Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Utilization of Electric Arc Furnace (EAF) Slag in Concrete as Coarse Aggregate: A Case Study in Bangladesh

Md. Muktadir Billah

mbillah@mme.buet.ac.bd

Bangladesh University of Engineering and Technology (BUET)

Surya Akter

Bangladesh University of Engineering and Technology (BUET)

Nusrat Jahan Snigdha

Bangladesh University of Engineering and Technology (BUET)

Md. Rajbanul Akhond

Bangladesh University of Engineering and Technology (BUET)

Munim Shahriar Jawad

Bangladesh University of Engineering and Technology (BUET)

Ahmed Sharif

Bangladesh University of Engineering and Technology (BUET)

Fahmida Gulshan

Bangladesh University of Engineering and Technology (BUET)

Research Article

Keywords: Electric Arc Furnace Slag, Heavyweight Concrete, Compressive Strength, Durability, Recycle

Posted Date: July 10th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10098760/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

UTILIZATION OF ELECTRIC ARC FURNACE (EAF) SLAG IN CONCRETE AS COARSE AGGREGATE: A CASE STUDY IN BANGLADESH

Md. Muktadir Billah*, Surya Akter, Nusrat Jahan Snigdha, Md. Rajbanul Akhond, Munim Shahriar Jawad, Ahmed Sharif, Fahmida Gulshan

Department of Materials and Metallurgical Engineering (MME), Bangladesh University of Engineering and Technology (BUET), Dhaka, 1000, Bangladesh

*Corresponding author: Email: mbillah@mme.buet.ac.bd

Abstract

The inclusion of electric arc furnace (EAF) slag as a partial replacement for natural coarse aggregate gives a sustainable solution for resource effectiveness and performance enhancement in concrete. The current research strictly investigates the mechanical and durability properties of 0–100% EAF slag-replaced concrete. Results show that up to 75% replacement increases 28-day compressive strength by approximately 8% and reduces water absorption. Chloride penetration resistance was improved by up to 50% but reduced at 100% marginally by interconnected porosity at high slag content. The findings indicate the benefits of the utilization of EAF slag as a high-performance aggregate for structures and infrastructure use, particularly where natural aggregate scarcity or sustainability needs demand substitutes. The research guides engineers towards safe and green use of EAF slag in concrete, recommending 50–75% replacement for maximum durability, strength, and workability, and for large-scale utilization in infrastructures.

Keywords

Electric Arc Furnace Slag; Heavyweight Concrete; Compressive Strength; Durability; Recycle

INTRODUCTION

Bangladesh has emerged as one of the fastest-growing steel markets in Asia. Increasingly, raw materials and advanced technologies for the manufacture of steel are being sought. In 2018, the country realized a GDP growth rate of 7.9%, which was higher compared to most other emerging economies. The national economic development is thus directly and greatly connected with the establishment and growth of the construction industry, specifically, its steel industries, and the supply of building materials. The estimated value of the industry at present is around 450 billion USD. The production of steel grew from 47,000 MT in 1971 to about 4 million MT in 2015, to approximately 8.5 million tons in 2018, recording its rapid industrial expansion. In 2019, installed capacity had been projected to cross 9 million MT, and an additional growth by 3–4 million MT was envisaged in the coming years with ongoing and announced expansion projects by major industrial players.[1], [2], [3].

Slag is the main by-product produced during manufacturing processes of iron and steel. Continued economic growth is very likely to increase generation of slag significantly, as per capita consumption of steel in Bangladesh is on the rise. Currently, only two steel plants in the country use the electric arc furnace (EAF) route, which currently produces around 1 million tons of steel per year, along with nearly 270,000 tons of slag. The characteristics and composition of slag depend on the type of steel produced and raw materials used during processing. In Bangladesh, two main types of slag are produced: induction furnace slag generated from several hundreds of small-scale steel industries, and electric arc furnace slag. In the last decades, both the variety of steel products and the total production has improved,

increasing the amount of slag produced with complex compositions.[4], [5] Although EAF steel slag has attracted research attention, its applications in construction are still under active study.

In recent decades, extensive international research has investigated the recycling of steel slag in construction materials, particularly in concrete and road infrastructure. Studies have demonstrated that EAF slag can function both as a coarse aggregate and, under certain conditions, as a supplementary cementitious material due to the presence of calcium silicate phases such as belite (C_2S). These mineral phases may contribute to limited hydraulic or latent hydraulic behavior when incorporated into cementitious systems. Consequently, steel slag has been explored not only for its mechanical contribution as an aggregate but also for its potential to influence hydration reactions and microstructural development in concrete matrices.[6], [7].

In principle, the feasibility of recycling industrial by-products in construction is controlled by their chemical composition, volume stability, and physical and mechanical properties. Thus, this study focuses on the treatment, recycling potential, and management of EAF steel slag in Bangladesh for developing environmentally friendly concrete and conserving natural geological resources. Currently, the lack of a comprehensive environmental and engineering performance dataset is a key obstacle to more general acceptance in infrastructure applications [10], [11]. Therefore, geometric, physical, mechanical, and chemical properties of EAF steel slag have been first assessed and compared with those of conventional natural aggregates. Then, concrete mixtures incorporating slag as partial replacement to natural coarse aggregate have been prepared and assessed for their performance.[8], [9], [10], [11], [12], [13], [14] Despite considerable research work carried out worldwide on the utilization of EAF slag, it has been observed that the chemical composition, mineralogy, and stability of EAF slag vary depending upon the raw materials, scrap materials, and furnace practices used during steelmaking by the EAF steelmaking process. At present, there is a scarcity of experimental data on the physicochemical properties and engineering characteristics of EAF slag used by steel industries located in Bangladesh, which are different from those located in other parts of the world.

The application of EAF slag in concrete addresses many of the significant problems facing modern construction. The natural aggregate resources are declining, and quarrying processes result in loss of habitat and emission of greenhouse gases[15]. EAF slag, as a steelmaking residue of electric arc, has higher density and better surface roughness, favoring mechanical interlock and paste–aggregate bonding, leading to improved compressive strength and low permeability[16], [17], [18]. Moreover, EAF slag application diverts enormous industrial wastages from landfills disposal to avoid leachate risk and ease compliance with circular economy needs (ISO 14044)[19]. Together, these benefits position EAF slag as technically sound and environmentally friendly for green infrastructure construction.[20], [21].

In addition to its aggregate function, several studies have reported that the mineralogical composition of steel slag, particularly the presence of calcium silicates, may impart limited cementitious or hydraulic reactivity. Although the present study focuses primarily on the use of EAF slag as a coarse aggregate, understanding its mineralogical characteristics is important for interpreting its influence on the mechanical and durability behavior of concrete.[22], [23], [24].

The present work deals with a detailed experimental investigation of the locally available EAF slag material in Bangladesh, in terms of the chemical composition, mineralogy, thermal stability, and micro-morphology of the material, as well as the detailed properties of the material in the form of blended cement with varying proportions of the slag content. By

linking experimental outcomes with ASTM and national building codes, the study enhances sustainable infrastructure development, reduces dependence on depletable natural aggregates, and facilitates circular economy objectives through valorization of steelmaking residues.

Despite extensive international research on steel slag utilization, limited systematic studies have been conducted on the physicochemical characteristics and engineering performance of EAF slag generated from Bangladeshi steel production systems. Variations in scrap composition, melting practices, and steelmaking technologies can significantly influence slag mineralogy, chemical composition, and stability, which in turn affect its suitability for use in concrete. Therefore, the present study aims to provide a comprehensive evaluation of Bangladeshi EAF slag, including its chemical, mineralogical, and physical characteristics, and to investigate how these properties influence the mechanical and durability performance of concrete when used as a coarse aggregate. By linking detailed material characterization with concrete performance, this work contributes region-specific data and mechanistic insights that help clarify the engineering potential of EAF slag derived from emerging steel industries.

