

Research Article

Performance of Electric Arc Furnace Slag as a Partial Cement Replacement in Concrete: A Bolomey Model Investigation

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Received: 25 January 2026 | Revised: 28 April 2026 | Accepted: 12 July 2026 | Published: 07 August 2026

Abstract

Designing economically and environmentally friendly concrete with adequate durability remains a challenge. Several methods are available for concrete mix design, including the Bolomey method. In this study, local materials from the southern coast of the Mediterranean Sea were utilized. Furthermore, Electric Arc Furnace Slag (EAFS), obtained from the iron and steel plant located in Benghazi, Libya, was used as a partial replacement for cement. The objective of this study is to investigate the effect of partially replacing cement with EAFS on the compressive strength of concrete. The results showed that replacing 10% of cement with EAFS did not adversely affect the compressive strength of concrete. For the 25 MPa mixture, the compressive strength increased from 27.6 MPa (reference) to 30.6 MPa (with EAFS), representing an 11% improvement. For the 45 MPa mixture, the compressive strength increased from 53.0 MPa to 54.7 MPa, representing a 3.2% improvement.

Keywords: Bolomey Mix Design Method; Compressive Strength; Electric Arc Furnace Slag (EAFS); Local Materials; Partial Cement Replacement.

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Cite This Article: Ziyad Othman Eisa, Yusuf Ali Belgasim, Hakim Abdelgader (2026). Performance of Electric Arc Furnace Slag as a Partial Cement Replacement in Concrete: A Bolomey Model Investigation. *Steps For Civil, Constructions and Environmental Engineering*, 4(3), 16–28. <https://doi.org/10.61706/sccee12011269>

Introduction

Concrete is the most widely used construction material worldwide. Global consumption is estimated at approximately 25 billion tons per annum (Humphreys & Mahasanen, 2002; World Business Council for Sustainable Development, The Cement Sustainability Initiative, Recycling Concrete, n.d.). As demonstrated in the report by the U.S. Geological Survey (2015), the production of cement alone reached approximately 4.1 billion tons in 2014. This figure reflects the significant level of dependency on cement-based materials. Concrete is a material that offers versatility and structural reliability. However, the environmental impact of its production, primarily the manufacturing of cement, has become a significant concern.

The design of concrete mixes is governed by several key performance parameters, including workability, compressive strength, durability, and cost efficiency. The properties of these substances are interdependent and must be balanced through appropriate proportioning of constituents. It is evident that production operations, including but not limited to mixing, transportation, and curing, are generally comparable across strength classes. Consequently, material optimisation emerges as the predominant variable in performance and cost control. Cement, as the most expensive and carbon-intensive component, plays a decisive role in this optimization process. Consequently, the central research objective is to reduce cement content without compromising mechanical and durability requirements.

The escalating demand for high-strength concrete in the construction of high-rise buildings and large-span infrastructure has further emphasised the necessity for reliable mix design methodologies. Conventional procedures, such as the American Concrete Institute (ACI) method (Dixon et al., 1991) and the British Standard (BS) method [6], have been extensively adopted and are founded on empirical correlations derived from experimental databases (Neville, 1995). Concurrently, the Three Equations Method was originally proposed by Bolomey and subsequently refined by Hakim. In 2012, S. Abdelgader and El-Baden published a seminal paper that provided a mathematically structured framework for mixture proportioning (Abdelgader & El-Baden, 2012). The method combines the following elements: The following three relationships have been identified in the extant literature: (i) a strength relationship linking the water-to-cement ratio to the compressive strength (S. Abdelgader et al., 2022); (ii) a volumetric balance equation ensuring that constituent volumes sum to one cubic metre (H. Abdelgader et al., 2020); and (iii) a workability expression defining aggregate

grading requirements (Bolomey, 1935). It has been demonstrated in previous studies that this approach can be used to make satisfactory strength predictions for both normal- and high-strength concrete (H. S. Abdelgader et al., 2010).

However, it is important to note that achieving compressive strengths in excess of 40 MPa through conventional proportioning frequently necessitates elevated cement contents. This poses significant environmental and technical challenges. As stated in the Cement Technology Roadmap 2009: Carbon Emissions Reductions up to 2050 (2009), cement production accounts for almost 5% of global anthropogenic CO₂ emissions. Furthermore, the emissions of CO₂ from the production of 1000 kg of cement are approaching 900 kg (MAHASENAN et al., 2003). Furthermore, an elevated cement content has been demonstrated to augment the heat of hydration, thereby potentially inducing thermal stresses and cracking in massive elements (Neville, 2012). These constraints underscore the imperative for integrating supplementary materials into high-strength mix designs.

The substitution of clinker with supplementary cementitious materials (SCMs) is considered to be one of the most effective strategies for reducing the carbon intensity of concrete (Gartner, 2004; Yang et al., 2015). A plethora of materials, including fly ash, ground granulated blast furnace slag (GGBFS), silica fume, and natural pozzolans, have been extensively adopted for this purpose. However, the global availability of some SCMs, particularly blast furnace slag, is influenced by shifts in steel production technology. The transition towards electric arc furnace (EAF) steelmaking has resulted in a decline in the supply of blast furnace slag, concurrent with an increase in the generation of electric arc furnace slag (EAFS) (Review of 11th Global Slag Conference, 2016, n.d.).

