72	2.91	3.01
Chloride content (water soluble, %)	<0.001	<0.001	<0.001	N/A	N/A
Alkali content (water soluble, %)	<0.01	<0.01	<0.01	N/A	N/A
Fines content (%)	9.0	1.0	0.4	17.3	9.7
Los angeles test (%)*	29.0			26.9	17.4

* Los Angeles test results indicate the results obtained from coarse aggregates.

aggregates. The notations 'C-E' and 'C-I' denote the concretes produced with BOFS obtained from two different plants, respectively. The numbers following the notations indicate the BOFSA replacement ratios with the limestone fine aggregate.

The raw materials were mixed for 2 minutes during concrete production, and then water and superplasticizer were added. The mixing continued for five more minutes until a homogeneous mixture was obtained. The fresh concrete properties were immediately tested after production. Fresh concrete was then cast in the relevant molds and stored for 24 hours in laboratory conditions. The samples were removed from their molds and cured in water at 20 °C until the testing age.

2.3. Concrete tests

The effect of BOFS on the aggregate's fresh and hardened concrete properties was researched by

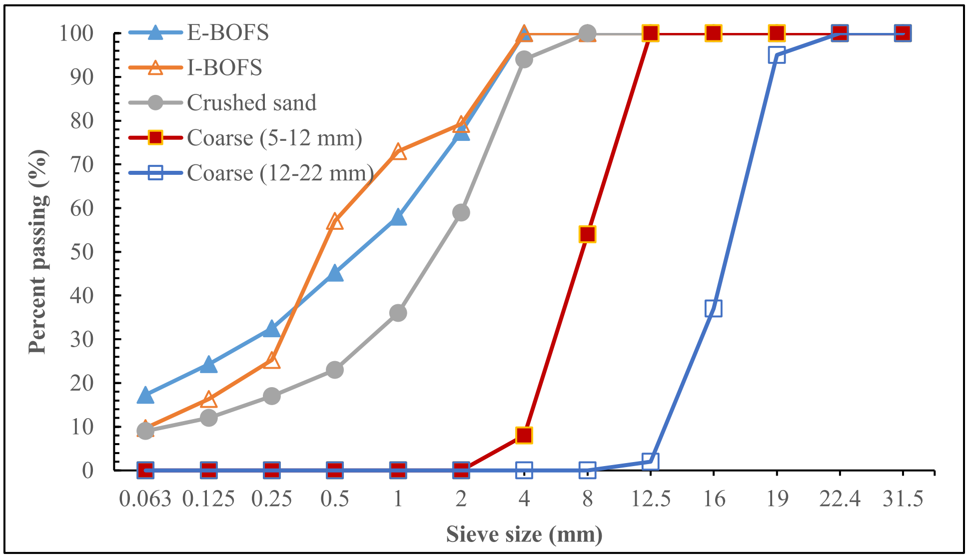

Fig. 4. Gradation curves of aggregates.

Table 4. Concrete mix designs.

Mix ID	Cement (kg/m^3)	w/c	Superplasticizer (kg/m^3)	Fine aggregate (kg/m^3)		Coarse aggregate (kg/m^3)		Slump values (mm)
				BOFSA	Crushed sand	5–12 mm	12–22 mm	
Ref	300	0.60	3.9	0	950	379	569	190
C-E20	300	0.62	3.9	195	731	379	569	180
C-E40	300	0.65	3.9	381	536	379	569	180
C-E60	300	0.72	3.9	564	347	379	569	200
C-E80	300	0.75	3.9	729	171	379	569	180
C-E100	300	0.82	3.9	890	0	379	569	190
C-I20	300	0.60	3.9	188	731	379	569	180
C-I40	300	0.60	3.9	375	548	379	569	200
C-I60	300	0.60	3.9	563	365	379	569	180
C-I80	300	0.60	3.9	750	183	379	569	170
C-I100	300	0.63	3.9	890	0	379	569	190