METHODOLOGY

EAF slag was used as coarse aggregates. Concrete specimens were made with a constant water/cement ratio of 0.45 for concrete mix design as shown in Table 1. The concrete mixtures were designed with a constant water-to-cement ratio to evaluate the effect of replacing natural coarse aggregate with EAF slag at different proportions.

Table 1: Concrete mix design.

Mix No.	Slag Type	Stone Chips	Sand	Slag	Water/Cement Ratio
Control Mix					
1	-	100	100	0	0.45
Replacement of Aggregates					
1	**EAF (Coarse)**	75	100	25	0.45
2		50		50	
3		25		75	
4		0		100	

Before concrete preparation, the particle size distribution of the EAF slag was identified by sieve analysis and directly compared to that of the natural coarse aggregate in terms of grading compatibility. The experimental program started with the determination of fresh concrete properties (Table 2), after which test specimens were prepared for the determination of mechanical and durability properties. Slump was measured based on ASTM C143, compressive strength according to ASTM C39, splitting tensile strength based on ASTM C496, and the modulus of elasticity determined in accordance with ASTM C469. Durability performance was determined through rapid chloride penetration testing in line with ASTM C1202 and water absorption tests based on ASTM C1585 (Table 3). All concrete specimens were water-cured and tested at curing ages of 7, 14, and 28 days.

Table 2: Physical and mechanical properties of EAF slag.

Properties of Slag	Standard for Test Procedure	Sample Description	No. of Sample
Moisture	BS 812 part 109	Fresh Slag	3
Absorption	ASTM C 127	Fresh Slag	3
Density	ASTM C 568	Fresh Slag	3
Drop Impact	BS 812 part 112	Mesh Size (12.7-9.51)	1

		mm	
Loss Angeles Abrasion	ASTM C 131	Mesh Size (19-12.7) mm and (12.7-9.51) mm	2
Crushing Test	BS 812 part 110	Mesh Size (19-12.7) mm, 300 KN and 25.4-19) mm, 400 KN	2
Flakiness	BS 812-105.1	Fresh Slag	2

Table 3: List of tests, corresponding standards and sample size.

Properties of Concrete	ASTM Standard	Sample Description	No. of Sample
Fresh Concrete			
Slump Value	C 143	Fresh Concrete	
Hardened Concrete (Physical Properties)			
Bulk Density	ASTM C642	4”X8” Cylinder	5
Porosity	ASTM C642	4”X8” Cylinder	5
Hardened Concrete (Mechanical Properties)			
Compressive Strength	C 39	4”X8” Cylinder	9
Splitting Tensile Strength	C 496	4”X8” Cylinder	9
Hardened Concrete (Durability Properties)			
Chloride Penetration	C 1202	4”X8” Cylinder	6
Water Absorption	C1585	4”X8” Cylinder	3

CHARACTERIZATION

Materials and Equipment

Ordinary Portland Cement (OPC) as per ASTM C150 Type I was utilized as the primary binder. Locally available natural river sand was adopted as the fine aggregate, and crushed stone imported was used as the normal coarse aggregate. The stone chips used as natural coarse aggregate were crushed limestone obtained from commercial construction suppliers. The material was clean, hard, and free from deleterious substances, and its grading satisfied the requirements for coarse aggregates used in structural concrete. Natural river sand was used as the fine aggregate. The sand was clean, well-graded, and free from organic impurities, conforming to the requirements for fine aggregates used in concrete production. Electric arc furnace (EAF) slag from the local steel plant substituted natural coarse aggregate partially or entirely in experimental mixtures. The EAF slag utilized in the present investigation, derived from a steel industry source, has been subjected to pre-treatment before usage to control the reactivity of the free CaO and MgO phases, which may lead to volumetric instability. The EAF slag has been stored in the open environment, where it has been subjected to natural exposure to outdoor moisture levels. This practice is employed to condition steel slag aggregate before the construction of concrete structures. The slag was allowed to weather for approximately 60 days prior to crushing and sieving to the required aggregate size fractions for concrete preparation. Superplasticizer or high-range water-reducing admixture was added in case of requirements to meet target slump and workability. Chemical composition of the EAF slag was analyzed using X-ray fluorescence (XRF) spectroscopy (Shimadzu 1800). The mineralogical phases were identified by X-ray diffraction (XRD) at room temperature (PANalytical PW 3040-X) using Cu-Kα radiation.

Morphological features were examined with the assistance of a field-emission scanning electron microscope (FESEM, JEOL JSM-7600F). Thermogravimetric analysis (TGA) was performed to examine the thermal stability and hydration capacity of the slag, subject to a controlled heating rate of 10 °C/min under a nitrogen environment that is considered ideal for tracing weight loss events corresponding to dehydration, dihydroxylation, and decarbonation with negligible thermal lag.

X-Ray Fluorescence (XRF) Analysis

Chemical stability of the EAF slag is a precondition for secure concrete mix performance, since excessive compositional fluctuation would significantly affect mix proportioning and behavior. The oxide composition profile, as determined through XRF over a one-year monitoring period summarized in Table 4, indicates only minor variation, reflecting the uniformity of the slag source. The major oxide phases identified in XRF were further verified by wet chemical analysis, shown in Fig. 1. The slag is primarily composed of CaO (~35%), SiO_2 (~20%), and FeO (~25%), and the secondary oxides include Al_2O_3 and MgO, around ~7–8%. The three dominant oxides account for almost 80% of the total slag composition. Changes in the oxide composition will largely depend on the scrap input and furnace operating conditions. According to the values measured, this corresponds well to the literature [26–28]. Conventionally, iron in slag is quantified as either FeO, Fe_2O_3, or total Fe, based on the analytical convention. This slag exhibited a basic nature with a basicity ratio Mb = (CaO + MgO)/(SiO_2 + Al_2O_3) of 1.5. The chemical profile of this particular slag is much different compared with blast furnace slag that is conventionally used in producing cements [22]. Contrary to natural coarse aggregates, which have higher contents of CaO/$CaCO_3$ and MgO/$MgCO_3$ causing expansive reactions, the free CaO and MgO content in the EAF slag was relatively low, indicating a smaller risk of volumetric instability. The volumetric stability of steel slag is also related to the free CaO and MgO content in the slag. When present in large amounts, free CaO and MgO can cause delayed expansions. The results obtained from the XRF test show that the content of CaO and MgO in the sample is within the range of stabilized EAF slag aggregates used in concrete production. Past studies have shown that aging and weathering reduce the reactivity of these phases, thus enhancing stability.

