Hapres | Journal of Sustainability Research

sustainability.hapres.com

Article

Sustainable Use of Electric Arc Furnace Slag as a Fine Aggregate Replacement for Concrete

Aaron Chadee [1,*], Davatee Maharaj [1], Yehan Rajapakse [2], Eleeda Rajack [1], Shayani Mendis [2], Hazi Md. Azamathulla [1], Darshan J. Mehta [3], Upaka Rathnayake [4]

[1] Department of Civil and Environmental Engineering, The Faculty of Engineering, The University of West Indies, St. Augustine 330110, Trinidad and Tobago; devimaha1222@hotmail.com (DM); eleeda.rajack@my.uwi.edu (ER); hazi.azamathulla@sta.uwi.edu (HMA)

[2] Department of Civil Engineering, Faculty of Engineering, General Sir John Kotelawala Defence University, Rathmalana 10390, Sri Lanka; yehanrajapakse@gmail.com (YR); mendisasm@kdu.ac.lk (SM);

[3] Department of Civil Engineering, Dr. S. & S. S. Ghandhy Government Engineering College, Surat 395001, Gujarat, India; ap_darshan_mehta@gtu.edu.in (DJM)

[4] Department of Civil Engineering and Construction, Faculty of Engineering and Design, Atlantic Technological University, Ash Lane, Sligo F91 YW50, Ireland; Upaka.Rathnayake@atu.ie (UR)

* Correspondence: Aaron Chadee, Email: aaron.chadee@sta.uwi.edu.

ABSTRACT

This research provides empirical insights into the mechanical properties of concrete made with fine electric arc furnace slag aggregates. The utilization of fine electric arc furnace slag as aggregates in concrete production could be a catalyst in addressing the current unsustainable extraction rates of the natural non-renewable resources thereby promoting circularity in the economy and achievement of sustainable developmental goals. Using four mix designs with varying percentages of Electric Arc Furnace (EAF) slag (0%, 10%, 15%, and 20%) as fine aggregates; a decrease in the compressive strength values compared to the control mix for concrete mixes containing 10% and 15% EAF slag of fine aggregates, but an increase in the compressive strength at 20% replacement. However, a steady decrease in the tensile strength value for all percentages of EAF slag replacement was noted. It was deduced that, all American Concrete Institute (ACI) 318, Eurocode (EC) 2, and Australian Standard (AS) 3600 standard design codes for normal concrete overestimate the 7-day and 28-day splitting tensile strengths of EAF slag concrete. Moreover, the comparison with related literature shows that EAF slag performs with a unique behaviour compared to other alternative materials which generally hinders both the compressive and tensile strengths of concrete.

KEYWORDS: concrete; electric arc furnace slag; recycle aggregates; durability; mechanical properties; circularity in the economy

Open Access

Received: 21 October 2024
Accepted: 28 February 2025
Published: 4 March 2025

INTRODUCTION

Concrete is the pillar of civil engineering projects and is known to be the most widely used construction material [1,2]. However, crucial environmental impacts have emanated from concrete production. These impacts are associated with significantly high carbon emissions, resource depletion, and waste generation. These are the severe sustainability issues that have arisen from the use of electric arc furnace slag. The environmental impacts of concrete construction and manufacturing are widespread and demand attention. Through the use of innovative technologies and the adoption of sustainable practices, the concrete industry could become more environmentally friendly [3,4]. As the world strives to find more sustainable solutions for concrete production construction, it is crucial to examine the environmental impacts of concrete construction and manufacturing and explore potential methods for mitigating these issues [5–7].

One of the sustainable practices adopted in concrete production is the replacement of natural aggregates with industrial by-products. One common industrial by-product is electric arc furnace slag. Electric arc furnace slag is an industrial by-product generated from the steel-making process. In Trinidad and Tobago, electric arc furnace slag aggregates have been generated in vast quantities [8]. These waste materials have been stored in stockpiles at a recently decommissioned steel production facility. Being industrial by-products, their constituents can induce chemical reactions when it comes into contact with moisture. These chemical reactions can be detrimental to nearby soil and water. Environmental sustainability becomes critically compromised if these stockpiles are not utilised in the medium term. Importantly, the geographic location of this Caribbean Small Island Developing State, together with microeconomic conditions in the construction sector, makes the cost of importing raw materials expensive, and unsustainable [9]. By using these materials in different local applications, environmental sustainability could be fostered.

The purpose of this research is to deduce the properties of concrete manufactured with electric arc furnace steel slag as fine aggregates produced by the Arcelor Mittal Steel Mill in Trinidad.

The objectives of the study are to:

1) Determine the fresh properties of concrete
2) Deduce the 7-day and 28-day compressive strength and splitting tensile strength using electric arc furnace slag as fine aggregates

Being an industrial by-product, the utilization of electric arc furnace slag as aggregates in concrete could be a viable alternative to natural aggregates in concrete production. This industrial product promotes recycling and reduces the need for the extraction of natural aggregates. This study provides insights into the quantification of the strength of concrete containing electric arc furnace slag as a fine aggregate replacement in concrete production. The effects of the percentage replacement of electric arc furnace slag as fine aggregates in the concrete mixture on its workability, compressive strength, and splitting tensile strength are determined. Additionally, a comparative study on the effectiveness of EAF slag over other types of replacement aggregates used and the applicability of standard codes of practice for EAF slag concrete are deduced.

LITERATURE REVIEW

Many studies have been conducted to evaluate the properties of concrete when manufactured with electric arc furnace slag [10]. Different types of recycled aggregates have been used and the effective use of industrial by-products in concrete production has happened for several decades [11–13]. This conserves the environment and landfill space. The demand for the extraction of natural resources could also be minimized, thereby promoting sustainable development on a global basis [7,14,15]. Some industrial by-products have good capabilities as building materials, implying the potential to be utilized in concrete production not just to conserve resources but also to enhance the mechanical properties and durability of concrete.

In general, researchers have made attempts to analyse the components of coarse aggregate, fine aggregate and cement by replacing them with various types of recycled aggregates or industrial by-products. Ganesan et al. [16] have evaluated the mechanical and durability performance of marine sand as a fine aggregate replacement for manufactured sand in concrete. Their findings indicated that all the compressive, split tensile, flexural as well as durability properties enhanced up to 60% replacement percentage, finally concluding it as the recommended replacement fraction for marine sand. On the other hand, Ullah et al. [17] have analyzed the mechanical and durability characteristics of fine aggregate partially replaced concrete using electronic plastic waste. The findings revealed that the incorporation of electronic plastic waste dropped both compressive and splitting tensile strength. However, it performed interestingly well under workability and durability aspects allowing the application where durability is of main concern.

In addition to above mentioned materials, electric arc furnace (EAF) slag has also proven to have possible applications in concrete production. EAF slag is a by-product of steel extraction produced through electric arc furnaces which accounts for more than 40% of global steel production [18]. These wastes end up in open air dump sites resulting in severe environmental issues questioning the sustainable development aspects. Hence, the importance of analyzing the feasibility of utilizing EAF slag in concrete production could be further highlighted.

Abu-Eishah et al. [18] varied the percentage of coarse EAF slag aggregates with 10 mm natural crushed stone and two types of fine sand: 5 mm sand, and dune sand. It was found that EAF steel slag needs to be crushed under controlled conditions to generate suitable grading and required maximum size to maximize the amount to be used in the mixture. It was concluded that EAF steel slag produced high-strength concrete compared to similar conventional concrete mixtures. The results of the tests on water permeability and water absorption show low values for most of the combinations, which indicates that they have good durability performance. However, the addition of supplementary cementing materials (SCM) such as fly ash and silica fume can vastly reduce water absorption and increase durability [18].

Roslan et al. [19] changed the percentage of EAF slag and steel sludge used as a cement replacement from 5% to 20%, with a controlled amount of oven-dried fine and coarse aggregates. It was found that the increased use of EAF as a replacement in concrete resulted in a deterioration in the material's workability, which supports the findings of Pellegrino et al. [20]. However, the strength of the concrete was not affected by replacements of up to 10% while concrete containing steel sludge improved water tightness and performed better than concrete containing steel slag [19].

MATERIALS AND METHODS

Materials and Specimen Sample Preparation

Ordinary Portland Cement (OPC), limestone aggregates as natural aggregates, and EAF slag as partial fine aggregate replacement were used in this study. The EAF slag was reduced to standard aggregate sizes using appropriate crushing procedures. Fine and coarse natural aggregates, blended fine EAF slag, and stockpile EAF slag were sieved. All samples were obtained with riffle boxes (refer to Figure 1) to appropriately depict aggregate source piles. The sieve analysis was conducted in accordance with ASTM-C33.