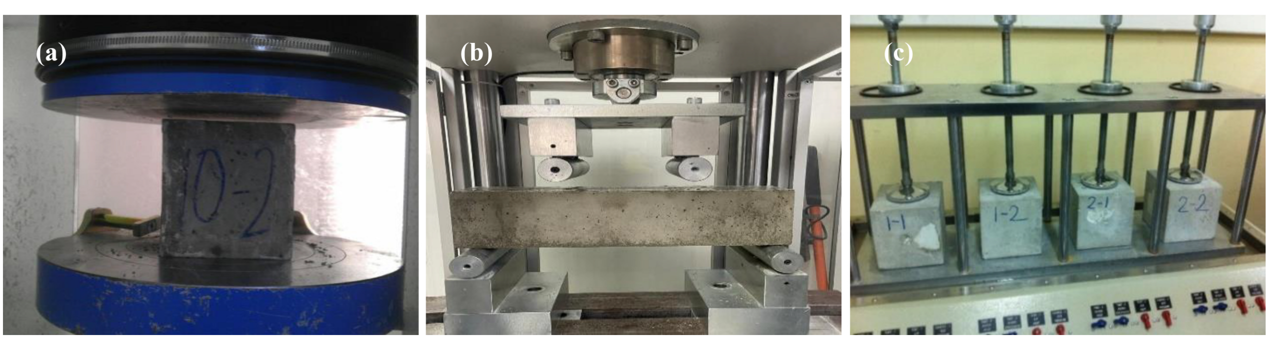

Fig. 5. Concrete tests: (a) compressive strength, (b) flexural strength, (c) water penetration depth.

determining the concrete's slump, water penetration depth, compressive strength, and flexural strength. The slump test followed the TS EN 12350-2 standard. The compressive strength of concrete mixes was determined on three 150×150×150 mm cubes at 28 days for each blend, according to TS EN 12390-3 (Fig. 5a). The test specimens were loaded at a constant rate of 0.6 MPa/s until failure. The compressive strength was determined as the ratio of the ultimate load to the cross-sectional area. The flexural strength test of the concrete specimens was performed at 28 days following the TS EN 12390-5 standard. The test was performed on three specimens with dimensions of 100×100×500 mm3 for each mix using a

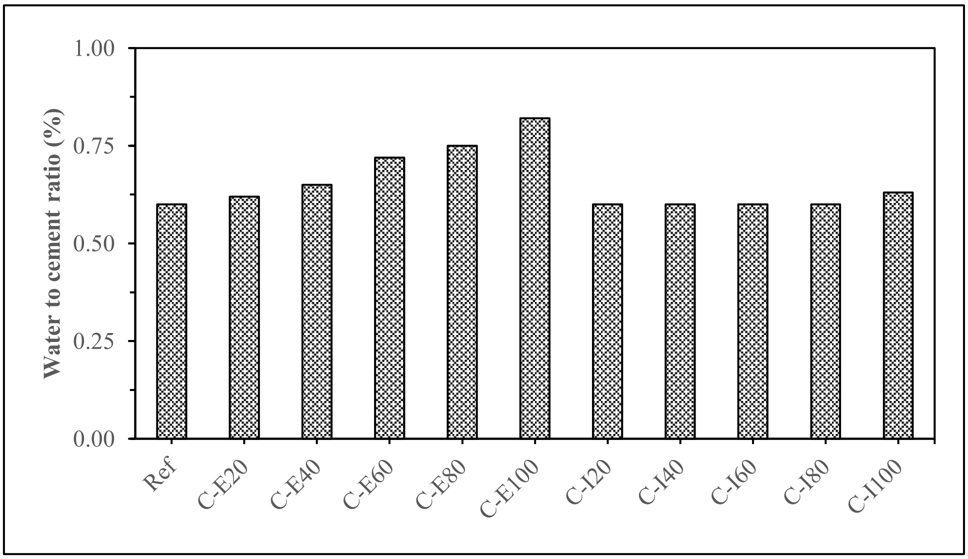

Fig. 6. The water-to-cement ratio of concrete mixes to achieve the target slump.

universal compression machine and applying a loading rate of 0.05 MPa/s (Fig. 5b). The flexural strength was calculated using Eq. (1), where N indicates the maximum load (N) achieved during the test, L is the distance between the lower supports, and d is the width of the specimen.

$$\text{Flexural strength} = \frac{(N \times L)}{d^3} \quad (1)$$

The water penetration depth was determined at 28 days on two replicate cubes with dimensions of 150×150×150 mm, following the TS EN 12390-8 standard. The test samples were exposed to a water pressure of 500 kPa (Fig. 5c) for 72 h, removed from the test apparatus, and split into two parts to measure the depth of water penetration through the sample.