As stated in the study by Muhmood et al. (2009), EAFS possesses a chemical composition that is partially comparable to cement clinker. Despite this similarity, its high iron oxide content and predominantly crystalline structure limit its intrinsic hydraulic and pozzolanic reactivity (Manso et al., 2004; Shi, 2004). Consequently, EAFS has been predominantly utilised as aggregate in road construction and landfill applications (Ionescu, 1999; Rojas & Sánchez De Rojas, 2004). However, recent investigations suggest that when finely ground and used at moderate replacement levels, EAFS may contribute to long-term strength development without severely affecting workability (Amin et al., 2017; Muhmood et al., 2009; Roslan et al., 2020). The extent of this contribution is contingent upon the fineness of

the particles, the replacement ratio, and the overall mix design strategy.

Research Gap and Novelty

Whilst a number of studies have previously investigated EAFS as a supplementary cementitious material, the novelty of this study lies in three aspects: The present study proposes a methodology for the application of the modified Bolomey method (Three Equations Method) to design EAFS-blended concrete. In addition, the utilisation of locally sourced EAFS from Libya is proposed, given that this region has limited published data on SCMs. Finally, the study proposes a systematic comparison of reference and EAFS mixtures across five target strength levels (25–45 MPa).

Within this framework, the present study evaluates the feasibility of incorporating locally sourced electric arc furnace slag, ground to a Blaine

fineness of approximately 350 m²/kg, as a 10% partial replacement of cement in concrete mixtures proportioned according to the Bolomey Three Equations Method. The materials under discussion were obtained from the southern Mediterranean coast of Libya. The experimental programme is centred on the assessment of workability and compressive strength, with a specific focus on the interaction between the incorporation of slag and the methodology of proportioning. The objective of this study is to ascertain whether this approach can produce structurally adequate high-strength concrete while concomitantly reducing cement consumption and enhancing environmental performance.

Methodology

Materials

The geographical locations of the material sources are illustrated in Figure 1.

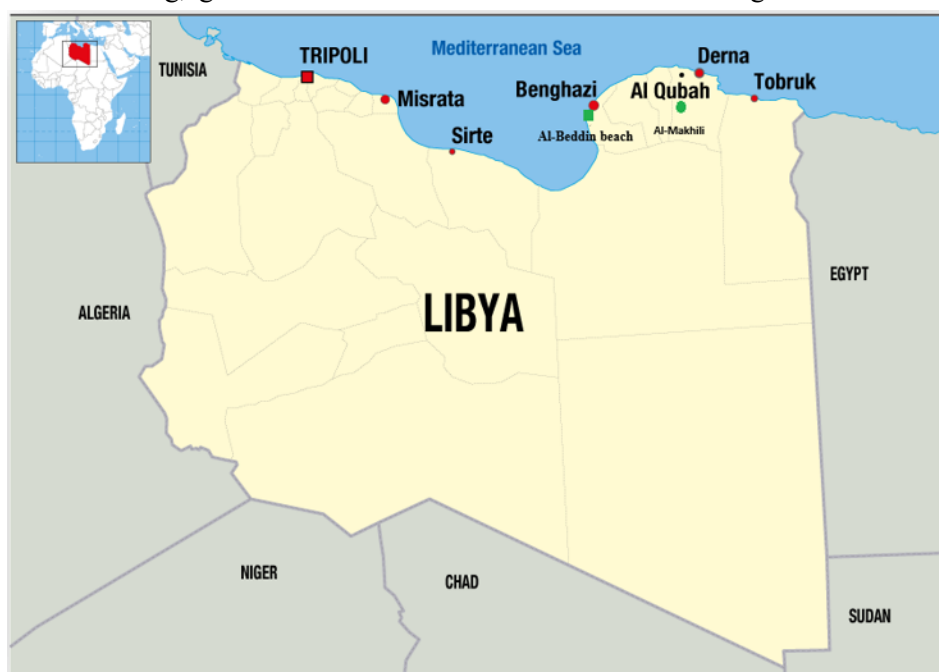


Figure 1. Map Showing the Sources of Materials Used in the Study: (1) Al Fataiah Derna Cement Factory (Eastern Libya), (2) EAFS Source (Benghazi), (3) Coarse Aggregate Source (Al-Makhili, Derna), and (4) Fine Aggregate Source (Al-Beddin beach).

Cement

Ordinary Portland cement (CEM I 42.5N) conforming to BS EN 197-1:2011 (Cement). The present study drew upon the 2019 publication entitled 'Part 1, Composition, Specifications and Conformity Criteria for Common Cements'. The cement in question was sourced from the Al Fataiah Cement Factory, which is located in the eastern region of Libya. The main physical and chemical properties of the substance under investigation are summarised in Table 1.

Electric Arc Furnace Slag (EAFS)

Electric arc furnace slag (EAFS) was obtained from a local steel plant in Benghazi, Libya. The as-received material was found to be in coarse aggregate form, with particle sizes ranging from approximately 2 to 5 centimetres (Figure 2). The primary physical and chemical properties of cement and EAFS are outlined in Table 1.