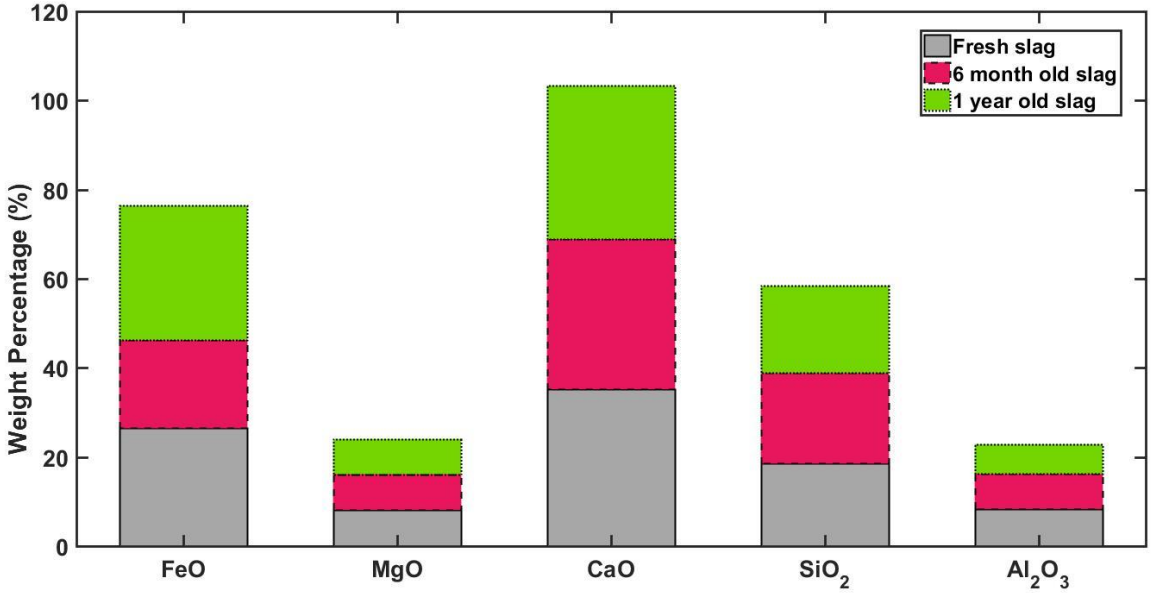


Figure 1: Chemical composition of EAF slag over time.

Table 4: Chemical composition of slag over time.

Chemical Compounds	Composition (wt. %)						
	Fresh Slag	6 Months Old Slag	1 Year Old Slag	EAF Slag from Other Sources [25]	Blast Furnace Slag [26]	Natural Aggregate	
						Limestone	Limestone
Iron oxide, FeO	26.44	19.78	30.22	17-35	0.20-1.60	2.50-3.50	0.10
Magnesium oxide, MgO	8.12	8.04	7.88	3-15	1-10	0.80-1.20	20.85
Calcium oxide, CaO	35.20	33.71	34.47	20-40	34-43	40-45	31.78
Silicon dioxide, SiO_2	18.51	20.30	19.62	6-23	27-38	10-14	0.49
Aluminum oxide, (Al_2O_3)	8.35	7.86	6.68	3-14	7-15	4-5	0.10
Free CaO/ $CaCO_3$	0.80	0.70	0.70	0.5-5	-	85-90	40-55
Free MgO	0.60	0.50	0.50	0-5	-	0.80-1.60	35-50

X-ray Diffraction (XRD) Analysis

The XRD pattern obtained for EAF slag is presented in Fig. 2; it indicates that the slag is mainly crystalline. The iron oxide phases detected by diffraction include wurtzite (W) and magnetite (M), while the silicate phases identified are larnite (L) and gehlenite. These results agree with previous works reported in the literature [32]. Besides these, small amounts of aluminum oxide were present. The content of the above-identified mineral phases, as quantified based on the XRD analysis, is presented in Table 5. The presence of calcium silicate phases such as larnite (C_2S) is particularly significant because these phases can exhibit latent hydraulic activity. When incorporated into cementitious systems, such phases may participate in secondary hydration reactions, contributing to additional formation of calcium–silicate–hydrate (C–S–H) gel. This mechanism may partially explain the improved compressive strength observed in the slag-containing concrete mixtures.

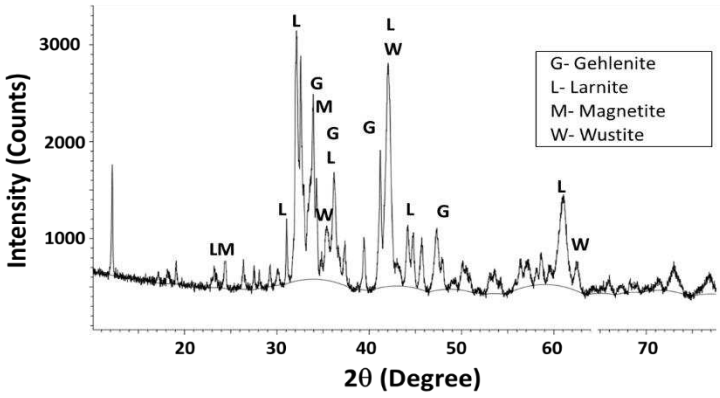


Figure 2: XRD of the EAF slag used (G= Gehlenite, L = Larnite, M = Magnetite, W = Wurtzite)

The diffraction peak observed at approximately $2\theta \approx 12.5°$ can be attributed to calcium aluminosilicate phases such as gehlenite, which are frequently reported in steel slag mineralogy.

Table 5: Percentages of the mineralogical constituents in the EAF slag according to the XRD analysis.

Minerals	Amount (wt. %)
Larnite {Ca_2SiO_4}	35
Gehlenite {$Ca_2Al(AlSi)O_7$}	27
Wustite {FeO}	23
Magnetite (Fe_3O_4)	10
Bredigite {$Ca_{14}Mg_2(SiO_4)_8$}	2
Free Calcium oxide (CaO)	<1
Aluminum oxide (Al_2O_3)	<1
Glassy Particles	<1

Coarse materials for concrete aggregate should be largely free from harmful constituents such as clay lumps, friable particles, salts, alkalis, organic matter, and other deleterious substances that may have adverse effects on concrete performance. The contents of such undesirable materials measured in the EAF slag are shown in Table 6. All the values recorded were much less than the maximum allowable limits for coarse aggregates in concrete, suggesting the suitability of the slag for structural applications.

Table 6: Weight of deleterious substances in EAF slag.

Substances	**EAF Slag wt. %**	**Specification Limits** [25] **wt. %**
Coal and Lignite	0	1.0
Soft and Friable Particles	< 0.1	2.0
Clay Lumps	< 0.1	2.0
Wood and Wood Matter	0	0.005
Plant Root Matter	0	0.005

Thermo-gravimetric Analysis

Thermogravimetric analysis (TGA) was employed to evaluate the hydroxide and carbonate phases present in the EAF slag. The resulting thermogram, shown in Fig. 3, illustrates the characteristic decomposition regions associated with moisture and calcium carbonate. The main mass loss regarding the evaporation of moisture occurred at about 120 °C; however, the main decarbonation reaction of $CaCO_3$ occurred at about 727 °C. Analysis of the TGA curve shows clear peaks in weight loss related to these events in thermal decomposition, confirming the presence and thermal behavior of the hydrated and carbonate phases within the slag matrix. The relatively low weight loss associated with free lime decomposition suggests a limited presence of reactive free CaO phases, which are typically responsible for volumetric instability in steel slag aggregates. This observation supports the chemical analysis results and indicates that the investigated slag possesses reduced expansion potential, thereby improving its suitability for use in concrete.