Figure 1. Sampling aggregates using riffle box.

Figure 2 illustrates the particle size distribution for coarse and fine natural aggregates and EAF slag aggregates. It is highlighted that the EAF Slag was graded within the recommended fine aggregate size, making it appropriate as a fine aggregate substitute in mix designs. It further shows that EAF Slag collected directly from the stockpile is distributed between the coarse and fine natural aggregate distributions.

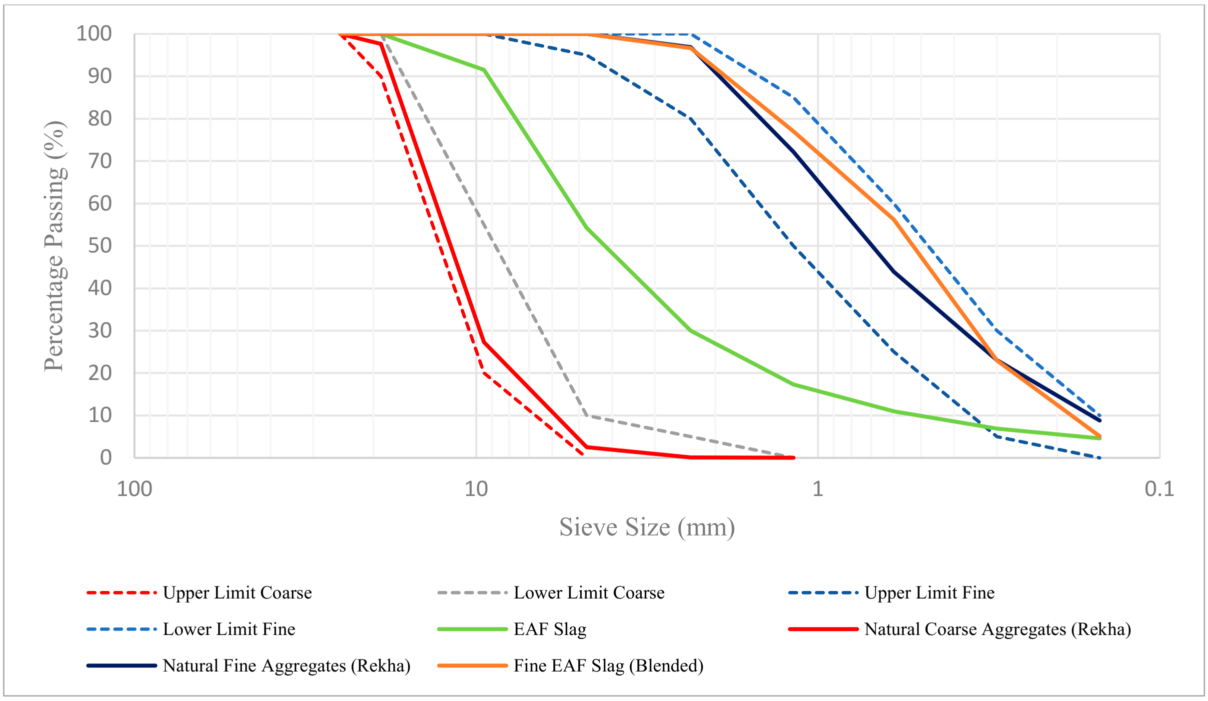


Figure 2. Particle size distribution of coarse and fine natural aggregates and electric arc furnace slag.

Determination of the Specidic Gravity, Water Absorption and Aggregate Density Tests

Specific gravity tests

Specific gravity, water absorption, and aggregate density tests were conducted based on ASTM C127-12. The coarse aggregates were cleaned and rinsed to remove any particles and contaminants before being weighed at 2500 g. The samples were soaked in water for 24 hours before being surface dried with a towel. The weight of surface dried samples was measured (B). The samples were then weighed while submerged in water, as the saturated weight (C). The samples were then dried in an oven at 120 ℃ for 24 hours until bone dry. The samples were then reweighed, as the bone dry mass (A).

The fine aggregates were surface wet by hand by progressively adding water to the sample, and a slump test was done to evaluate whether the aggregates were sufficiently wet to be deemed surface wet. When the slump is able to sustain a peak as the slump cone is removed, the sample is deemed as surface moist, as shown in Figure 3.

Figure 3. Slump test to determine if surface wet was achieved.

After passing the slump test, 500 g of aggregates were weighed (B). The sample was then immersed in water in a bottle that had been filled to the brim with water, capped, and weighed. The saturated weight of the aggregates (C) was calculated by subtracting the weight of the bottle, water, cap, and aggregate from the weight of the bottle, water, cap, and aggregate. The sample was then oven-dried overnight at a constant temperature of 120 °C, and the oven-dried weight (A) was measured. The corresponding equations for calculations are listed from equation (1) to (5).

$$\mathrm{SG(OD)} = {}^{A}\!/_{(B-C)} \tag{1}$$

$$\mathrm{SG(SSD)} = {}^{B}\!/_{(B-C)} \tag{2}$$

$$\mathrm{SG(ARD)} = {}^{A}\!/_{(A-C)} \tag{3}$$

$$\text{Water Absorption Percentage, Water Absorption (\%)} = \left(\frac{B-A}{A}\right) \times 100\% \tag{4}$$

$$\text{Density (OD) (kg/m}^3) = 997.5 \times \left(\frac{A}{B-C}\right) \tag{5}$$

Where,
Specific Gravity (OD) = Specific Gravity on the Basis of Oven Dry Aggregate;
Specific Gravity (SSD) = Specific Gravity on the Basis of Saturated Surface Dry Aggregate;
Apparent Specific Gravity (ARD) = Apparent Relative Density;
Density (OD) = Density on the basis of oven-dry aggregates;
A = Mass of oven-dry test sample in air (g);
B = Mass of saturated-surface-dry test sample in air (g);
C = Apparent mass of saturated test sample in water (g).

Table 1. Specific Gravity, water absorption and density of aggregates.

Item	Coarse Natural Aggregates (NA)	Coarse EAF Slag	Fine Natural Aggregates (NA)	Fine EAF Slag
Oven Dry Weight, A (g)	2490	2469	496	473
Surface Dry Weight, B (g)	2531	2563	500	500
Saturated Weight, C (g)	1547	1789	308	325
Specific Gravity (OD)	2.53	3.19	2.58	2.70
Specific Gravity (SSD)	2.57	3.31	2.60	2.86
Specific Gravity (ARD)	2.64	3.63	2.63	3.19
Water Absorption (%)	1.65	3.80	0.81	5.71
Density (OD) (kg/m^3)	2531.44	3190.32	2577.02	2701.16

From Table 1, it is evident that the specific gravity values of coarse and fine electric arc furnace slag aggregates are higher than those of natural aggregates. Moreover, it shows that the electric arc furnace slag has much higher water absorption than natural aggregates, with fine EAF slag having the maximum absorption percentage.

Sample preparation

The experiments were carried out using four (4) mix designs as shown below. The slag levels were controlled to investigate their properties on concrete.

1) M1: Controlled mix design with 0% EAF Slag (100% Natural Aggregates)
2) M2: EAF Slag (blended) replacing 10% Fine Aggregates
3) M3: EAF Slag (blended) replacing 15% Fine Aggregates
4) M4: EAF Slag (blended) replacing 20% Fine Aggregates

The percentage of electric arc furnace slag utilized in the concrete mixtures was selected based on physical constraints (accessibility) within the timeframe of the research. This is because the EAF slag was being sourced from the Decommissioned Steel Facility in Trinidad. This selection enabled preliminary testing to be conducted in order to evaluate how the strength of the concrete changed as the percentage of the EAF slag aggregates in the concrete increased by these specified amounts.

Three specimens were used for each test for each concrete mix design (1–4) for 7-day and 28-day compressive and splitting tensile strength tests. Cubes were utilized for compressive testing, and cylinders were used for tension testing. Grade 40 concrete mix design with a water to cement ratio of 0.4 was developed using the American Concrete Institute's (ACI) 211.1-91 standard. This mix design served as the foundation for the development of four different mix designs (known as Mixes 1–4), each with a different percentage of EAF slag as a partial replacement for fine aggregates. This base mix design was used to calculate the mass of cement, water, fine aggregates, and coarse aggregates for each of the four mix designs as given in Table 2.

Table 2. Proportions for each mix design.