3. Results and discussion

3.1. Fresh properties

Fig. 6 shows the required water-to-cement (w/c) ratio of concrete mixes to achieve the target slump value of 180 ± 20 mm. The results demonstrate that the w/c ratios for the concretes produced with E-BOFSA varied between 0.62% and 0.82%, while the w/c ratio of the reference concrete (Ref) was 0.60%. Incorporating E-BOFSA increased w/c ratio by about 3%, 8%, 25%, and 37%, with 20%, 40%, 80%, and 100% BOFS, respectively. Tang et al. [34] reported that incorporating BOFS fine aggregates increased the superplasticizer demand to achieve a similar slump value. Furthermore, the results indicate that the I-BOFSA does not significantly impact the workability of concrete up to 80% replacement with sand; only the C-I100 mix required a slightly higher w/c ratio of 0.63 to satisfy the target slump value. The higher w/c ratio demand for concrete mixes incorporating E-BOFSA fine aggregate could be due to its higher water absorption properties and fine content than I-BOFSA. As previously noted, the water absorption and fines content of E-BOFS fine aggregate are roughly 40% and 78% greater than I-BOFS's, consequently increasing the water demand to achieve similar workability.

3.2. Mechanical properties

The compressive strength test results of the concrete samples are presented in Fig. 7. The results show that the 28 days' compressive strength varies between 21.9 MPa and 36.8 MPa and 25.5 MPa and 36.8 MPa for the concrete mixes incorporating BOFS fine aggregates, respectively. The increase in E-BOFSA content reduced the compressive strength from 36.8 MPa (Ref) to 21.9 MPa (C-E100). The results also show that using E-BOFSA beyond the 40% replacement ratio decreased the compressive strength by more than 28%. Concrete mixes produced with I-BOFSA had a lower water demand (water-to-cement ratio) than those made with E-BOFS. Consequently, the concretes produced using I-BOFSA showed superior performance. The reduction in the compressive strength of concrete produced using I-BOFSA as an 80% replacement of crushed sand was only 13.9%, which is quite acceptable. The mechanical properties of the aggregates also have a critical role in the concrete properties. The Los Angeles test results conducted on both BOFSAs indicate that the I-BOFSA has a higher abrasion resistance

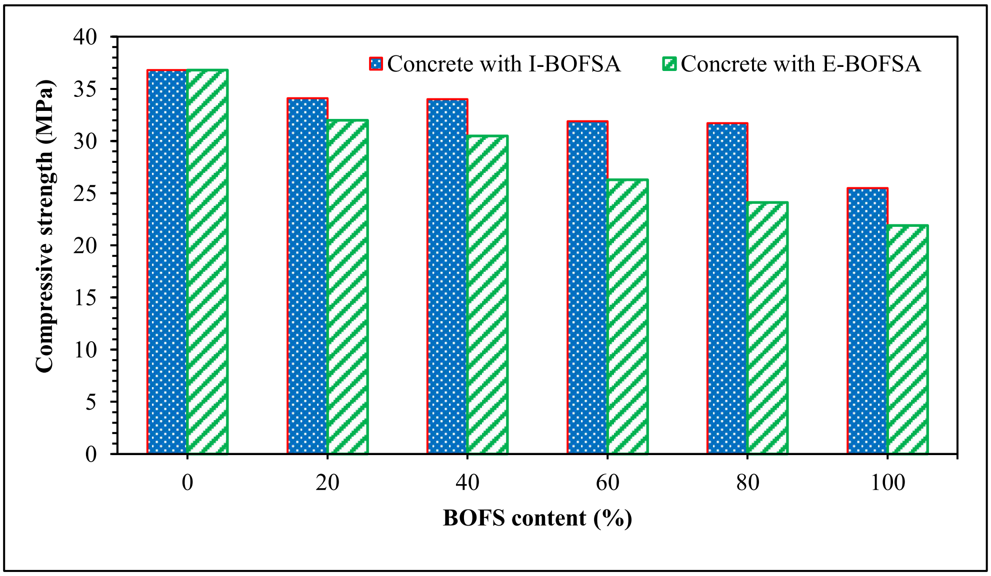

Fig. 7. The 28-day compressive strength results of concrete mixes.