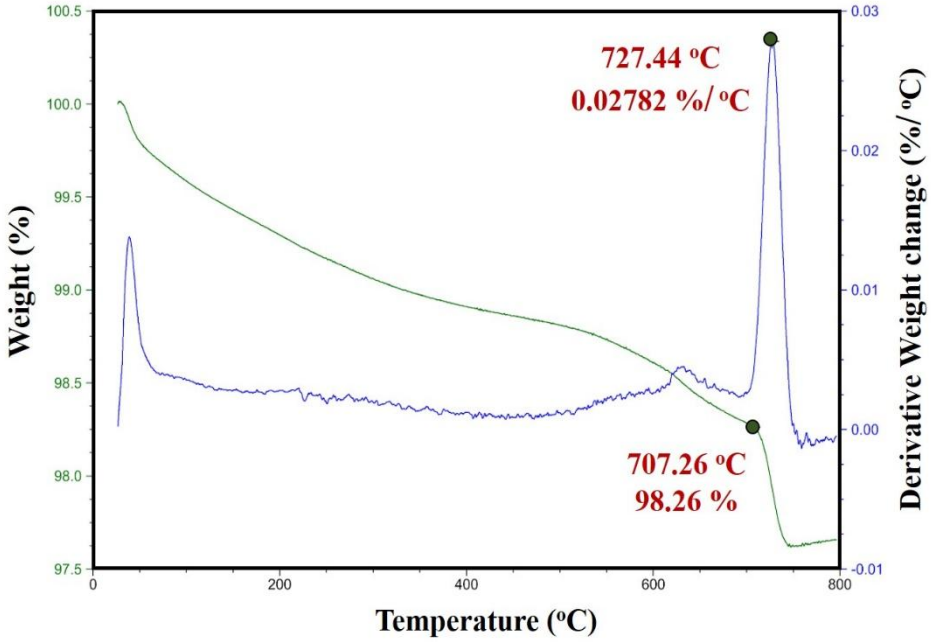


Figure 3: TGA curve of EAF slag showing weight changes with temperature.

In this case no dehydration of portlandite ($Ca(OH)_2 \rightarrow CaO + H_2O$) was observed at 450°C which indicates that all the free Ca was is in the form $CaCO_3$. From the mass loss of the TGA curve at 727°C, the amount of $CaCO_3$ was measured to be 1.4 wt. % in the slag sample. [28], [29]

Sieve Analysis

Table 7 shows the sieve analysis results of the EAF steel slag. It can be seen from the results that the Nominal Maximum Size (NMS) of the aggregate is 38 mm (Fig. 4).

Table 7: Data of sieve analysis.

Sieve Size	Material Retained	Percent Material Retained	Cumulative Percent Retained	Percent Finer	Specification limits ASTM C 33 [30]
mm	kg	wt. %	wt. %	wt. %	wt. %
38.	0.7122	1.819	1.819	98.181	100
25.4	3.190	8.147	9.966	90.044	95-100
19.0	6.175	15.778	25.744	74.256	-
13.3	7.120	18.184	43.928	56.072	-
12.7	1.100	2.809	46.736	53.262	25-60
9.51	5.115	13.063	59.80	40.20	-
4.75	6.195	15.821	75.631	24.369	0-10

2.36	4.920	12.565	88.181	11.819	0-5
1.68	2.060	5.261	93.442	6.558	-
0.841	1.200	3.065	96.507	3.493	-
0.595	0.4627	1.182	97.689	2.311	-
0.210	0.6712	1.714	99.403	0.597	-
0.105	0.1737	0.4436	99.8466	0.1534	-
Passing 0.105	0.1152	0.294	100.00	0	-
Total	39.21kg	100			

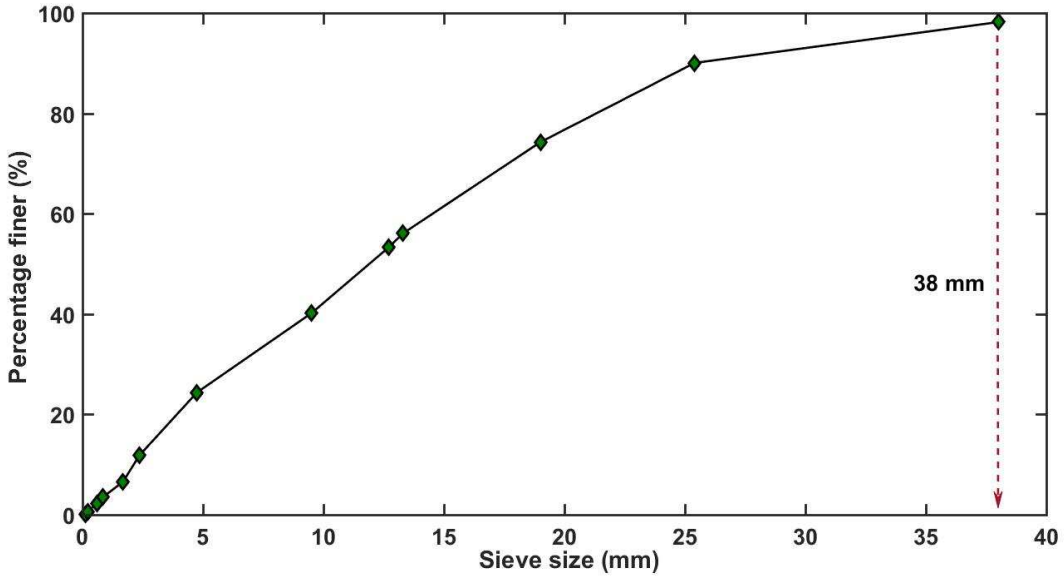


Figure 4: Gradation chart for sieve analysis of EAF slag.

Slag Morphology

Fig. 5 shows the morphology of EAF slag. As observed, the surface texture of the aggregate particles is porous and rough. Fig. 6 shows scanning electron microscope (SEM) images at different magnification of the EAF slag showing the porous and rough characteristics of the particles' surface. The SEM images reveal a relatively rough and angular surface morphology with visible pores and irregularities. Such surface characteristics can enhance the mechanical interlocking between the aggregate and the cement paste, leading to a stronger interfacial transition zone (ITZ). This improved interfacial bonding likely contributes to the higher compressive and tensile strengths observed in concrete mixtures incorporating EAF slag.



Figure 5: Optical micrograph of the EAF slag showing its porous and rough surface texture.

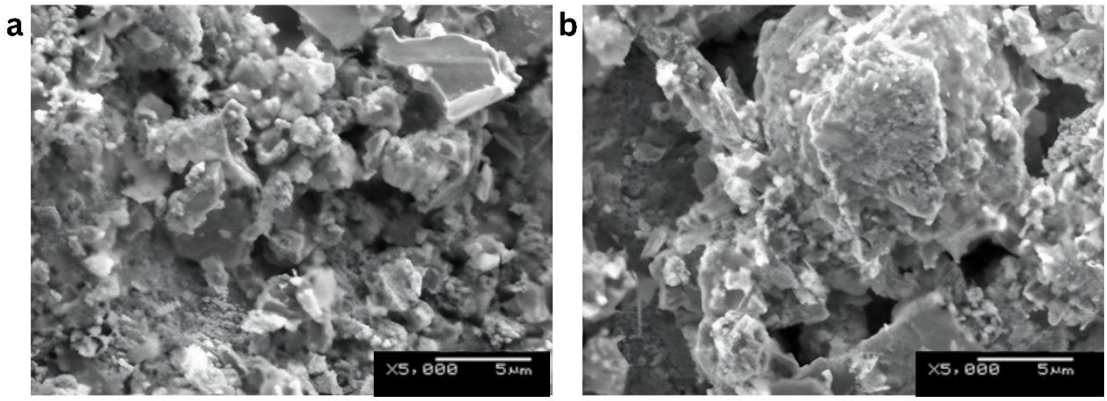


Figure 6: SEM images of the EAF steel slag showing its porous and rough surface texture.

RESULTS AND DISCUSSIONS

Slag Properties

Table 8 summarizes the physical properties of the EAF slag evaluated for its suitability as a concrete aggregate. It is worth noting that no additional chemical or thermal stabilization treatment was applied prior to testing. However, the slag had undergone natural aging through outdoor stockpiling before use, which allows partial hydration and carbonation of reactive free CaO and MgO phases and helps reduce the expansion potential of the material. The specific gravity of EAF slag was about 20% higher compared to conventional natural aggregates, owing to its high total iron content. Thus, the steel slag was much denser than crystallized slag and limestone aggregate and therefore suitable for producing heavyweight concrete. Its water absorption capacity and abrasion resistance, determined by the standard abrasion and impact test, ASTM C131/C131M, were like those of natural aggregates. However, the relatively higher absorption of crystallized slag should be taken into careful consideration during concrete mix proportioning.