Mix Design	Water Content (W/C)	Water (kg)	Cement (kg)	Fine Aggregate (kg)		Coarse Aggregate (kg)
				NA	EAF Slag	NA
M1	0.4	4.715	11.788	13.88	0	23.55
M2	0.4	4.715	11.788	10.14	3.74	23.55
M3	0.4	4.715	11.788	9.02	4.86	23.55
M4	0.4	4.715	11.788	7.39	6.49	23.55

First, coarse aggregates were placed in the drum mixture, then the cement, and finally the fine aggregates. This mixture was dry blended for 15 seconds before adding water. It was then blended for a total of 1 minute before the slump test was performed. The mixture was then split into moulds and vibrated for 1 minute on the vibration table to settle the concrete and expel air voids. After allowing the specimens to cure overnight, they were removed and placed in a water bath to cure at 20 °C for 7 and 28 days.

Mechanical Strength

The mechanical properties of the concrete mixes were evaluated by determining the compressive and splitting tensile strengths of the specimens.

Compressive strength test

After curing for 7 and 28 days, the compressive test was performed on three cube specimens from each design mix in accordance with American Society for Testing and Materials (ASTM) C39/C39M. Each specimen was weighed then tested. The maximum strength of the specimens was measured, and the average of the three samples was calculated.

Splitting tensile strength test

After curing for 7 and 28 days, the splitting tensile test was performed on three cylindrical specimens from each design mix in accordance with the ASTM C496 uniaxial splitting test. Each specimen was weighed and then tested. The maximum strength of the specimens was measured, and the average of the three samples was calculated.

RESULTS AND DISCUSSION

Fresh Properties

Figure 4 indicates that there is a significant decrease in the slump height as the EAF slag content increases. The slump measured for M1 having 0% EAF slag was 420 mm, while the slump measured for the slag-containing mixtures was less than 100 mm resulting zero slump value in M4. This decline in the height of the slump is consistent with the findings of Faleschini et al. [21]. It can be further explained using the water absorption values calculated in Table 1 which shows a clear rise in water absorption of EAF slag compared to natural aggregates, leaving less amount of water in the mix ultimately decreasing the water content leading to a low slump value. Moreover, the decrease in workability is justified as EAF slag is more porous than natural aggregates and hence, can reduce the workability of the concrete mixture by reducing its fluidity and making it more difficult to handle.

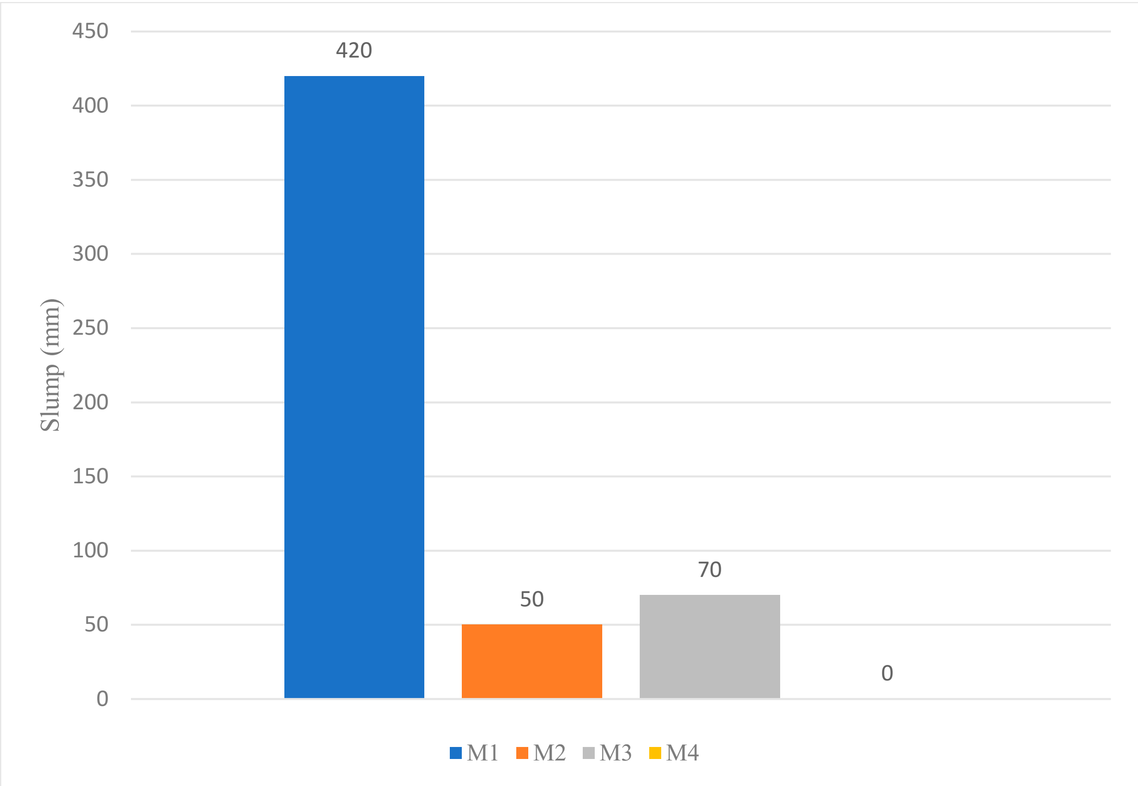


Figure 4. Variation of workability for each mix.

Mechanical Properties

Each mix design (0%, 10%, 15%, and 20%) consists of THREE samples, and the values of the Average Compressive Strength with the corresponding standard deviation and coefficient of variation values deduced after 28 days and the tensile strength values are recorded in Table 3.

Table 3. Compressive strength (MPa) and tensile strength (MPa) value of each of the mixes.

Mix 1 (0% electric arc furnace slag)			
Sample	**Maximum Compressive Strength (MPa)**		
	28 Day Test	**Wetting/Drying**	**Strength Loss**
1	28.209	37.869	
2	53.452	33.113	
3	31.116	32.985	
Average	37.592	34.656	−2.937
Standard Deviation: 1.381			
Coefficient of Variation: 0.035			
Mix 2 (10% electric arc furnace slag)			
Sample	**Maximum Compressive Strength (MPa)**		
	28 Day Test	**Wetting/Drying**	**Strength Loss**
1	35.001	25.211	
2	23.914	26.544	
3	25.952	36.353	
Average	28.289	29.369	1.080
Standard Deviation: 5.900			
Coefficient of Variation: 0.210			
Mix 3 (15% electric arc furnace slag)			
Sample	Maximum Compressive Strength (MPa)		
	28 Day Test	Wetting/Drying	**Strength Loss**
1	33.070	31.961	
2	30.710	30.617	
3	29.816	33.248	
Average	31.199	31.942	0.743
Standard Deviation: 1.680			
Coefficient of Variation: 0.054			
Mix 4 (20% electric arc furnace slag)			
Sample	**Maximum Compressive Strength (MPa)**		
	28 Day Test	**Wetting/Drying**	**Strength Loss**
1	39.711	39.764	
2	39.729	45.295	
3	41.740	43.115	
Average	40.393	42.725	2.331
Standard Deviation: 1.170			
Coefficient of Variation: 0.029			

Figure 5 illustrates the variation of the Compressive Strength of the samples. It can be deduced that the Compressive Strength of the sample containing 20% EAF slag had the highest Compressive Strength values and maintained this constant value during the testing.

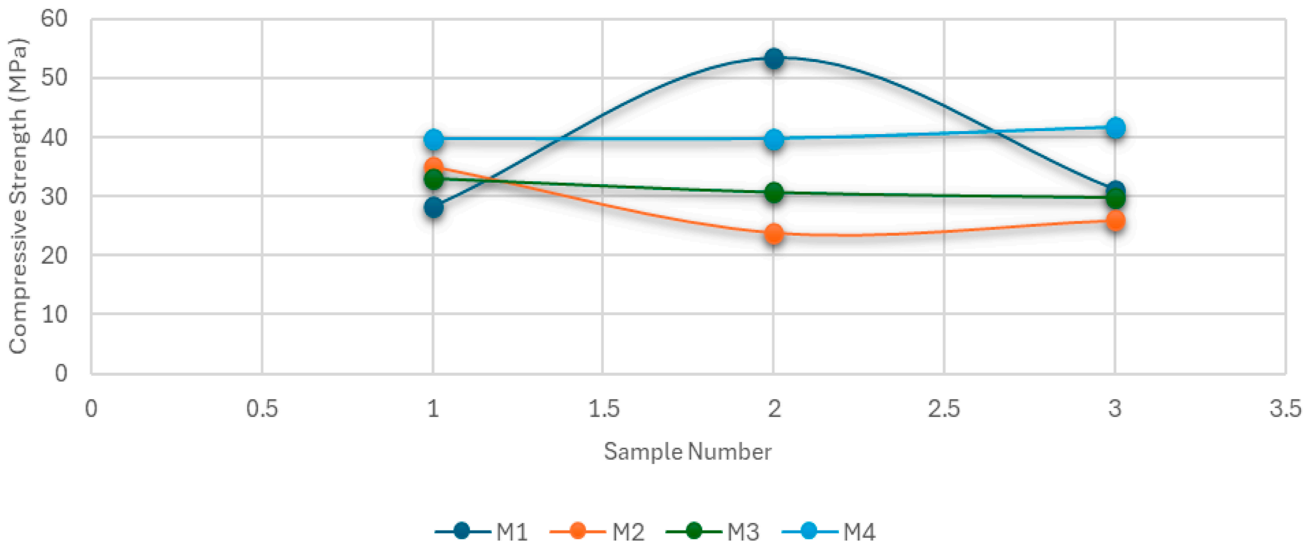


Figure 5. Compressive strength value with sample number.