In order to achieve the requisite level of fineness, a two-stage grinding process was adopted. The initial grinding of the slag was conducted using a ball mill operating at a speed of 30 rpm for a duration of 30 minutes, with the objective of achieving coarse

reduction. Subsequently, a ring mill was utilised for fine grinding for a period of 15 minutes (two cycles of 15 minutes each at 300 rpm, with a 10-minute interval between cycles). The two-stage process was selected to efficiently reach the target fineness, as reported in

previous studies (Amin et al., 2017), with a view to enhancing the pozzolanic reactivity of EAFS. The particle size distribution (D50, D90) of the ground slag was not measured, and it is acknowledged that this is a limitation of the study.

Table 1. Physical and Chemical Analysis of Cement, and EAF Slag.

Item	OPC	EAFS
Physical properties		
L.O.I	2.52	-
Specific gravity (g/cm ³)	3.13	3.19
Fineness (m ² /kg)(Blaine)	320	350
Chemical properties (Oxides, % by weight)		
SiO ₂	20.86	35.8
Al ₂ O ₃	5.6	13.5
CaO	62.39	25.2
Fe ₂ O ₃	4	10.4
MgO	1	1.52
SO ₃	2.93	
K ₂ O		0.38
TiO ₂		1.54
MnO		8.6
Cr ₂ O ₃		0.93
ZnO		0.42
ZrO ₂		0.38
BaO		0.75



Figure 2. Slag Before and After Grinding

Coarse Aggregate

The study utilized crushed angular coarse aggregate. The material was obtained from a quarry in the Al-Makhili area, which is located approximately 80 km south of Derna, Libya (Figure 3). Sieve analysis

was conducted in accordance with the standard ASTM C136-06 (ASTM C136-06, 2025), and the resulting grading curve is presented in Figure 4. The physical and mechanical properties of the coarse aggregate are presented in Table 2.

Table 2. Physical and Mechanical Properties of the Coarse Aggregate

Test	Specific Gravity	Absorption (%)	Crushing Value (%)	Impact Value (%)
Standard	(BS 812: part 2: 1995)		(BS 812: part 110: 1990)	(BS 812: part 112: 1990)
Value	2.57	1.46	22.1	17.3
Limits	2.7 – 2.5	3>	45>	45>

Fine Aggregate

Natural fine aggregate was sourced from Al-Beddin beach along the Mediterranean coast, approximately 100 km west of Benghazi, Libya (see

Figure 3. Sieve analysis was conducted in accordance with the provisions of BS 812-103:1992 (BS 812-103, 1992), and the resulting grading curve is presented in Figure 5. The physical properties of the fine aggregate are presented in Table 3.

Table 3. Physical Properties of the Fine Aggregate

Test	Specific gravity (BS 812: part 2: 1995)	Absorption (%)	Fine materials (%) ASTM C142: 06
Standard Value	2.62	0.51	0.7
Limits	2.7 – 2.5	3>	3>