The aggregate geometry of the slag was further tested through the flakiness index test. Flaky particles are those possessing a least dimension less than 0.6 times their mean size, and BS 812 Part 105.1 indicates that no more than 25% of such particles should be present in any construction aggregate. Table 9 shows that the flakiness index of EAF slag is far less than this threshold, indicating its geometric fitness for concrete production as well. Furthermore, the increased resistance of steel slag to abrasion and impact degradation suggests better mechanical performance of the resultant concrete. From the physical property characterizations above, EAF slag can be deemed a technically reliable alternative source to natural coarse aggregate. These findings also provide region-specific experimental evidence for the suitability of Bangladeshi EAF slag, linking its chemical composition, mineralogical structure, and surface morphology with the observed mechanical performance of slag-containing concrete mixtures.

Table 8: Physical properties of EAF slag.

Properties of Slag	**Values**	**Standard Values for Limestone**	**Standard Limits** [31]
App. specific density (kg/m^3)	3390	2680	-
Loose bulk density (kg/m3)	1670	1385	-
Water Absorption (%)	1.6	0.75	Max. 2%
Percentage of voids (%)	51.4	48.3	-
Drop Impact (%)	3.07	10-20	-
Loss Angeles Abrasion Test (%)	6.85	-	Max. 45

Crushing Value (%)	12.5	24.1	Max. 45

Table 9: Results of Flakiness test.

Sieve Size (mm)	Test Weight (g)	Weight Passing (g)	% Flaky	Flakiness Index (%)	
				EAF Slag	Specified Limit
38.1	1000	0	**0**	**8.62**	**< 30**
25.4	1000	140	**14**		
19.0	1000	170	**17**		
13.3	1000	60	**6**		
9.51	500	25	**5**		
6.35	200	10	**5**		
Total	**4700**	**405**			

Workability of Fresh Concrete

Fig. 7 illustrates the variation of slump with increasing EAF slag replacement in the concrete mixtures. A slight increase in slump was observed when 25% of the natural coarse aggregate was replaced with slag. This behavior may be attributed to improved particle packing and better distribution of aggregates within the mix at lower replacement levels. However, as the slag content increased further, a gradual reduction in slump was observed. This reduction is mainly associated with the higher water absorption capacity and angular particle shape of the slag compared to natural aggregates. The rough and porous surface of the slag particles tends to absorb part of the mixing water and increases internal friction between particles, which limits the mobility of the fresh concrete. At 100% replacement, the mixture exhibited a sticky consistency and reduced flowability, although the measured slump values remained within the range generally considered acceptable for workable concrete mixtures.

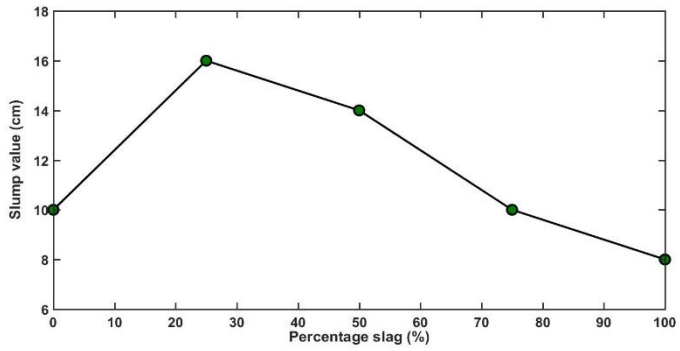


Figure 7: Workability of coarse aggregate replacement by different types of slag.

Physical and Mechanical Properties of Hardened Concrete

Figure 8 shows the trend of bulk density and porosity for concretes made with EAF slag. An increase in slag content resulted in an increased value of bulk density and a corresponding decrease in the value of porosity, which means the internal structure became denser and more compact. Many mechanical properties are directly or indirectly related to compressive strength; therefore, the above-mentioned behavior of concrete is very important. Compressive strength was determined following ASTM C39 on properly cast and water-cured concrete cylindrical specimens, 4 inches in diameter and 8 inches in height. The compression testing machine, used to apply axial load at a controlled rate until specimen failure, was a standard machine. The potential expansion of steel slag aggregates is commonly evaluated using standardized methods such as ASTM D4792 or EN 1744-1, which assess the volumetric stability of slag aggregates. Although such expansion tests were not performed in the present

study, the combination of slag aging and the relatively low reactive oxide contents suggests a reduced risk of delayed expansion in the investigated material.

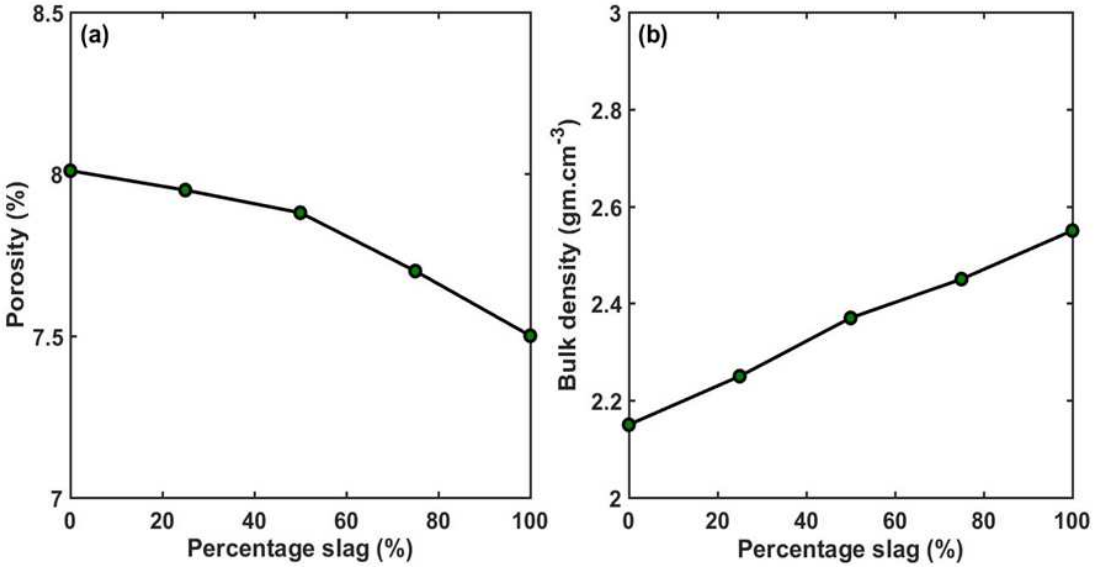


Figure 8: Comparison of (a) porosity and (b) bulk density of concrete containing EAF slag coarse aggregate.

Fig. 9 shows the compressive strength results at 7, 14, and 28 days of age for all concrete mixes. The compressive strengths of the control mixture without slag were 4109 psi, 4448 psi, and 4399 psi at 7, 14 and 28 days, respectively. This figure clearly depicts that concretes made with various EAF slag replacement levels resulted in higher compressive strength than the control mixture at each corresponding age. Another important point shown by the figure is that the trend of strength gain is increasingly higher (on average) with increasing percentages of slag. The highest 28-day strength had been recorded as 5850 psi for the mixture having 75% slag, with the 100% replacement mixture also doing well and reaching a strength of 5705 psi. These strength enhancements can be attributed to the combined influence of the slag's surface morphology and mineralogical composition. The rough and porous surface of the EAF slag observed in SEM analysis promotes stronger mechanical interlocking at the aggregate–paste interface, improving the interfacial transition zone (ITZ). In addition, the presence of calcium silicate phases such as larnite identified in the XRD analysis may contribute to limited secondary hydration reactions, which further densify the microstructure and enhance compressive strength. The concrete mixtures containing EAF slag exhibited acceptable workability in the fresh state, as indicated by the slump test results. Although a slight reduction in slump was observed at higher slag replacement levels, the mixtures remained within the range generally considered to represent good workability for structural concrete.