A high workability reduces the strength of the concrete [22]. This is evident from Figure 4 and Figure 5, respectively. The value of zero slump height indicates that the mixture is not workable.

The compressive strength is reduced for the 10% and the 15% for the fine electric arc furnace slag content but increases for the 20% fine electric arc furnace slag content. This could be attributed to the particle packing of the fine aggregates and the coarse aggregates. The microstructure of the concrete can change with different slag contents. At 10% and 15%, the slag might introduce more voids or micro-cracks, reducing strength. At 20%, the slag could help refine the pore structure, reducing porosity and increasing strength.

Figure 6 illustrates a decrease in the compressive strength value with a slag content of 10% and an increase in the slag content from 10% and 20%. This could be attributed to the low reactivity of the slag during the early strength curing process of the concrete [20].

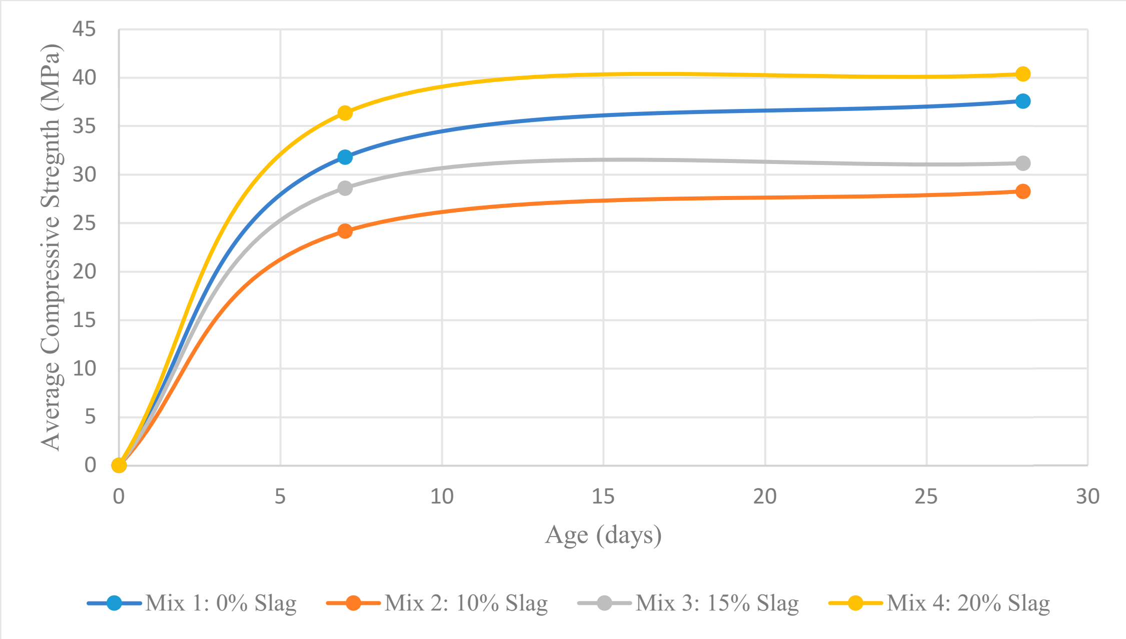
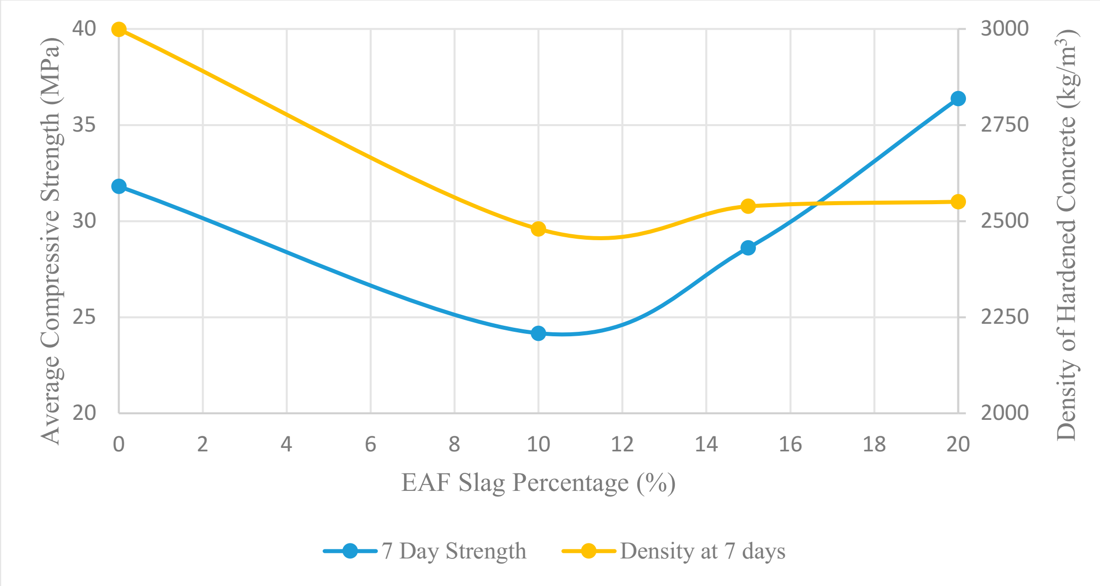


Figure 6. Average compressive strength variation with time.

As seen in Figure 5 and Figure 6, the compressive strength of M2 (10% electric arc furnace slag) and M3 (15% electric arc furnace slag) was less than that of the control M1 (0% electric arc furnace slag). However, the compressive strength of M4 (20% electric arc furnace slag) was greater than M1. This trend was consistent in both the 7-day and 28-day tests. A similar behaviour was noted by Subathra Devi and Gnanavel [23] where the 40% steel slag replacement surpassed the compressive strength of the control mix. Comparing the mixes that contained EAF slag, it can be inferred that the compressive strength increased when the electric arc furnace slag content increased to 20%. The percentage of the electric arc furnace slag for this mix design that will match the compressive strength of the controlled mix lies between 15% and 20%.

Figure 7a and Figure 7b compare the compressive strength with the density of hardened concrete at 7 days and 28 days respectively which overall show an identical trend. The only outlier is the density of M4 (20% electric arc furnace slag) being lower than that of M1 (0% electric arc furnace slag) at 7 days, while the compressive strength of M4 is higher than that of M1 at both ages. This supports the findings of Iffat [24] as it suggests, that hardened density can be an indicator of compressive strength. The density of the aggregates influences the hardened density of the concrete, whereas EAF slag has a higher density than natural aggregates. Denser aggregates have a smaller volume and are made up of particles that are more closely packed together, resulting in a higher packing density. This could happen as there is less space between the particles and fewer voids in the hardened concrete. This reduction in voids can result in a more compact and stronger concrete structure since, fewer air gaps in the concrete allow for more effective load transfer through the hardened concrete matrix, hence increasing compressive strength. Reduced air gaps minimize the chance for moisture to enter the concrete structure, weakening the bond between the cement paste and the aggregates. Due to these reasons, the EAF slag concrete performed better in compression compared to traditional concrete.