Figure 3. The Aggregate Used in Research

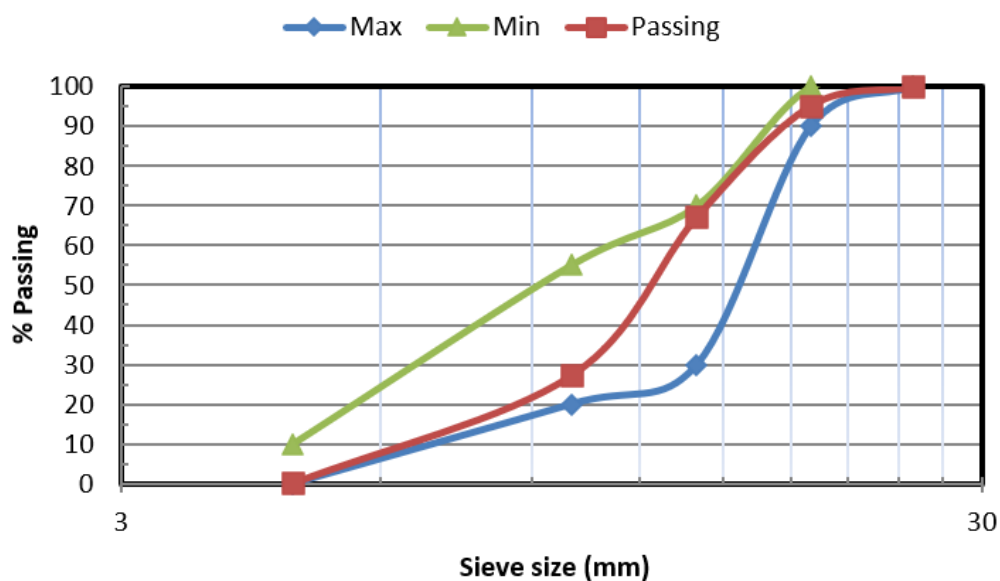


Figure 4. Grading Curve of Coarse Aggregate

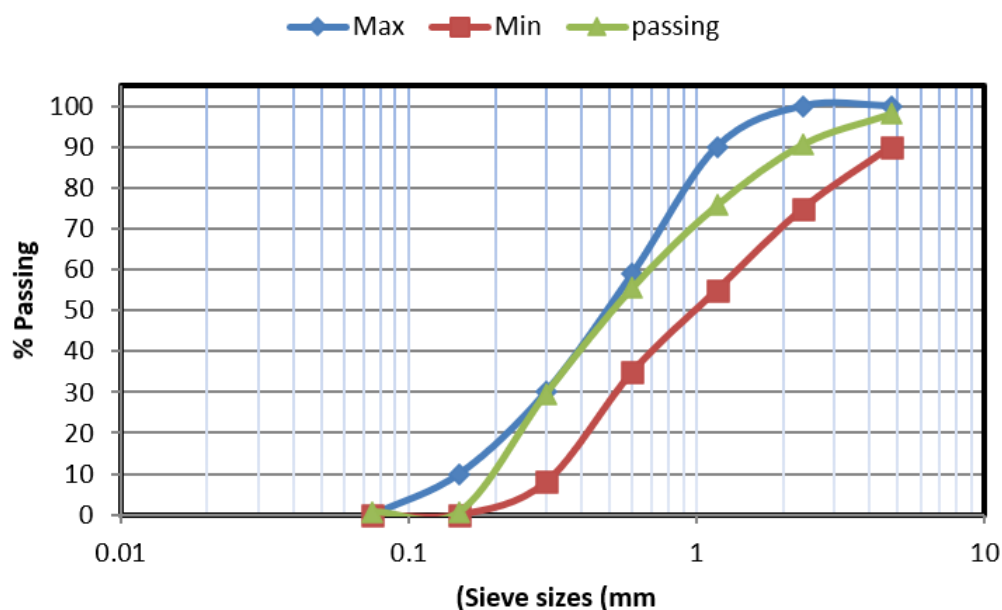


Figure 5. Grading Curve of Fine Aggregate

Mixing Water

Potable water, free from visible impurities, was used for all mixes throughout the experimental programme.

Mix Design Using the Modified Bolomey Method (Three Equations Method)

The concrete mix design was executed in accordance with the Bolomey method, which comprises the following steps:

1. Determination of target compressive strength: The requisite compressive strength, denoted by $[fc']$, was stipulated in accordance with the stipulated design requirements.
2. The following experiment will determine the cement-to-water ratio (C/W). The C/W ratio was

calculated using either equation 1 or equation 2, which represent the first Bolomey equation.

$$\frac{c}{w} = \left[\frac{fc'}{A_1} + 0.5 \right] \quad \text{If } (C/W) < 2.5 \quad (1)$$

$$\frac{c}{w} = \left[\frac{fc'}{A_2} - 0.5 \right] \quad \text{If } (C/W) \geq 2.5 \quad (2)$$

where:

C/W = cement-to-water ratio by mass; fc' = target compressive strength of concrete (MPa); A_1 and A_2 = coefficients depending on the shape and maximum size of coarse aggregate, as well as the cement strength. These coefficients were determined from Table 4.

Table 4. Values of Coefficients A_1 and A_2 for the First Bolomey Equation

Aggregate Shape	Variable of A	Compressive Strength of Cement (MPa)		
		32.5	42.5	52.5
Round	A_1	18.0	20.0	21.0
	A_2	12.0	13.0	14.5
Angular	A_1	20.0	22.0	24.0
	A_2	13.5	14.5	16.0

3. The requisite quantity of water for the concrete mixture (W_{Total}) is calculated using equation 3, which is regarded as the second equation of design.

$$W_{Total} = C * (WC) + A * (WA) \quad (3)$$

where: Water (W), aggregate (A), cement (C), WC and WA represent the index by Stern for cement

and water, respectively. The quantity of water required to achieve the specified consistency and workability of the aggregate fraction is determined by the index of Stern (Table 5). This index is defined as the ratio of water required to moisten 1 kg of the specified aggregate fraction.

Table 5. Stern Water Demand Indices for Aggregate Fractions

Sieve Size (mm)	Workability	
	Medium	High
25	0.013	0.015
19	0.016	0.018
14	0.02	0.023
10	0.026	0.029
4.75	0.032	0.037
2.36	0.043	0.048
1.18	0.058	0.065
600	0.084	0.095
300	0.122	0.137
150	0.150	0.160
75	0.013	0.015

Footnote for Table 5: The medium workability is characterised by a slump range of 30–60 mm. It has been demonstrated that high workability is associated with a slump range of 100–150 mm. The Stern index values presented herein are theoretical values adopted from the extant literature. The values for the 150- μ m sieve have been revised from their original source, with the values previously recorded as 0.239 for Medium and 0.225 for High being corrected to more logical values of 0.150 and 0.160, respectively.

4. The third equation is concerned with the calculation of the total volume of all components, which is required to be 1 m³. The formula is expressed as follows: Equation 4:

$$w + \frac{C}{\rho_c} + \frac{A}{\rho_a} = 1 \text{ m}^3 \quad (4)$$

Where: Cement (C) and aggregate (A) and ρ_c and ρ_a are the specific densities of cement and aggregate, respectively.

5. For concrete with (EAFS):

$$w + \frac{0.9C}{\rho_c} + \frac{A}{\rho_a} + \frac{0.1C}{\rho_s} = 1 \text{ m}^3 \quad (5)$$

Where: ρ_s is specific density of (EAFS).

Calculate the quantities of the mix (W&C&A): solving the three equations.

Mixed Proportions

A total of ten concrete mixtures were designed with target compressive strengths of 25, 30, 35, 40, and 45 megapascals (MPa), all with medium workability. Five mixtures were utilized as reference materials (0% EAFS replacement), and the remaining five mixtures contained 10% EAFS as a partial replacement of cement by weight of total binder. The proportioning of all mixtures was conducted using the same local materials (cement, aggregates, and water), in accordance with the modified Bolomey method (Three Equations Method).