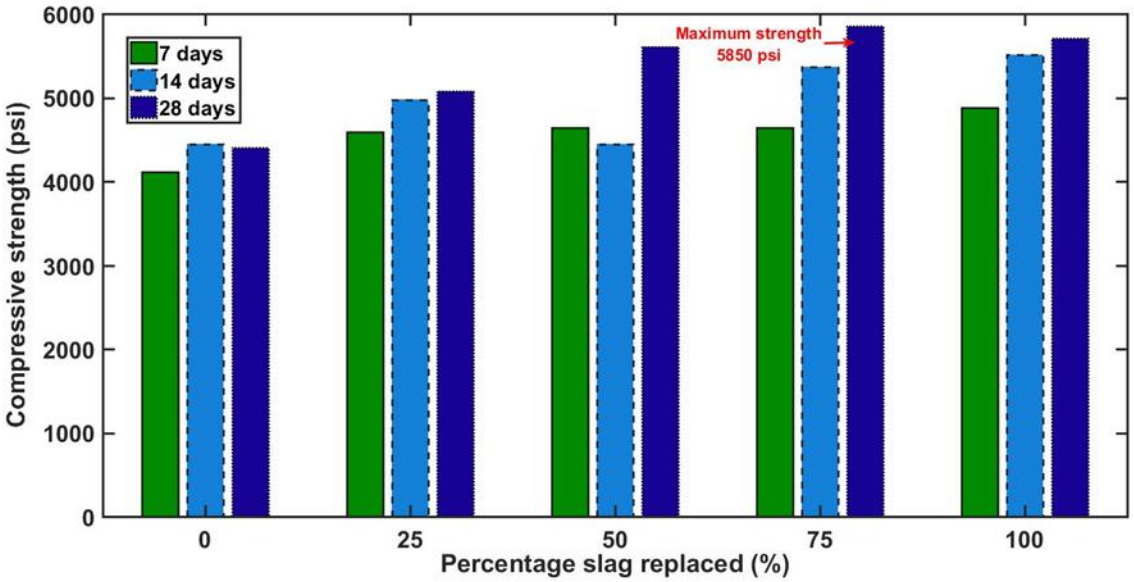


Figure 9: Compressive strength of EAF slag coarse aggregate containing concrete.

The splitting tensile strength of the concrete specimens was tested at curing ages of 7, 14, and 28 days according to ASTM C496. Test specimens were prepared at the same time as the compressive strength samples using cylindrical molds 4 inches (102 mm) in diameter and 8 inches (203 mm) in height. Figure 10 shows the development of splitting tensile strength for all mixes at various curing ages. This test gives an indirect measure of the tensile capacity of concrete, keeping in mind that concrete has significantly lower strength in tension than in compression and thus it fails at relatively small, applied loads. For the slag-added mixes, the tensile strength values were highest at 50% replacement after 7 days and at 100% replacement after 14 days of curing. The better early-age tensile performance probably relates to the calcium-rich phases in the slag. All slag-bearing concretes exhibited constantly higher splitting tensile strength than the slag-free control mix.

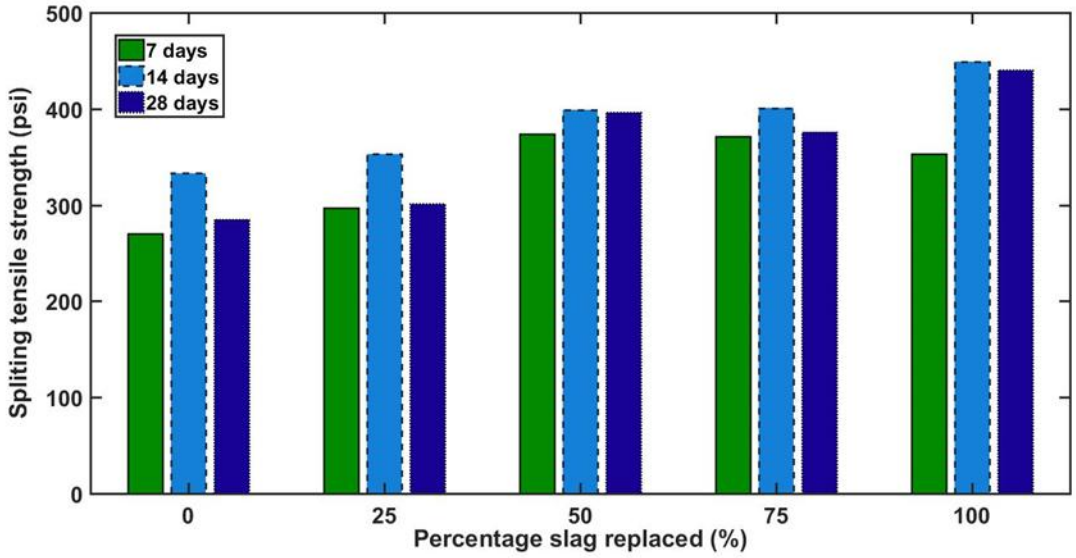


Figure 10: Splitting tensile strength of EAF slag coarse aggregate containing concrete.

Durability of Hardened Concrete

Figure 11 shows the water absorption of concrete made with EAF slag. Water absorption decreased progressively with the addition of slag. Upon replacing natural aggregate with EAF

slag, the overall water absorption of the concrete decreased slightly despite the higher intrinsic absorption capacity of the slag aggregate itself. A minimum value of absorption was observed for concrete with 100% slag. The total decrease in absorption was relatively small, increasing only to a maximum of about 6.5%. This indicates that slag has only a minor effect on this property. This apparent contradiction between the higher absorption capacity of the slag aggregate and the lower absorption observed in the concrete can be explained by microstructural effects at the composite level. The angular and rough surface texture of the slag particles improves particle packing and mechanical interlocking within the concrete matrix. This promotes a denser interfacial transition zone (ITZ) between the aggregate and cement paste. As a result, the connectivity of capillary pores within the hardened concrete is reduced, leading to lower overall water absorption at the structural scale despite the higher intrinsic absorption of the slag aggregate. [32], [33]Also shown in the same figure is the chloride ion penetration, which first decreases for slag contents of up to 50% and then increases. The slight increase in chloride penetration observed at higher slag replacement levels may be associated with changes in pore structure and pore connectivity within the concrete matrix rather than the chemical composition of the slag itself. However, the increase in chloride penetration at 100% slag replacement was relatively small (approximately 18%) and remains within acceptable limits for structural concrete applications. The increase at higher slag contents may be related to the angularity and surface roughness of slag particles, which can slightly increase local water demand and influence the distribution of capillary pores. Nevertheless, the overall permeability behavior suggests that the incorporation of EAF slag does not significantly compromise the durability performance of the concrete.[34], [35], [36]