(a)



(b)

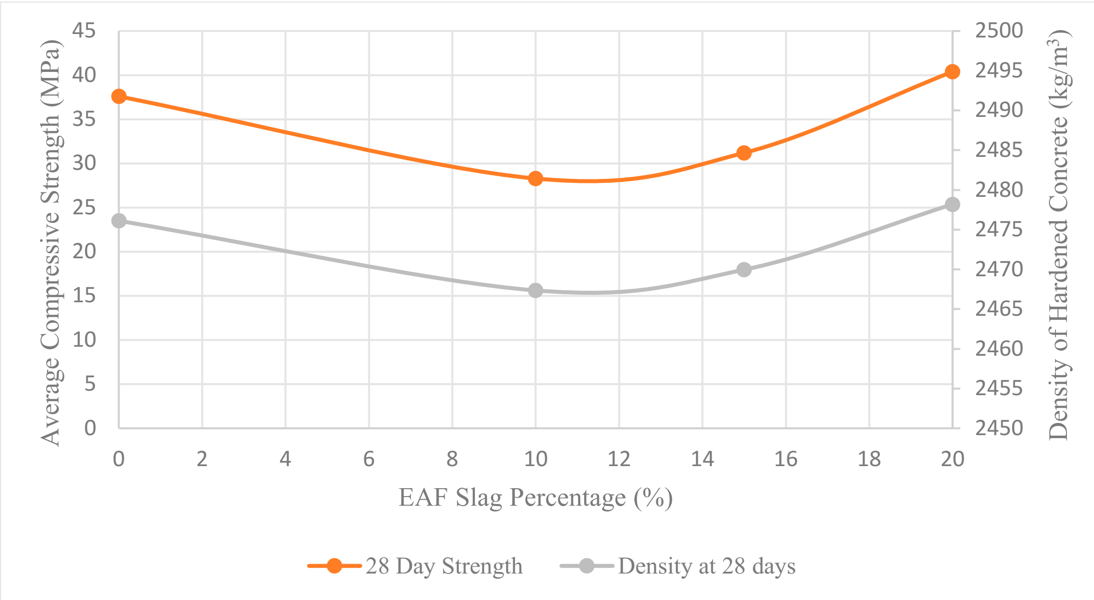


Figure 7. Comparison of average compressive strength and density at; (**a**) 7 days and (**b**) 28 days.

Figure 8 displays a comparison of the compressive strength before and after 25 wetting/drying cycles along with the percentage strength loss. It is noted that the compressive strength of the mixes after the 25 wetting/drying cycles followed a similar trend with respect to the EAF slag percentage as the 28-day compressive strength. After the 25-day wetting/drying cycles, it was found that the compressive strength of M1 decreased from 37.6 MPa to 34.7 MPa, while the same increased between 0.7 MPa to 2.4 MPa for M2 to M4 which contained EAF slag. This implies that EAF slag can improve the durability of concrete when subjected to weathering compared to natural aggregates.

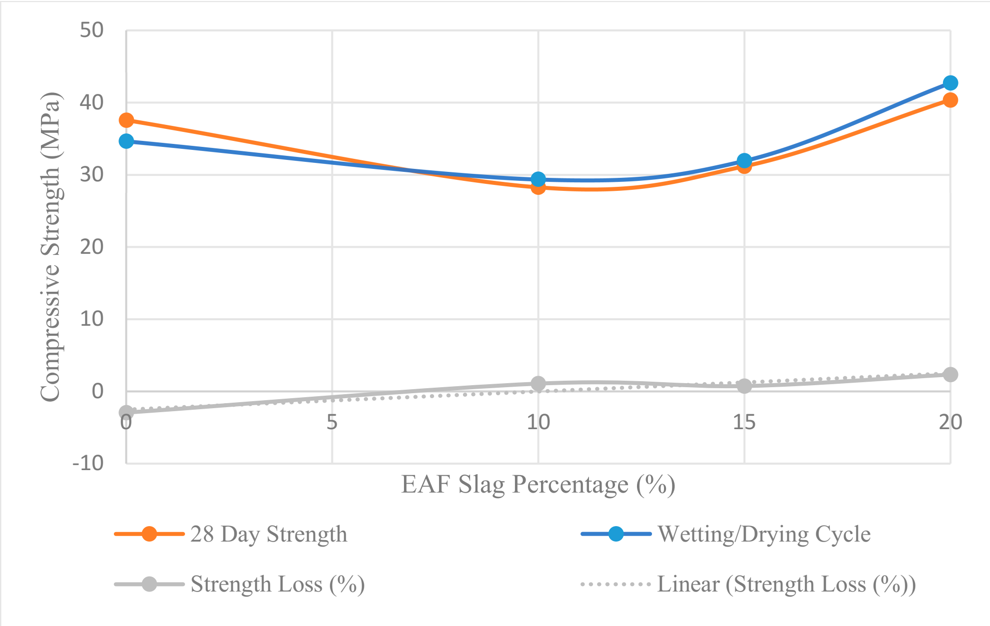


Figure 8. Average compressive strength variation before and after wetting/drying cycles.

However, this contradicts the findings of Pellegrino et al. [20], in which a decrease in compressive strength was reported. The compressive strength of concrete is unlikely to exhibit an increase subsequent to wetting/drying cycles. This is attributed to the formation of internal cracking within the concrete matrix, which is caused by the constant expansion and contraction of the material. This increases the number of air voids, which is furthered by the absorption of water in the concrete specimen and decreases the density of the concrete. The results of this study indicated that the addition of EAF slag will not only increase the durability of concrete under simulated weather but interestingly can improve the compressive strength of the concrete past the 28-day curing period while undergoing rapid aging. The present study proposes extending the wetting/drying phase to a cycle length of 50–100 days which may yield more precise outcomes and thus warrants further exploration.

As illustrated in Figure 9, the splitting tensile strength of concrete consistently decreased at 7 days and 28 days as the percentage of EAF slag increased. This finding is not in agreement with the work done by Pellegrino et al. [20], Maharaj et al. [8], and Faleschini et al. [21], in which EAF slag increased the tensile strength, while Rondi et al. [25] found that the EAF slag did not have a significant effect on the tensile strength of concrete. This decrease in the tensile strength may be attributed to the angular shape of EAF slag which created a weak contact zone between the cement paste and the aggregate [24].

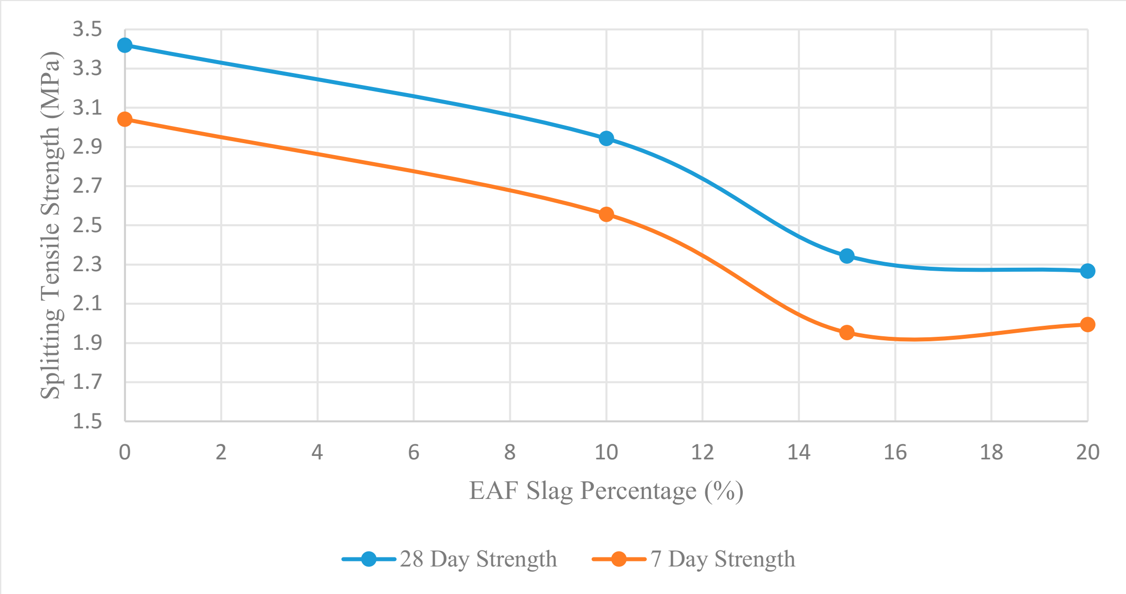


Figure 9. Variation of splitting tensile strength with EAF slag percentage.

Figure 10 shows a decrease in the volume of aggregates as the proportion of EAF slag increases in each mixture. The reason behind this decrease in volume is the mass-based mix design approach used in the study. Since electric arc furnace slag has a higher density than natural aggregates, the same mass of slag occupies a smaller volume. Therefore, the total volume of aggregates decreases as the percentage of electric arc furnace slag replacement increases. This decrease in aggregate volume has a direct impact on the tensile strength of the concrete as highlighted by Neville [26], where it decreases with increasing EAF slag content. By comparing Figure 5 and Figure 9, it can be deduced that as the Compressive Strength increased; the Tensile Strength decreased with an increase in the percentage of the fine electric arc furnace slag aggregate. This variation could be attributed to a number of different characteristics of the concrete mixture. According to Pellegrino et al [27]; these characteristics are the:

- Particle shape and texture in which the angularity enhance the bonding within the concrete matrix, leading to higher compressive strength. However, this same rough texture can create stress concentrations and micro-cracks under tensile loads, reducing tensile strength
- Chemical Composition: The presence of certain oxides in the EAF slag could incur chemical reactions which may benefit the compressive properties but not the tensile properties of the concrete.