Specimen Preparation and Testing

For each mixture, five cubic specimens measuring 100 × 100 × 100 mm were cast. The sequence of operations involved in the mixing process is outlined below: Initially, the coarse aggregate and the fine aggregate were subjected to a dry mixing process for a duration of one minute. Subsequently, cement (and EAFS, when applicable) was added and mixed for a further 60 seconds. The initial step involved the incorporation of approximately 70% of the mixing water, which was then subjected to a 2-minute mixing process. The remaining water was then added, and the mixture was left to stand for a further 120 seconds. This process was carried out using a laboratory concrete mixer.

The compaction process was accomplished through the utilization of a vibrating table, with each layer undergoing a 10-second cycle (comprising two layers per specimen). Subsequent to casting, the specimens were covered with plastic sheets and left in the laboratory at 22 ± 2°C for 24 hours. The specimens were subsequently demolded and cured in a water tank at a temperature of 20 ± 1°C and a relative humidity of 95 ± 5% until testing at 28 days, in accordance with the ASTM C192 (C192/C192M-26, 2026) standard. Following a 28-day period of curing, the specimens were retrieved from the curing tank and the tests were conducted. The subsequent compressive strength testing was conducted in accordance with the standard (BS EN 12390-3, 2011), employing a compression testing machine as the designated apparatus for measurement.

Results and Discussion

The detailed mix compositions for reference and EAFS-modified mixtures are presented in Tables 6 and 7, respectively. The water-to-cement ratio (w/c) for reference mixtures and the water-to-cementitious materials ratio (w/cm) for EAFS mixtures were adjusted for each target strength.

Table 6. Mix Proportions for Reference Concrete Mixtures with Different Target Compressive Strengths (0% EAFS Replacement)

Target Strength (MPa)	Cement (kg/m ³)	Fine Aggregate (kg/m ³)	Coarse Aggregate (kg/m ³)	Water (L/m ³)	w/c
25	272	687	1276	164	0.60
30	335	657	1219	177	0.52
35	408	621	1154	192	0.47
40	497	578	1074	211	0.43
45	636	511	950	240	0.38

Table 7. Mix Proportions for Concrete Mixtures with Different Target Compressive Strengths (10% EAFS Replacement)

Target Strength (MPa)	Cement (kg/m ³)	EAFS Slag (kg/m ³)	Fine Aggregate (kg/m ³)	Coarse Aggregate (kg/m ³)	Water (L/m ³)	w/cm
25	249.9	27.77	674.2	1252.2	167.4	0.603
30	310.2	34.4	641.5	1191.4	182.3	0.530
35	381	42.4	602.7	1119.4	200	0.472
40	467	51.9	556.43	1033.4	221.1	0.426
45	610.9	67.9	478.3	888.4	256.6	0.378

*Note: EAFS content represents 10% by weight of total binder (cement + slag). w/cm = water-to-cementitious materials ratio.

Table 8 provides a synopsis of the blend proportions and characteristics of the reference concrete mixtures (0% EAFS). The cement content increased from 272 kg/m³ to 636 kg/m³ as the target strength rose from 25 MPa to 45 MPa, while the water-to-cement ratio decreased from 0.60 to 0.38. Slump

values ranged from 35 mm to 215 mm, reflecting changes in mixture composition. It was observed that all mixtures attained 28-day compressive strengths that exceeded their target values, thereby indicating that the selected proportions satisfied the requisite performance criteria.

Table 8. Mix Proportions, Water-to-Cement Ratio, 28-Day Compressive Strength, and Slump of Reference Concrete Mixtures (0% EAFS Replacement).

Target Strength (MPa)	Cement Content (Kg)	w/c	Actual 28-Day Strength (MPa)	Slump(mm)
25	272	0.60	27.6	35
30	335	0.52	36.2	70
35	408	0.47	42.1	120
40	497	0.43	46.4	195
45	636	0.38	53	215

It should be noted that the values for individual specimens from the five replicates of the mixture were not recorded. Consequently, the standard deviation is not reported.

The mix proportions and main properties of concrete mixtures incorporating 10% EAFS as a partial cement replacement are summarized in Table 9. The substitution of a proportion of the cement with slag resulted in a decrease in the cement content, while the

total binder volume remained commensurate with that of the reference mixtures.

The water-to-cementitious materials ratio (w/cm) ranged from 0.603 to 0.378. It was observed that all mixtures attained 28-day compressive strengths that exceeded their target values. However, the slump values were lower than those of the reference mixtures, ranging from 20 mm to 120 mm. This reduction in workability is attributed to the higher fineness of the ground slag, which increases water demand.

Table 9. Mix Proportions, Water-to-Cementitious Materials Ratio (w/cm), 28-Day Compressive Strength, and Slump of Concrete Mixtures with 10% EAFS Replacement

Target Strength (MPa)	Cement Content (Kg)	EAFS (Kg)	w/cm	Actual 28-Day Strength (MPa)	Slump(mm)
25	249.9	27.77	0.603	30.64	20
30	310.2	34.4	0.530	38.30	40
35	381	42.4	0.472	44.90	85
40	467	51.9	0.426	47	70
45	610.9	67.9	0.378	54.7	120

It Should Be Noted That the Values for Individual Specimens from the Five Replicates of the Mixture Were Not Recorded. Consequently, The Standard Deviation is not Reported.