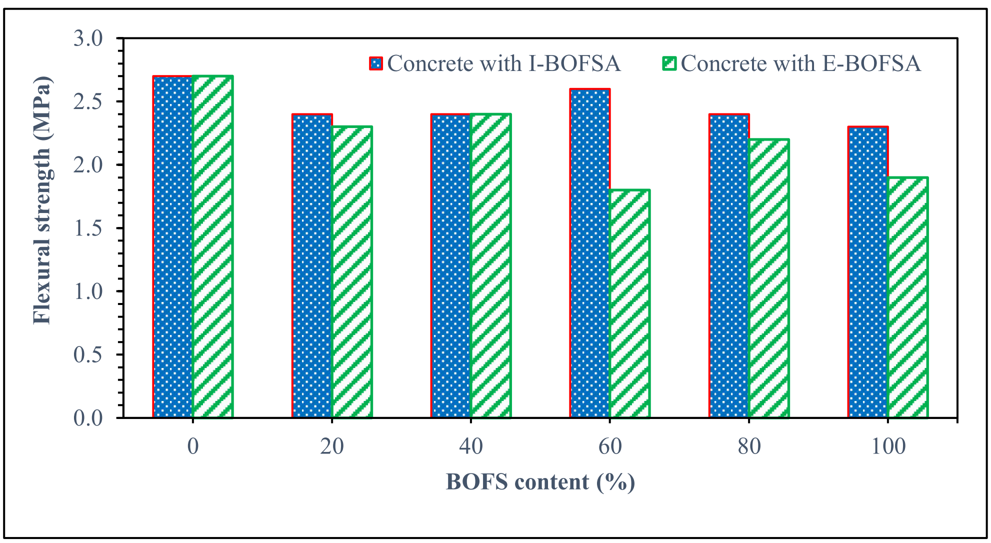

Fig. 8. The 28-day flexural strength results of concrete mixes.

(loss on abrasion is 17.4%) compared to E-BOFSA (loss on abrasion is 26.9%), which further shows that the I-BOFSA is superior to that of E-BOFSA in terms of mechanical properties. This also explains the higher compressive strength values of concrete manufactured with I-BOFSAs. The compressive strength drop with the incorporation of both BOFSAs, especially at higher ratios, could be due to their high water absorption compared to crushed sand, which might have a negative impact on the cement hydration reactions, increase the air content, and reduce the amount of hydration reaction products [35].

The flexural strength values varied from 1.8 MPa to 2.7 MPa and from 2.3 MPa to 2.7 MPa for the concrete mixes produced with E-BOFSA and I-BOFSA, respectively, as shown in Fig. 8. With the increment of the BOFS content, the flexural strength decreased from 2.7 MPa to 1.8 MPa for the E-BOFSA incorporating mixes. The utilization of BOFS fine aggregate beyond 60% did not significantly affect the flexural strength. Concretes produced using I-BOFSA were less affected by the increase in BOFS ratio, as the flexural strength decreased by 14.8% at the maximum utilization ratio. The results also indicate that I-BOFSA showed better performance in terms of flexural strength compared to E-BOFSA. The flexural strength drop of concrete produced using I-BOFSA up to an 80% replacement ratio was only 11.1%, which is quite acceptable.