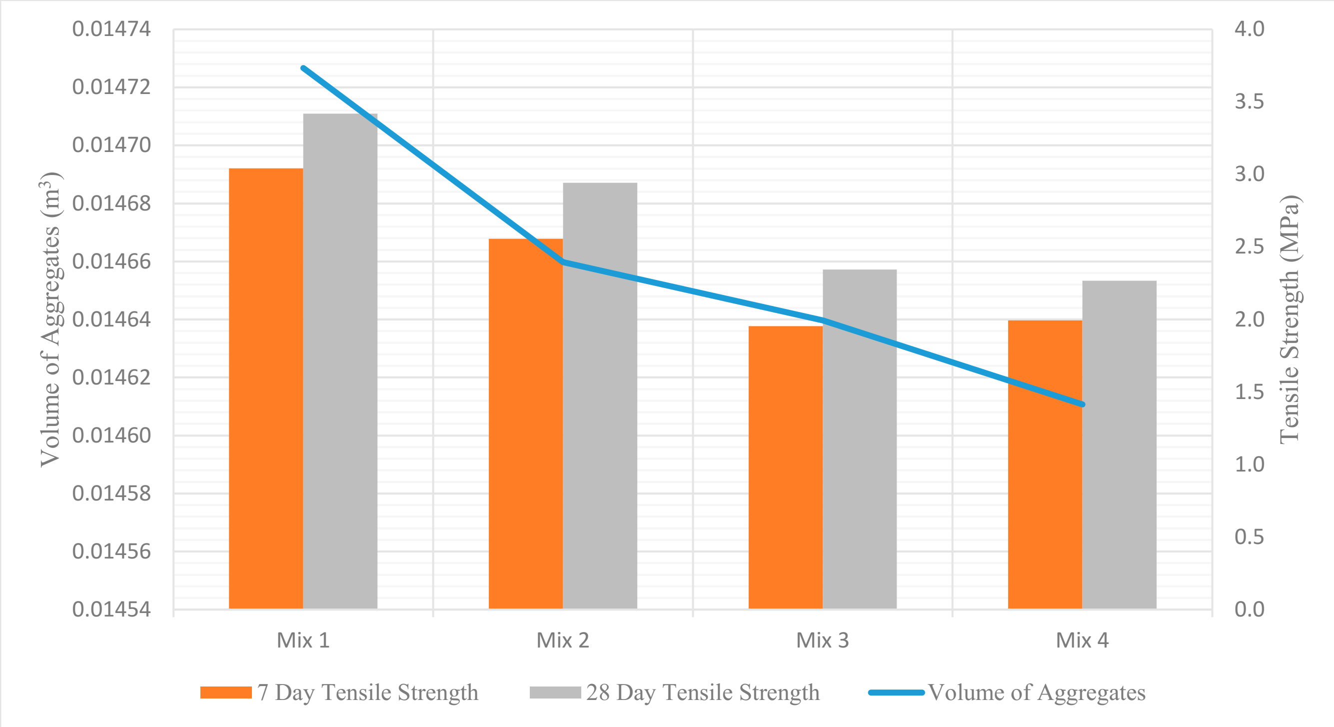


Figure 10. Comparison between volume of aggregates and tensile strength.

Comparison of Results with Related Previous Work

This sub-section compares the influence of EAF slag concrete on its mechanical properties relative to several other studies (refer to Table 4) that have used different alternative materials to replace different components in the concrete mix. 28-day compressive and splitting tensile strengths were extracted and the ratio to the corresponding control sample was calculated for the comparison where the plotted results are displayed in Figure 11.

Limitation in Study

Due to limitation of resources in funding, the chemical composition of the electric arc furnace slag was not tested. This is the main limitation in this study.

Table 4. Details of related previous work considered.

Reference	Alternative material used	Replaced material	Replaced amount	28-day compressive strength (MPa)	Ratio to control sample	28-day splitting tensile strength (MPa)	Ratio to control sample
This study	Electric Arc Furnace Slag (EAF-FA)	Fine aggregate	0%	37.59	1.00	3.42	1.00
			10%	28.29	0.75	2.94	0.86
			15%	31.20	0.83	2.34	0.69
			20%	40.39	1.07	2.27	0.66

Table 4. *Cont.*

Reference	Alternative material used	Replaced material	Replaced amount	28-day compressive strength (MPa)	Ratio to control sample	28-day splitting tensile strength (MPa)	Ratio to control sample
Subathra Devi and Gnanavel [23]	Steel Slag (SS)	Fine aggregate	0%	20.67	1.00	2.26	1.00
			10%	19.56	0.95	-	-
			20%	20.10	0.97	-	-
			30%	21.78	1.05	-	-
			40%	28.30	1.37	2.47	1.09
			50%	19.32	0.93	-	-
Tamayo et al. [28]	Electric Arc Furnace Slag (EAF-CA)	Coarse aggregate	0%	52.50	1.00	3.25	1.00
			20%	51.00	0.97	3.30	1.02
			50%	52.00	0.99	3.45	1.06
			100%	50.50	0.96	3.20	0.98
Liu et al. [29]	Crumb Rubber (CR)	Fine aggregate	0%	34.76	1.00	2.35	1.00
			5%	34.52	0.99	2.33	0.99
			10%	34.19	0.98	2.32	0.99
			15%	33.82	0.97	2.31	0.98
			20%	33.41	0.96	2.29	0.97
Kim and Lee [30]	Coal Bottom Ash (CBA)	Fine aggregate	0%	75.00	1.00	-	-
			25%	62.00	0.83	-	-
			50%	70.00	0.93	-	-
			75%	71.00	0.95	-	-
			100%	72.00	0.96	-	-
Hirashkar and Patil [31]	Blast Furnace Slag (BFS)	Coarse aggregate	0%	39.40	1.00	4.18	1.00
			50%	38.70	0.98	3.93	0.94
			75%	33.40	0.85	3.14	0.75
			100%	38.70	0.98	3.25	0.78
Kou et al. [32]	Fly Ash (FA)	Cement	0%	48.60	1.00	3.32	1.00
			25%	43.60	0.90	3.28	0.99
			35%	40.70	0.84	2.90	0.87

Figure 11a shows the variation of compressive strength ratio with respect to the replaced fraction of recycled aggregate according to different studies using different alternative materials as specified in Table 4. In general, the replacement of alternative materials has resulted in a decline in the compressive strength of the concrete except for the unique behaviour in EAF-FA (Present study) and SS. EAF-FA shows a drastic drop in compressive strength up to 10% replacement and then follows with a dramatic rise, ending up with a 7.5% compressive strength increment at a replacement fraction of 20%. This could be due to the increase in hardened density of the concrete mix as a result of high-density EAF slag replacement.