Compressive Strength and Water-to-Binder Ratio

As demonstrated in Figure 6, there is a direct correlation between the water-to-binder ratio and the 28-day compressive strength. For the reference mixtures, the water-to-cement ratio decreased from

0.60 to 0.38 as the compressive strength increased from 27.6 MPa to 53.0 MPa. A comparable trend was observed for the EAFS mixtures, where the w/cm ratio decreased from 0.603 to 0.378, with an increase in strength from 30.6 MPa to 54.7 MPa.

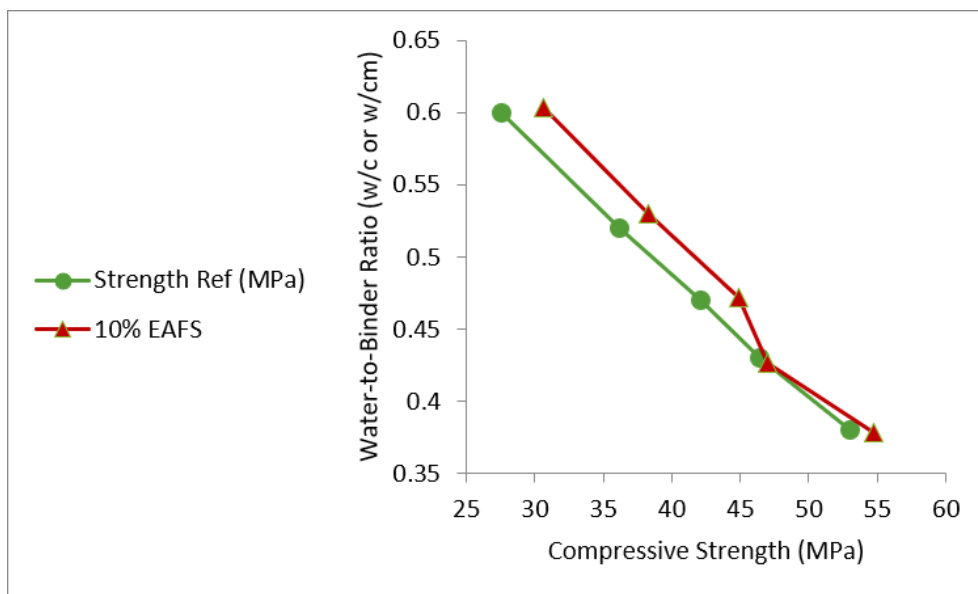


Figure 6. Relationship Between Water-to-Binder Ratio (w/c for Reference Mixtures, w/cm for EAFS Mixtures) and 28-Day Compressive Strength. The Figure Shows the Expected Inverse Relationship for Both Series, with EAFS Mixtures Achieving Slightly Higher Strengths at Comparable Target Strength Levels.

In summary, the two-mixture series demonstrated the anticipated inverse correlation between water content and compressive strength.

Cement Content and Compressive Strength

As illustrated in Figure 7, there is a clear correlation between the variation of cement content and compressive strength, both for the reference mixtures and for those incorporating 10% EAFS.

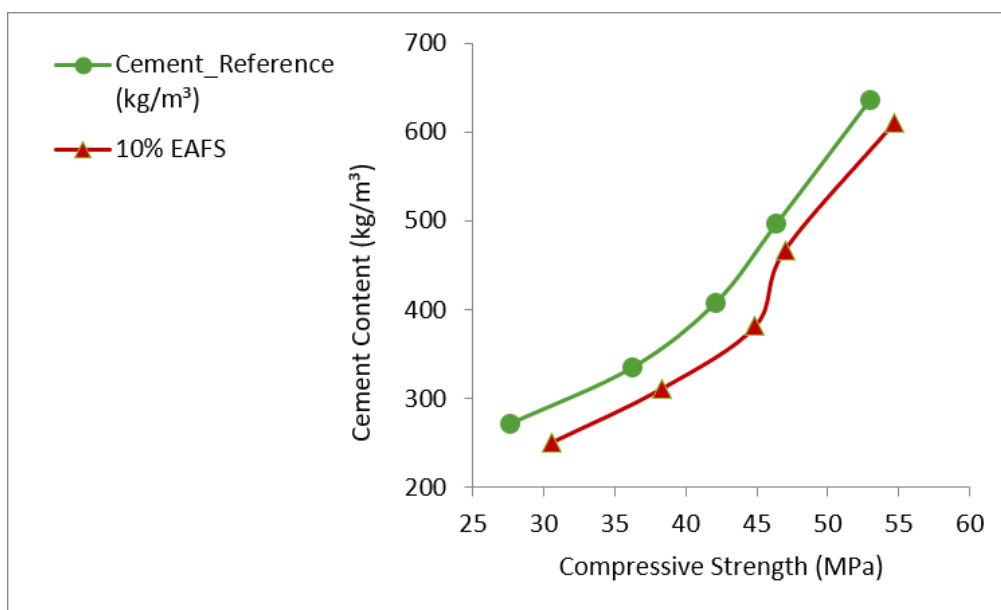


Figure 7. Cement Content Versus Compressive Strength for Reference and EAFS-Modified Concrete Mixtures.