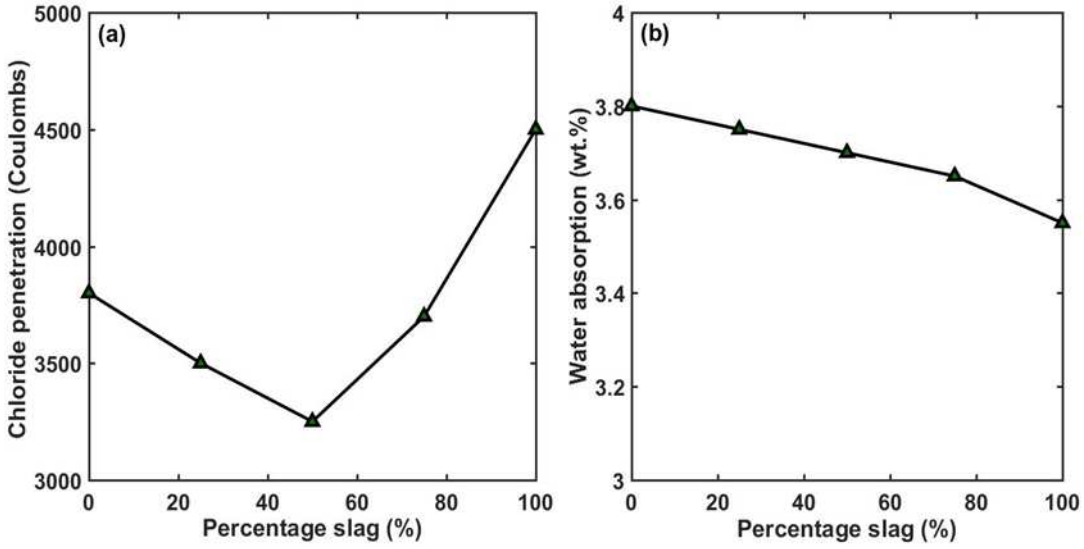


Figure: 11: Comparison of (a) chloride penetration and (b) water absorption of concrete containing EAF slag coarse aggregate.

CONCLUSION

The concretes containing oxidizing EAF slag as coarse aggregate exhibited superior performance both in the fresh and hardened states, justifying their suitability for widespread structural use. Slump tests revealed that even at 100% replacement, the workability was only slightly affected, rating the mixes as having good workability. Compressive strengths were always greater than the control mix with a peak value of 5850 psi, thus demonstrating that slag concrete can be produced as strong as regular structural concrete (3000–6000 psi range).

Splitting tensile tests supported additional performance gain with the highest value recorded at 50% replacement for curing 7 days and 100% replacement for curing 14 days, with all mixes containing slag performing better than the control. The incorporation of EAF slag improved bulk density, reduced porosity, and assisted in attaining a denser microstructure. Although even slight increases in chloride penetration were observed in 100% replacement, potentially due to higher Fe content, overall durability remained within acceptable values. These results support the utilization of EAF slag as an industrial by-product-based high-performance aggregate replacement that promotes sustainability while meeting strength and durability requirements for structural concrete.

AI USAGE DECLARATION

The authors declare that no artificial intelligence (AI)–assisted tools were used in the writing, analysis, or preparation of this manuscript. All content was developed, reviewed, and finalized solely by the authors.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

Not Applicable.

CONSENT FOR PUBLICATION

Not Applicable.

AVAILABILITY OF DATA AND MATERIAL

Not Applicable.

COMPETING INTERESTS

The authors declare that they have no competing interests.

FUNDING

Not Applicable.

AUTHOR CONTRIBUTIONS: MMB, SA, NJS, MRA and MSJ conducted experiments and analysis, and prepared the initial manuscript; MMB, AS and FG reviewed the manuscript.

ACKNOWLEDGEMENTS

Not Applicable.

REFERENCES

[1] R. M. Rezaul, R. Atahar, T. Bin Tasnim, A. S. W. Kurny, R. Momtaz, and F. Gulshan, “Feasibility study of Bangladeshi electric arc furnace steel slag as an alternative for conventional fine aggregate,” *AIP Conf. Proc.*, vol. 1980, Jul. 2018, doi: 10.1063/1.5044307.

[2] S. S. Sharif, S. Ahmad, D. C. Nababan, M. A. Rhamdhani, and F. Gulshan, “Thermodynamics analysis and experimental investigation of EAF slag-based ceramics materials for circular economy,” *Ceram. Int.*, vol. 50, no. 20, pp. 40058–40068, Oct. 2024, doi: 10.1016/j.ceramint.2024.07.390.

[3] R. Atahar, R. M. Rezaul, https://buetcse.academia.edu/RiadRezaul, and https://independent.academia.edu/RaihanAtahar, “PROSPECT OF USING BANGLADESHI ELECTRIC ARC FURNACE STEEL SLAG AS A REPLACEMENT OF COARSE AGGREGATE IN CONSTRUCTION MATERIALS,” 2012, Accessed: Mar. 05, 2026. [Online]. Available: https://www.academia.edu/35562040/PROSPECT_OF_USING_BANGLADESHI_ELECTRI

C_ARC_FURNACE_STEEL_SLAG_AS_A_REPLACEMENT_OF_COARSE_AGGREGATE_IN_CONSTRUCTION_MATERIALS
[4] "December 2023 crude steel production and 2023 global crude steel production totals - worldsteel.org." Accessed: Mar. 05, 2026. [Online]. Available: https://worldsteel.org/media/press-releases/2024/december-2023-crude-steel-production-and-2023-global-totals/
[5] M. A. Haque and A. Abdullah, "EBL Securities Limited Bangladesh Steel Industry: A Comprehensive Review θ Growing demand for graded steel products θ Self-reliant industry having sufficient capacity to feed local demand θ Also self-reliant for intermediate raw-material billet productio…," 2019.
[6] A. Sekaran, M. Palaniswamy, and S. Balaraju, "A Study on Suitability of EAF Oxidizing Slag in Concrete: An Eco-Friendly and Sustainable Replacement for Natural Coarse Aggregate," *The Scientific World Journal*, vol. 2015, p. 972567, 2015, doi: 10.1155/2015/972567.
[7] H. Xu, S. Wu, H. Li, Y. Zhao, and Y. Lv, "Study on Recycling of Steel Slags Used as Coarse and Fine Aggregates in Induction Healing Asphalt Concretes," *Materials*, vol. 13, no. 4, p. 889, Feb. 2020, doi: 10.3390/ma13040889.
[8] A. Sekaran, M. Palaniswamy, and S. Balaraju, "A Study on Suitability of EAF Oxidizing Slag in Concrete: An Eco-Friendly and Sustainable Replacement for Natural Coarse Aggregate," *The Scientific World Journal*, vol. 2015, no. 1, p. 972567, Jan. 2015, doi: 10.1155/2015/972567.
[9] D. Kvočka, J. Šušteršič, A. Mauko Pranjić, and A. Mladenović, "Mass Concrete with EAF Steel Slag Aggregate: Workability, Strength, Temperature Rise, and Environmental Performance," *Sustainability (Switzerland)*, vol. 14, no. 23, p. 15502, Dec. 2022, doi: 10.3390/SU142315502/S1.
[10] P. O. Awoyera, O. E. Babalola, and O. G. Aluko, "The use of slags in recycled aggregate concrete," *The Structural Integrity of Recycled Aggregate Concrete Produced With Fillers and Pozzolans*, pp. 145–170, Dec. 2021, doi: 10.1016/B978-0-12-824105-9.00009-3.
[11] Y. Jiang, T. C. Ling, C. Shi, and S. Y. Pan, "Characteristics of steel slags and their use in cement and concrete—A review," *Resour. Conserv. Recycl.*, vol. 136, pp. 187–197, Sep. 2018, doi: 10.1016/j.resconrec.2018.04.023.
[12] M. Skaf, J. M. Manso, Á. Aragón, J. A. Fuente-Alonso, and V. Ortega-López, "EAF slag in asphalt mixes: A brief review of its possible re-use," *Resour. Conserv. Recycl.*, vol. 120, pp. 176–185, 2017, doi: 10.1016/j.resconrec.2016.12.009.
[13] A. Chadee *et al.*, "Sustainable Use of Electric Arc Furnace Slag as a Fine Aggregate Replacement for Concrete," *Journal of Sustainability Research*, vol. 7, no. 1, 2025, doi: 10.20900/JSR20250012.
[14] F. Faleschini, K. Brunelli, M. A. Zanini, M. Dabalà, and C. Pellegrino, "Electric Arc Furnace Slag as Coarse Recycled Aggregate for Concrete Production," *Journal of Sustainable Metallurgy*, vol. 2, no. 1, pp. 44–50, Mar. 2016, doi: 10.1007/S40831-015-0029-1/FIGURES/7.
[15] S. Dias, J. Almeida, A. Tadeu, and J. de Brito, "Alternative concrete aggregates - Review of physical and mechanical properties and successful applications," *Cem. Concr. Compos.*, vol. 152, p. 105663, Sep. 2024, doi: 10.1016/J.CEMCONCOMP.2024.105663.
[16] K. Kishore, M. N. Sheikh, and M. N. S. Hadi, "A critical analysis of electric arc furnace (EAF) slag for sustainable geopolymer concrete production," *Materials Today Sustainability*, vol. 29, p. 101064, Mar. 2025, doi: 10.1016/J.MTSUST.2024.101064.
[17] J. M. Manso, J. A. Polanco, M. Losañez, and J. J. González, "Durability of concrete made with EAF slag as aggregate," *Cem. Concr. Compos.*, vol. 28, no. 6, pp. 528–534, Jul. 2006, doi: 10.1016/J.CEMCONCOMP.2006.02.008.
[18] F. Faleschini, K. Brunelli, M. A. Zanini, M. Dabalà, and C. Pellegrino, "Electric Arc Furnace Slag as Coarse Recycled Aggregate for Concrete Production," *Journal of Sustainable Metallurgy*, vol. 2, no. 1, pp. 44–50, Mar. 2016, doi: 10.1007/S40831-015-0029-1/FIGURES/7.