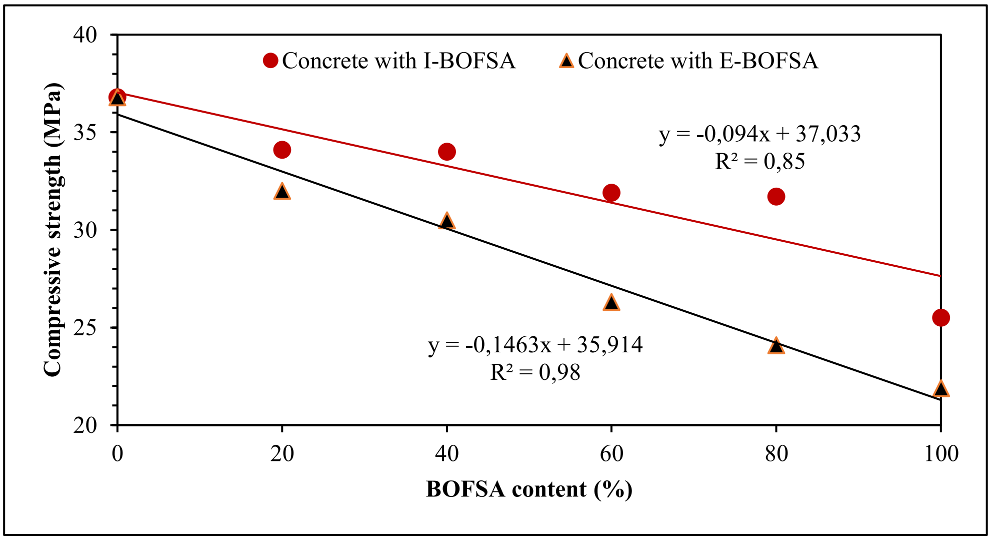

Fig. 9. The relationship between compressive strength and BOFS content.

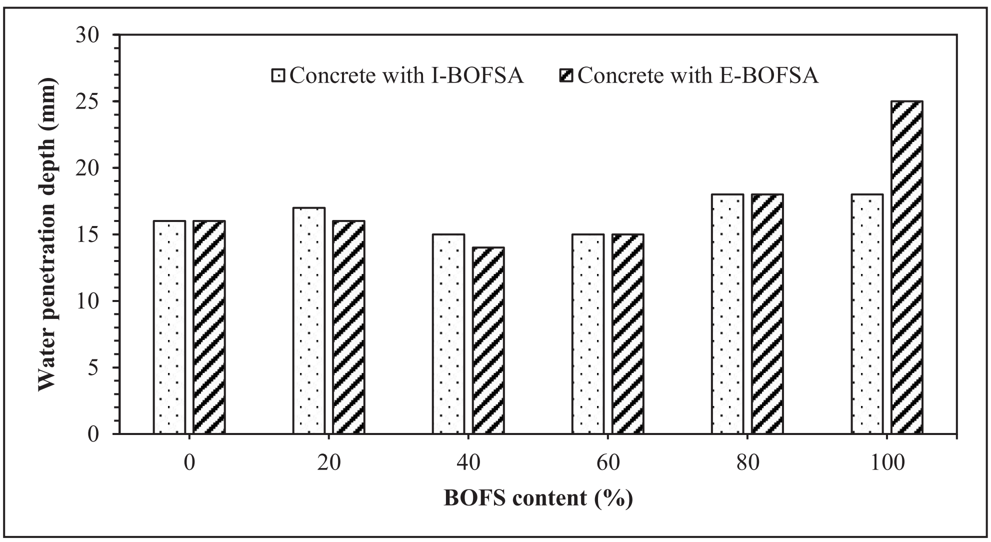

Fig. 10. The water penetration depth results of the concrete mixes.

On the other hand, the comparatively lower flexural strength of E-BOFSA incorporating mixes could be due to its higher fine content, which requires more cement to coat these very fine particles to achieve better mechanical properties [34].

The trend in Fig. 9, explained by the linear regression model, revealed that the compressive strength highly depends on the BOFS content. The concretes produced with E-BOFSA were responsive to the utilization ratio regarding compressive strength. The linear equation's coefficient of determination (R2) revealed 0.98, indicating that the model can accurately forecast the compressive strength. The results also showed that utilizing I-BOFSA tends to suppress the adverse effect of the BOFS fines on compressive strength. This could be attributed to the poor hydraulic property and low amorphous SiO2 content of E-BOFS compared to that of I-BOFS and the higher water demand of E-BOFSA to obtain workable concrete.