For the reference mixtures, the cement content exhibited a consistent increase with target strength, ranging from 272 kg/m³ at 25 MPa to 636 kg/m³ at 45 MPa. This behaviour is consistent with conventional mix design principles, where higher strength requires higher binder content and lower water-to-cement ratios.

Conversely, mixtures containing 10% EAFS exhibited a consistent reduction in cement content at equivalent strength levels. The cement content

exhibited a range from 249.9 kg/m³ to 610.9 kg/m³. The reduction in cement usage exhibited a range between 3.9% and 8.1%, with an average reduction of approximately 6.5%.

The findings of this study suggest that partial replacement with EAFS can effectively reduce cement demand without compromising compressive strength, thereby offering clear environmental benefits.

Workability (Slump) and Compressive Strength

The relationship between slump and compressive strength is illustrated in Figure 8.

For reference mixtures, slump increased with strength, ranging from 35 mm at 25 MPa to 215 mm at 45 MPa. This phenomenon can be attributed to the increased paste volume associated with higher cement content.

However, the EAFS mixtures exhibited lower workability overall, with slump values ranging between 20 mm and 120 mm. The reduction in the aforementioned parameter became more pronounced at higher strength levels. For instance, at 40 MPa, the slump diminished to 70 mm in comparison to 195 mm for the reference mixture.

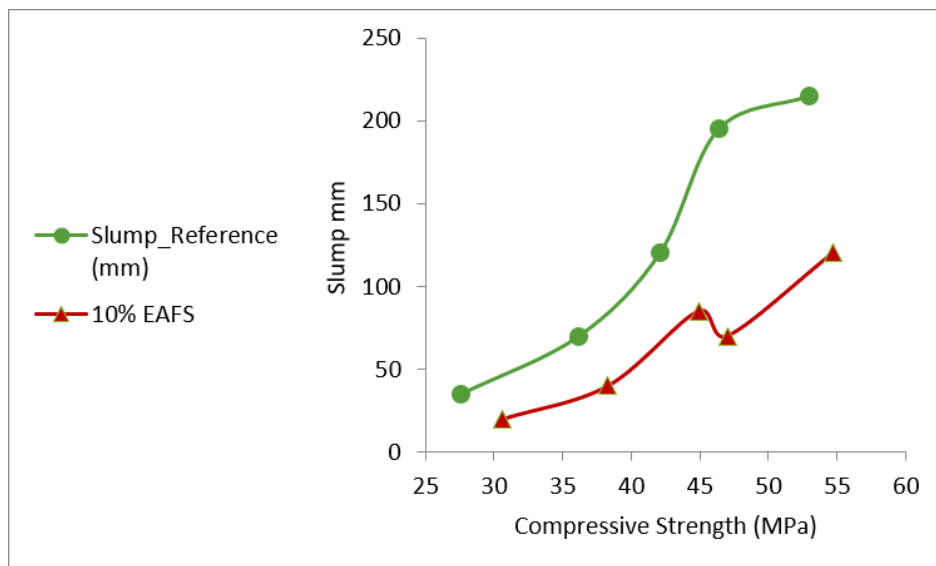


Figure 8. Slump Versus Compressive Strength for Reference and EAFS-Modified Concrete Mixture

This behaviour is attributed to the higher fineness of the ground EAFS, which increases water demand and reduces flowability. Consequently, the utilization of superplasticizers may be imperative, particularly in mixtures that exceed 35 MPa.

The most significant reduction (8.1%) was observed at 25 MPa, while the least significant reduction (3.9%) occurred at 45 MPa. This finding indicates that the efficiency of cement replacement is more significant at lower strength levels.

Cement Reduction Efficiency

As illustrated in Figure 9, a 10% reduction in cement content is achieved through the use of 10% EAFS.

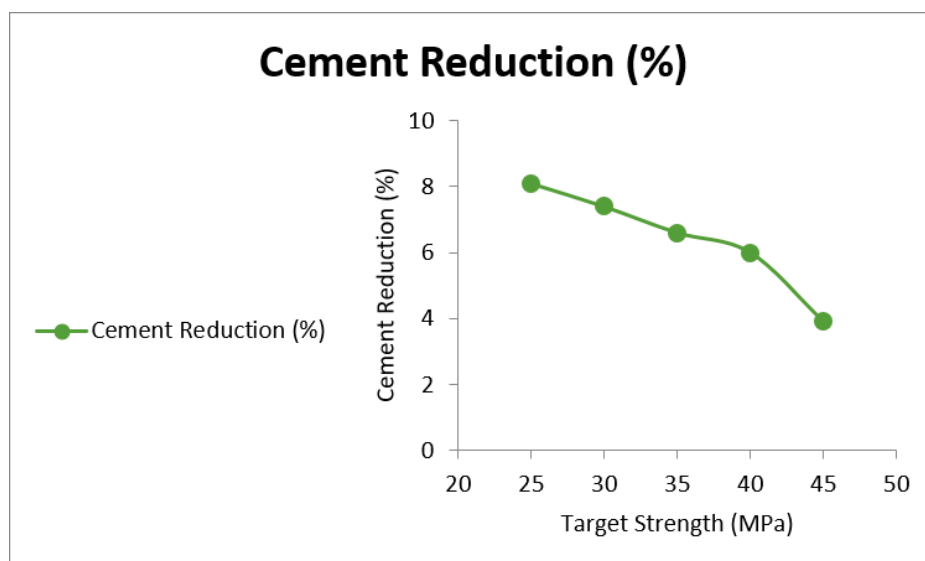


Figure 9. Cement Reduction Percentage Versus Target Compressive Strength for Mixtures with 10% EAFS Replacement

The average reduction achieved was approximately 6.5%, a figure which directly contributes to a reduction in CO₂ emissions and overall material cost.