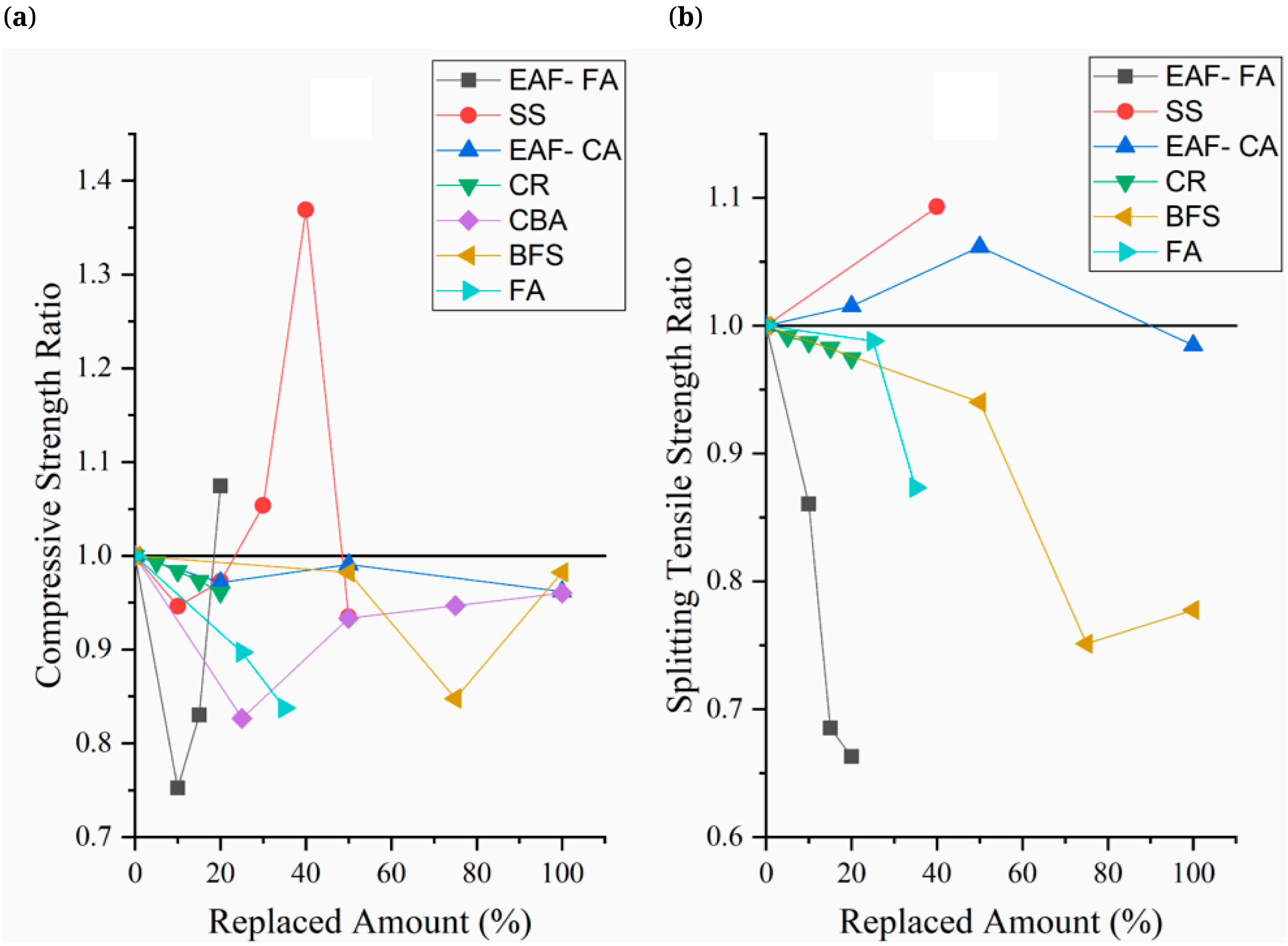


Figure 11. Influence of different materials to the 28-day; (**a**) compressive strength and (**b**) splitting tensile strength of concrete.

Figure 11b depicts the comparison of the splitting tensile strength ratio versus the percentage of aggregate replacement extracted from several previous studies. Overall, similar to the compressive strength, the splitting tensile strength of the concrete mix displays a decrease regardless of the alternative material used for the replacement. However, the concrete with replaced coarse aggregate using EAF slag (EAF-CA) shows a smooth fluctuation, ending up at almost the same splitting tensile strength of the controlled sample at a 100% replacement ratio. Due to this behaviour, Tamayo et al. [28] have concluded that EAF slag performs very similarly to natural aggregate concrete at any replacement percentage which confirms the use of EAF slag as a replacement for coarse aggregate with minimum compensation on the tensile strength [8].

Comparison of Results with Standard Design Code Predictions

Standard design codes that are in practice provide guidance to predict the mechanical properties of normal concrete. However, the absence of such standard for EAF slag concrete is identified and hence, this sub-section evaluates the applicability of the standards developed for normal concrete into the context of EAF slag concrete. Design standards from ACI, Eurocode, and Australian standards were considered for the study where the corresponding splitting tensile predictions were calculated using the equations listed in Table 5. Calculated design code predictions for splitting tensile strength were compared by calculating the corresponding ratio between the experimental and the standard prediction as given in Table 6 and Figure 12.

Table 5. Standard predictions specified in codes of practice for splitting tensile strength of normal concrete.

Design Code	Splitting Tensile Strength (MPa)
ACI 318 [29]	$f_{ctm,sp} = 0.556\ (f_c)^{1/2}$
EC 2 [30]	$f_{ctm,sp} = 0.330\ (f_c)^{2/3}$
AS 3600 [31]	$f_{ctm,sp} = 0.560\ (f_c)^{1/2}$

Note: $f_{ctm,sp}$—Splitting Tensile Strength; f_c—Compressive Strength.

Table 6. Calculated values of standard predictions and ratio to experimental.

Splitting Tensile Strength (MPa)							
7-day							
Mix Design	**Experimental**	**ACI 318**	**Ratio to experimental**	**EC 2**	**Ratio to experimental**	**AS 3600**	**Ratio to experimental**
M1	3.042	3.136	0.970	3.313	0.918	3.158	0.963
M2	2.557	2.733	0.936	2.758	0.927	2.753	0.929
M3	1.953	2.974	0.657	3.087	0.633	2.996	0.652
M4	1.993	3.353	0.594	3.623	0.550	3.377	0.590
28-day							
Mix Design	**Experimental**	**ACI 318**	**Ratio to experimental**	**EC 2**	**Ratio to experimental**	**AS 3600**	**Ratio to experimental**
M1	3.420	3.409	1.003	3.703	0.924	3.433	0.996
M2	2.943	2.957	0.995	3.064	0.961	2.978	0.988
M3	2.344	3.106	0.755	3.270	0.717	3.128	0.749
M4	2.267	3.534	0.642	3.885	0.584	3.559	0.637

Figure 12a shows the variation of the ratio between the experimental to predicted 7-day splitting tensile strength for each design code considered. Overall, the results depict that, all three design codes overestimate the 7-day splitting tensile strength at any amount of EAF slag replacement up to 20%. ACI 318 and AS 3600 display a very similar prediction pattern whereas EC 2 always provides a greater overprediction compared to the other two codes. The maximum overestimate for the considered range of replacement percentage was recorded around 85% at 20% replacement in EC 2. However, no clear linear trendline is visible according to the variation plotted.

According to Sosa et al. [33], an insight into the discrepancy encountered by the overestimation of the tensile strength by the design codes could be due to increased research and data collection. This collection of data on the performance of EAF slag concrete can help refine design codes to better reflect its properties [33].

Figure 12b depicts the variation of the ratio between the experimental to predicted 28-day splitting tensile strength and also displays a similar pattern to Figure 12a. It is highlighted that ACI 318 and AS 3600 predict the 28-day splitting tensile strength with very high accuracy within the replaced amount range of 0% to 10% providing almost the exact experimental value. However, a clear linear trendline could not be seen in the 28-day splitting tensile strength ratio as well.

(a) **(b)**

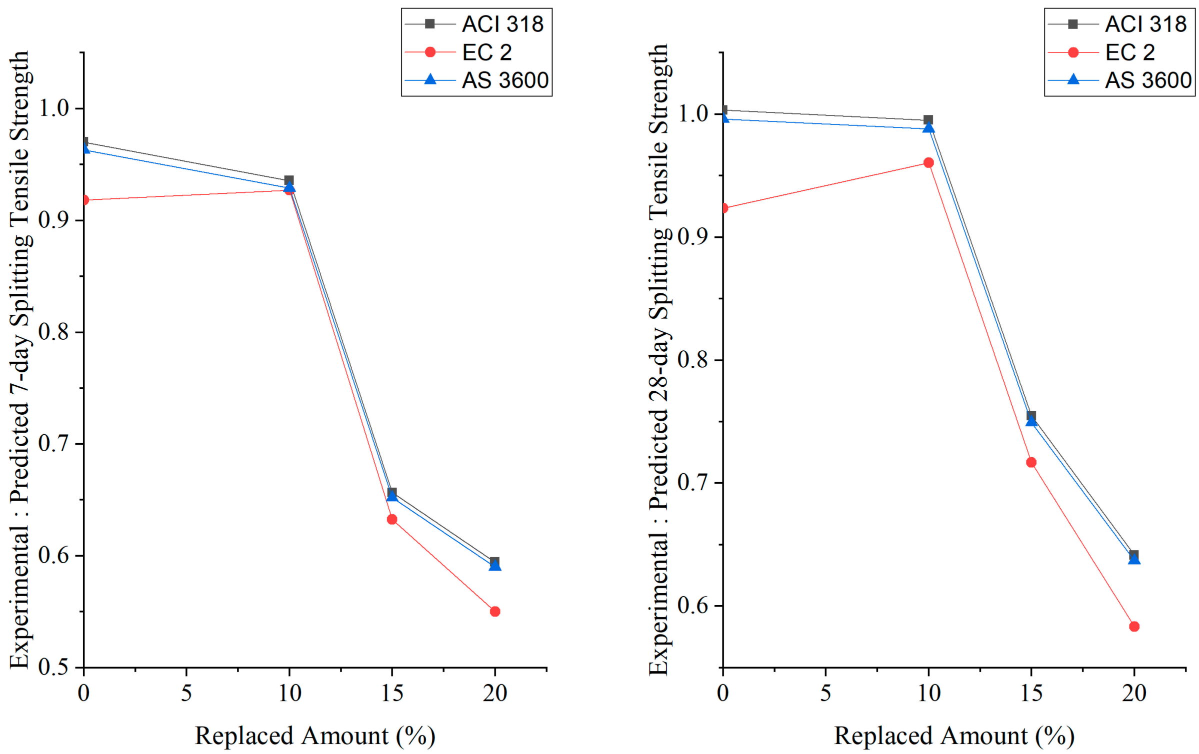


Figure 12. Variation of splitting tensile strength ratio at; **(a)** 7-day and **(b)** 28-day under different design codes.