[19] "ISO 14044:2006 - Environmental management — Life cycle assessment — Requirements and guidelines." Accessed: Sep. 13, 2025. [Online]. Available: https://www.iso.org/standard/38498.html
[20] A. Diotti, L. Cominoli, A. P. Galvin, S. Sorlini, and G. Plizzari, "Sustainable Recycling of Electric Arc Furnace Steel Slag as Aggregate in Concrete: Effects on the Environmental and Technical Performance," *Sustainability 2021, Vol. 13, Page 521*, vol. 13, no. 2, p. 521, Jan. 2021, doi: 10.3390/SU13020521.
[21] "ENVIRONMENTALLY COMPATIBLE OPTIMIZATION OF EAF SLAG FOR LOW-CARBON ADVANCED GREEN CEMENT," Oct. 2025, doi: 10.3030/101221259.
[22] S. S. Chandel, A. Lavakumar, N. S. Randhawa, and P. K. Singh, "Unique hot stage modification technique to enhance cementitious properties of electric arc furnace steel slag," *J. Environ. Manage.*, vol. 376, Mar. 2025, doi: 10.1016/j.jenvman.2025.124398.
[23] J. Y. Lee, J. S. Choi, T. F. Yuan, Y. S. Yoon, and D. Mitchell, "Comparing Properties of Concrete Containing Electric Arc Furnace Slag and Granulated Blast Furnace Slag," *Materials*, vol. 12, no. 9, p. 1371, 2019, doi: 10.3390/ma12091371.
[24] K. Rani, K. Senthil, A. Boora, and A. K. Tiwary, "Optimization of cementitious and fine electric arc furnace slag on the concrete mixes through mechanical, durability, and microstructural testing," *Sci. Rep.*, vol. 15, no. 1, p. 45589, Dec. 2025, doi: 10.1038/s41598-025-29513-1.
[25] Y. K. Sabapathy, V. B. Balasubramanian, N. Shiva Shankari, A. Yeshwant Kumar, and D. Ravichandar, "Experimental investigation of surface modified EOF steel slag as coarse aggregate in concrete," *Journal of King Saud University - Engineering Sciences*, vol. 29, no. 4, pp. 388–393, Oct. 2017, doi: 10.1016/J.JKSUES.2016.07.002.
[26] D. Srinadh*, P. Praneeth, D. M. reddy, K. S. Chamberlin, and N. S. Kumar, "Stabilization of Black Cotton Soil using Lime and G.G.B.S (Ground Granulated Blast Furnace Slag) As A Admixtures," *International Journal of Innovative Technology and Exploring Engineering*, vol. 9, no. 2, pp. 2133–2136, Dec. 2019, doi: 10.35940/IJITEE.B7577.129219.
[27] I. Netinger, M. J. Rukavina, and A. Mladenovič, "Improvement of Post-fire Properties of Concrete with Steel Slag Aggregate," *Procedia Eng.*, vol. 62, pp. 745–753, Jan. 2013, doi: 10.1016/J.PROENG.2013.08.121.
[28] A. Santamaria *et al.*, "Dimensional stability of electric arc furnace slag in civil engineering applications," *J. Clean. Prod.*, vol. 205, pp. 599–609, Dec. 2018, doi: 10.1016/J.JCLEPRO.2018.09.122.
[29] K. M. A. Naimi, T. Delclos, and N. Calvet, "Industrial Waste Produced in the UAE, Valuable High-temperature Materials for Thermal Energy Storage Applications," *Energy Procedia*, vol. 75, pp. 2087–2092, Aug. 2015, doi: 10.1016/J.EGYPRO.2015.07.320.
[30] "C33/C33M Standard Specification for Concrete Aggregates." Accessed: Sep. 13, 2025. [Online]. Available: https://store.astm.org/c0033_c0033m-18.html
[31] M. Bhawan, B. Shah, and Z. Marg, "PM/ IS 383/ 2/ MAY 2020 BUREAU OF INDIAN STANDARDS PRODUCT MANUAL FOR COARSE AND FINE AGGREGATE FOR CONCRETE ACCORDING TO IS 383 : 2016".
[32] N. H. Roslan, M. Ismail, N. H. A. Khalid, and B. Muhammad, "Properties of concrete containing electric arc furnace steel slag and steel sludge," *Journal of Building Engineering*, vol. 28, p. 101060, Mar. 2020, doi: 10.1016/j.jobe.2019.101060.
[33] A. Sekaran, M. Palaniswamy, and S. Balaraju, "A Study on Suitability of EAF Oxidizing Slag in Concrete: An Eco-Friendly and Sustainable Replacement for Natural Coarse Aggregate," *The Scientific World Journal*, vol. 2015, p. 972567, 2015, doi: 10.1155/2015/972567.
[34] J. C. J. Ting, F. W. Lee, K. H. Yeap, R. J. Chin, M. K. Yew, and C. C. Yip, "Revolutionizing Concrete: Performance Enhancement and Elemental Insights with Electric Arc Furnace (EAF) Slag Replacement," *Materials*, vol. 18, no. 7, p. 1528, Apr. 2025, doi: 10.3390/ma18071528.
[35] R. M. Abendeh, D. Salman, and R. Al Louzi, "Study of properties and behavior of concrete containing EAF slag as coarse aggregate," *Developments in the Built Environment*, vol. 14, p. 100137, Apr. 2023, doi: 10.1016/j.dibe.2022.100080.
[36] J. I. Lee and S. J. Choi, "Compressive strength, chloride-ion-penetration resistance, and crack-recovery properties of self-healing cement composites containing cementitious material

capsules and blast-furnace-slag aggregates," *Journal of CO2 Utilization*, vol. 86, p. 102916, Aug. 2024, doi: 10.1016/j.jcou.2024.102916.