Limitations of the Study

The authors acknowledge the following limitations:

- **Single Replacement Level:** It is important to note that only 10% replacement was tested.
- **The present study is part of a limited experimental programme.** It is evident that no durability tests were conducted.
- **The EAFS is characterised by a singular presence,** with a solitary steel plant in Benghazi, Libya.
- **Absence of Superplasticizers:** The process did not involve the use of chemical admixtures.
- **Statistical Analysis:** It is important to note that the standard deviation of the data has not been documented.
- **The term 'Particle Size Distribution' (PSD)** is employed to denote the range of sizes of particles in a given sample. The D50 and D90 were not measured.
- **Microstructural Analysis:** No XRD/SEM analysis was performed.
- **Mix Design Validation:** It should be noted that the aforementioned model has not been validated against ACI/BS methods.

The following Environmental Impact Estimate (EIE) is hereby presented for consideration: It should be noted that the estimates of CO₂ are approximate and do not include the processes of grinding or transportation.

Conclusion

The experimental results obtained allow the following conclusions to be drawn:

- **Compressive Strength:** It is evident that all EAFS mixtures attained compressive strengths that surpassed their target values at the 28-day mark. The 11% improvement observed at 25 MPa (30.6 MPa vs. 27.6 MPa) was the most pronounced, while higher-strength mixtures exhibited smaller gains (3.2% at 45 MPa).
- **Workability:** The incorporation of EAFS resulted in a decline in workability, particularly at higher strength levels. The slump values for EAFS mixtures ranged from 20 mm to 120 mm, in comparison to the 35–215 mm range observed for reference mixtures.

- **Water-to-Binder Ratio:** A clear inverse relationship between w/cm and compressive strength was observed, consistent with Abrams' law. The modified Bolomey method was found to be an effective means of maintaining this relationship in the context of EAFS-blended concrete.

- **Cement Reduction:** The utilisation of 10% EAFS resulted in a consistent reduction in cement content, ranging from 3.9% to 8.1%, with an average of 6.5%. This reduction corresponds to a CO₂ saving of approximately 20–25 kg/m³ for lower-strength mixtures (25–30 MPa).

- **Method Validity:** The Bolomey Three Equations Method was found to be suitable for the design of EAFS-blended concrete mixtures, provided that the water demand of the slag is properly accounted for, as demonstrated by the successful achievement of target strengths.

- **Broader Contributions:** The present study demonstrates that locally sourced EAFS can be effectively utilised as a partial cement replacement in regions where conventional SCMs (e.g. fly ash, GGBFS) are scarce. The Bolomey method is a systematic approach that provides a validated framework for such sustainable mix designs.

Recommendations

It is recommended that the following course of action be taken in light of the findings.

- **The utilization of superplasticizers**

For mixtures with target strengths in excess of 35 MPa, the employment of a polycarboxylate ether-based superplasticizer at a dosage of 0.5–1.0% by weight of cement is recommended in order to compensate for the reduced workability caused by the high fineness of EAFS. The dosage under consideration is based on standard practice in the field of concrete technology, as no superplasticizers were subjected to testing in this particular case.

- **The Control of Slag Fineness**

It was determined that a Blaine fineness of approximately 350 m²/kg provided an optimal balance between strength enhancement and workability. It is hypothesized that finer grinding may result in enhanced strength; however, this process is predicted to increase water demand and necessitate elevated dosages of superplasticizers.

- **Sustainability and Economic Considerations**

The utilization of locally available EAFS is strongly advocated, as it has been demonstrated to engender a reduction in cement consumption (by an average of 6.5%) and CO₂ emissions (by approximately 20–25 kg/m³ for lower-strength

concrete). In order to achieve a more precise economic evaluation, it is recommended that a full life-cycle assessment be conducted, with the inclusion of grinding, energy and transportation costs.

- **Durability Studies**

It is recommended that future research focus on investigating long-term durability, including sulfate resistance, chloride penetration (a key consideration in coastal regions), carbonation, and freeze-thaw behaviour of EAFS-blended concrete.

- **Higher Replacement Levels and Microstructure**

Further studies are required to evaluate higher replacement ratios (e.g., 15–20%) and to perform microstructural analyses (XRD, SEM) to enhance comprehension of the hydration mechanisms and the interaction between EAFS and the cement matrix.

Declarations

Authors' Contributions

Z.O.E.: Methodology, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing.

Y.A.B.: Methodology, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing.

H.A.: Conceptualization, Methodology, Writing – review & editing, Supervision.

Conflict Of Interest

The authors declare that there are no conflicts of interest.

Funding

The authors declare that this research received no external funding.

Declaration on the Use of Generative AI And AI-Assisted Technologies

AI-assisted tools were used solely for manuscript formatting.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgement

The authors would like to express their appreciation to the Concrete Laboratory, Department of Civil Engineering, Omar Al-Mukhtar University, Libya, for providing laboratory facilities during the experimental work.

Ethics

This study did not involve human participants or animals; hence, no ethical approval was required.

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