3.3. Water penetration depth

The results of water penetration under hydrostatic pressure are shown in Fig. 10. The results demonstrate that all mixes have high impermeability according to the TS 13515 standard, which declares an upper limit of 50 mm for a single test result and 40 mm as the average test result. The BOFSA replacement of up to 60% showed no significant impact on the water penetration depth. However, the water penetration depth increased beyond this ratio due to the higher capillary pores resulting from a higher water-to-cement ratio. The water penetration depth of concrete mixes incorporating both BOFSAs showed comparable results, yielding similar values. The only exception was observed at a 100% replacement ratio. Among all mixes, the highest water penetration depth of 25 mm was observed in the concrete blend incorporating 100% E-BOFS fine aggregate, which is still satisfactory for impermeability.

4. Conclusion

In this experimental study, the BOFS aggregates acquired from two different sources and stored in open stock areas were used in place of the limestone fine aggregate, and their effects on the performance of conventional concrete were researched. The water demand of fresh concrete and the compressive and flexural strength of hardened concrete mixes were determined to compare their fresh and mechanical properties; on the other hand, water penetration depth was determined to investigate their durability performance. Based on the test results, the following conclusions might be drawn.

1. The BOFS aggregates acquired from two sources presented significant differences in chemical composition and physical and mechanical properties, affecting the fresh and hardened concrete properties.
2. Considering the concrete mixes incorporating E-BOFSA, as the replacement ratio increased, the w/c ratio was significantly increased to maintain the workability of fresh concrete. In contrast, the concrete mixes incorporating I-BOFSA maintained a more consistent w/c ratio at all substitution ratios, except the C-I100 mix, where the w/c ratio was slightly elevated to 0.63. The rest of the concrete mixes incorporating Isdemir BOFS aggregate achieved the target slump with the same w/c ratio of 0.6 as the Reference concrete. The lower water absorption and fine content of I-BOFSA compared to E-BOFSA were determined as the key factors affecting concrete demand.
3. The effect of BOFSA type and content on the compressive strength was significant, resulting in consistent drops with increased BOFSA content. The compressive strength of mixes produced with I-BOFSA was noticeably superior to that of E-BOFSA at all replacement ratios. The compressive strength of concrete made with 100% E-BOFSA was reduced from 36.8 MPa to 21.9 MPa, causing about a 40% drop, whereas, in the case of 100% I-BOFSA, the compressive strength reduction was about 30%. Furthermore, at an 80% replacement ratio, there is only a 14% loss in the strength of concretes containing I-BOFSA.
4. The increase in BOFSA substitution ratio negatively impacted the flexural strength of concrete mixes incorporating both BOFSAs, but the effect was more pronounced in E-BOFSA mixes. On the other hand, the concrete mixes incorporating I-BOFSA achieved comparable flexural strength compared to the Reference concrete, and the highest reduction, approximately 15%, was observed at a 100% replacement ratio..
5. The water penetration depth of concrete mixes incorporating both BOFS aggregates demonstrated similar values to the Reference concrete, up to a 60% substitution ratio. The highest water penetration depth was noted for the concrete incorporating 100% Eregli BOFS aggregate as 25 mm, which still satisfied the water impermeability requirements per the TS 13515 standard.
6. The results indicate that BOFS obtained from two different sources stored under outdoor conditions might be utilized as an aggregate in concrete up to a specific limit that could help minimize the stock areas and associated environmental problems. The study also shows that the inherent BOFSA characteristics, such as mechanical strength (Los Angeles abrasion), water absorption, and fines content, significantly affect the fresh and hardened concrete properties that require detailed testing before using such aggregates.

Conflict of interest

The author declares no conflict of interest.

Data availability statement

The author confirms that the data of this research are available in the text. The raw data substantiating the research findings are available upon reasonable request.

Financial disclosure

The author declares that this study has received no financial support.

Author's contribution

None.

Ethics

There are no ethical issues with the publication of this paper.

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