CONCLUSIONS

Using four mix designs with varying percentages of EAF slag (0%, 10%, 15%, and 20%) as fine aggregates; the fresh and hardened properties of concrete, including workability, compressive strength, and splitting tensile strength were evaluated. The findings of the study indicate a significant decrease in the workability of concrete-manufactured EAF slag aggregates. Additionally, the results show a decrease in the compressive strength values compared to the control mix for concrete mixes containing 10% and 15% EAF slag of fine aggregates, but an increase in the compressive strength at 20% replacement. However, a steady decrease in the tensile strength value for all percentages of EAF slag replacement is noted. It is also concluded that, all ACI 318, EC 2, and AS 3600 standard design codes for normal concrete overestimate the 7-day and 28-day splitting tensile strengths of EAF slag concrete. Moreover, the comparison with related literature shows, that EAF slag performs with a unique behaviour compared to other alternative materials which generally hinders both the compressive and tensile strengths of concrete. Overall, EAF slag performed reasonably well under mechanical properties as a partial fine aggregate replacement and shows a strong potential to be utilized in the production of sustainable concrete, ultimately easing the overburdened demand for natural aggregates.

DATA AVAILABILITY

Data used in this paper are available on request for research purposes.

AUTHOR CONTRIBUTIONS

Conceptualization, AC and ER; Methodology, DM; Software, DM; Validation, AC, ER and SM; Formal Analysis, DM and YR; Investigation, DM; Resources, HMA; Data Curation, DM; Writing—Original Draft Preparation, AC, YR, and SM; Writing—Review & Editing, HMA and UR; Visualization, ER and DJM.; Supervision, AC and ER; Project Administration, UR; Funding Acquisition, UR.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

REFERENCES

1. Meddage D, Chadee A, Jayasinghe M, Rathnayake U. Exploring the applicability of expanded polystyrene (EPS) based concrete panels as roof slab insulation in the tropics. Case Stud Constr Mater. 2022;17:e01361.
2. Kim T, Chae C, Kim G, Jang H. Analysis of CO_2 emission characteristics of concrete used at construction sites. Sustainability. 2016;8(4):348.
3. Davim JP. Materials and manufacturing engineering: A bibliometric analysis. Mari Papel Corrugado. 2024;1:57-8.
4. Davim JP. Sustainable manufacturing. London (UK): Wiley-ISTE; 2010.

5. Machado C, Davim JP. Circular economy and manufacturing. Cambridge (US): Elsevier; 2024.
6. Machado C, Davim JP. Circular economy and engineering: A New Ecologically Efficient Model. Cham (Switzerland): Springer Nature; 2020.
7. Kazjonovs J, Bajare D, Korjakins A. Designing of high density concrete by using steel treatment waste. Mod Build Mater Struct Tech. 2010;10:138-42.
8. Maharaj D, Parris J, Mwasha A. Physical and mechanical properties of concrete manufactured using electric arc furnace slag as coarse aggregates. Int J Environ Waste Manag. 2017;20(1):21-34.
9. Chadee A, Ali H, Gallage S, Rathnayake U. Modelling the implications of delayed payments on contractors' cashflows on infrastructure projects. Civ Eng J. 2023:9(1):52-71.
10. Kaish A, Odimegwu TC, Zakaria I, Abood MM. Effects of different industrial waste materials as partial replacement of fine aggregate on strength and microstructure properties of concrete. J Build Eng. 2020;35:102092.
11. Ghamari A, Powęzka A, Kytinou VK, Amini A. An Innovative Fire-Resistant Lightweight Concrete Infill Wall Reinforced with Waste Glass. Buildings. 2024;14(3):626.
12. Menor MCP, Caballero MJA, García AM, Ros PS. Multiproperty characterization of non-structural concrete for block made with granulated cork with bark. Constr Build Mater. 2024;418:135404.
13. Monosi S, Ruello ML, Sani D. Electric arc furnace slag as natural aggregate replacement in concrete production. Cement Concrete Comp. 2016;66:66-72.
14. Kytinou VK, Metaxa ZS, Zapris AG, Kosheleva RI, Prokopiou VD, Alexopoulos ND. Exploitation of extruded polystyrene (XPS) waste for lightweight, thermal insulation and rehabilitation building applications. Develop Built Environ. 2024;20:100580.
15. Odimegwu TC, Kaish ABMA, Zakaria I, Abood MM, Jamil M, Ngozi K. Nondestructive determination of strength of concrete incorporating industrial wastes as partial replacement for fine aggregate. Sensors. 2021;21(24):8256.
16. Ganesan K, Kanagarajan V, Dominic JRJ. Influence of marine sand as fine aggregate on mechanical and durability properties of cement mortar and concrete. Mater Res Express. 2022;9(3):035504.
17. Ullah K, Qureshi MI, Ahmad A, Ullah Z. Substitution potential of plastic fine aggregate in concrete for sustainable production. Structures. 2022;35:622-37.
18. Abu-Eishah SI, El-Dieb AS, Bedir MS. Performance of concrete mixtures made with electric arc furnace (EAF) steel slag aggregate produced in the Arabian Gulf region. Constr Build Mater. 2012;34:249-56.
19. Roslan NH, Ismail M, Khalid NH, Muhammad B. Properties of concrete containing electric arc furnace steel slag and steel sludge. J Build Eng. 2020;28:101060.
20. Pellegrino C, Cavagnis P, Faleschini F, Brunelli K. Properties of concretes with Black/Oxidizing Electric Arc Furnace slag aggregate. Cement Concrete Comp. 2013;37:232-40.
21. Faleschini F, Fernández-Ruíz MA, Zanini MA, Brunelli K. High performance

concrete with electric arc furnace slag as aggregate: Mechanical and durability properties. Constr Build Mater. 2015;101:113-21.
22. Shilstone JSM. Concrete Mixture Optimization. Concrete Int. 1990;12(6):33-9.
23. Subathra Devi V, Gnanavel BK. Properties of concrete manufactured using steel slag. Procedia Eng. 2014;97:95-104.
24. Iffat S. Relation Between Density and Compressive. Concrete Res Lett. 2015;6:182-9.
25. Rondi L, Bregoli G, Sorlini S, Cominoli L, Collivignarelli C, Plizzari G. Concrete with EAF steel slag as aggregate: A comprehensive technical and environmental characterisation. Compos Part B Eng. 2016;90:195-202.
26. Neville A. Properties of Concrete. 5th ed. London (UK): Pearson Education Limited; 2011.
27. Pellegrino C, Faleschini F. Electric Arc Furnace Slag Concrete. In: Pellegrino C, Faleschini F, editors. Sustainability Improvements in the Concrete Industry: Green Energy and Technology. Cham (Switzerland): Springer; 2016. p. 45-58.
28. Tamayo P, Pacheco J, Thomas C, de Brito J, Rico J. Mechanical and durability properties of concrete with coarse recycled aggregate produced with electric arc furnace slag concrete. Appl Sci. 2019;10(1):216.
29. Liu H, Wang X, Jiao Y, Sha T. Experimental investigation of the mechanical and durability properties of crumb rubber concrete. Materials. 2016;9(3):172.
30. Kim HK, Lee HK. Use of power plant bottom ash as fine and coarse aggregates in high-strength concrete. Construct Build Mater. 2011;25(2):1115-22.
31. Hiraskar KG, Patil C. Use of Blast Furnace Slag Aggregate in Concrete. Int Conf Innov Civil Eng. 2013:4(5):95-8.
32. Kou SC, Poon CS, Chan D. Influence of Fly Ash as Cement Replacement on the Properties of Recycled Aggregate Concrete. J Mater Civ Eng. 2007;19(9):709-17.
33. Sosa I, Thomas C, Polanco JA, Setién J, Tamayo P. High Performance Self-Compacting Concrete with Electric Arc Furnace Slag Aggregate and Cupola Slag Powder. Appl Sci. 2020;10(3):773.

How to cite this article:
Chadee A, Maharaj D, Rajapakse Y, Rajack E, Mendis S, Azamathulla HM, et al. Sustainable Use of Electric Arc Furnace Slag as a Fine Aggregate Replacement for Concrete. J Sustain Res. 2025;7(1):e250012. https://doi.org/10.20900/jsr20250012