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Evaluation of EAF Slag as a Sustainable Aggregate in Counterweight Concrete within the Scope of Green Transformation

Optimized Low-Cement, High-Strength Mix Designs for the White Goods Industry

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Abstract

Electric arc furnace (EAF) slag has strong potential as a sustainable high-density aggregate, yet it remains underutilized in current industrial practice. In this study, EAF slag was used as the main aggregate in counterweight concretes for white-goods applications.

Five low-cement mixtures were developed by reducing **Portland cement content from 14% to 6%** while increasing **EAF slag content from 84.5% to 92.5%**. The prepared mixtures were cast, cured for 2, 7, and 28 days, and evaluated through apparent density, water absorption, porosity, compressive strength, visual inspection, and ultrasonic pulse velocity testing.

All formulations exceeded the 44 MPa 28-day compressive strength target. The optimized **R5 mixture**, containing only 6% Portland cement and 92.5% EAF slag, **achieved 80.89 MPa at 28 days with an apparent density of 2.93 g/cm³**. The results confirm that EAF slag can be used to produce high-density, high-strength counterweight concrete while supporting slag valorization and lower cement use.

INTRODUCTION

Electric Arc Furnace (EAF) slag is a high-density by-product of scrap-based steel production, characterized by strong mechanical properties and a rough, angular particle morphology. Despite its significant potential, insufficient valorization in current industrial practice leads to the wastage of this valuable raw material. **Approximately 5 million tons of EAF slag waste are generated annually in Turkey alone**, creating substantial storage and inventory costs for steel producers.

In the white goods industry, **counterweight concrete (>2,600 kg/m³)** is used in ovens and washing machines to prevent tipping and ensure operational stability. Current commercial formulations rely heavily on Portland cement, mill scale, quartz, and gravel — a combination associated with high natural-resource consumption and cement-related environmental burden.

This study investigates the **full replacement of conventional aggregates with EAF slag** to produce **high-density, low-cement, high-strength counterweight blocks**, directly aligned with circular economy principles and the green transformation objectives of the steel and white-goods industries.

MATERIAL CHARACTERIZATION

Water-cooled EAF slag supplied by İÇDAŞ A.Ş. was used after one month of open-air aging. Portland cement CEM I 42.5R and microsilica 920U were used as binder components.

The slag contains high **Fe_2O_3 (38.36%)** and **CaO (27.55%)** with very low **Free CaO (0.02%)**, suggesting a reduced free-CaO-related expansion risk; however, long-term expansion and durability validation is still required.

Table 1: Chemical Composition of Raw Materials

Elements %	EAF Slag Water Cooled	Portland Cement Cem I / 42,5R	Microsilica 920U
Al_2O_3	10,39	4,5	0,12
SiO_2	16,29	18,66	95,6
CaO	**27,55**	64,34	0,48
Cr_2O_3	1,59	-	-
Fe_2O_3	**38,36**	3,23	0,35
MnO	3,52	-	-
K_2O	0,01	-	1,1
MgO	1,9	0,85	0,52
Na_2O	0,39	0,14	0,44
P_2O_5	0,56	-	-
S	0,08	3,38	-
TiO_2	0,35	-	0,02
Loss on Ignition	-	3,28	-
Free CaO	**0,02**	1,31	-

As presented in Table 2, EAF slag demonstrates an apparent **density of 3.15–3.20 g/cm³** with water absorption below 1.40% and apparent porosity below 4.56%, confirming its suitability as a high-density structural aggregate without any supplementary weighting additives.

Table 2: Physical Properties of EAF Slag (ASTM C 20)

Sample ID	Water Absorption (%)	Apparent Porosity (%)	Apparent Density (g/cm³)
EAF Slag Sample 1	1,36	4,33	3,19
EAF Slag Sample 2	1,22	3,15	3,2
EAF Slag Sample 3	1,4	4,56	3,15

BENCHMARK

Characterization of the existing BSH oven counterweight concrete was conducted at Matil A.Ş. laboratories. XRD analysis revealed a composition dominated by **Wüstite FeO (60.4%), Magnetite Fe_3O_4 (4.2%), Quartz SiO_2 (10.4%), Albite (6.3%), and Larnite Ca_2SiO_4 (8.8%)**, confirming the use of dense iron-rich constituents and cementitious phases in the reference product.

The **CaO content (15.01%)** indicates the contribution of Portland cement and other CaO-bearing constituents in the reference formulation. Mechanical characterization showed **compressive strengths of 27–48 MPa** across different regions, with **apparent densities between 3.03 and 3.41 g/cm³.**

These findings confirmed that the reference product relies on dense iron-rich constituents and relatively high cement content, providing the **baseline for developing lower-cement alternative formulations.**

RECIPE DEVELOPMENT

Five distinct mix designs (R1–R5) were developed. **Portland CEM I 42.5R content was systematically reduced from 14% to 6%** by weight, while **EAF slag content was correspondingly increased from 84.5% to 92.5%.** A **constant water-to-mix ratio of 6%** was maintained throughout all recipes, together with 1.5% combined microsilica and superplasticizer admixture to ensure workability at low water demand. This systematic reduction strategy enables the evaluation of the strength–cement-content relationship and the potential reduction of cement-related CO_2 impact.

Table 3: Mix Design Compositions

Raw Materials (%)	R1	R2	R3	R4	R5
EAF Slag 0-6 mm	84,5	86,5	88,5	90,5	**92,5**
Portland Cement	14	12	10	8	**6**
Additives	1,5	1,5	1,5	1,5	**1,5**

EXPERIMENTAL PROCEDURE

Dry mixes were homogenized and blended with water at **6% by weight.** Flowability was assessed using a self-flow spread test before casting. Specimens were cast into **5 × 5 × 5 cm molds** and compacted by vibration.

Curing was performed for **2, 7, and 28 days**, followed by **24 h drying at 110 °C** to constant weight.

- **Physical tests:** Apparent density, water absorption, and apparent porosity according to ASTM C 20.
- **Mechanical performance**: Compressive strength testing at each curing stage.
- **Microstructural integrity:** Ultrasonic Pulse Velocity (UPV) testing for internal microcrack detection.
- **Visual inspection:** Macro surface analysis for crack propagation, FeO exudation, and dimensional stability.

Table 4: Physical & Mechanical Test Results

Environmental Conditions	Recipe No	Density	Compressive Strength (MPa)
2 Days Curing, 24h 110°C Drying	Recipe 1	2,94	75,18
	Recipe 2	2,84	69,38
	Recipe 3	2,91	69,21
	Recipe 4	2,89	64,39
	Recipe 5	2,85	42,15
7 Days Curing, 24h 110°C Drying	Recipe 1	2,96	98,07
	Recipe 2	2,79	94,55
	Recipe 3	2,91	97,14
	Recipe 4	2,98	77,2
	Recipe 5	2,97	59,22
28 Days Curing, 24h 110°C Drying	Recipe 1	2,85	117,87
	Recipe 2	2,91	107,63
	Recipe 3	3	99,59
	Recipe 4	3,01	83,45
	Recipe 5	**2,93**	**80,89**

FINDINGS & DISCUSSION

At 28 days, **all formulations exceeded the 44 MPa target**. The optimized **R5 mixture, containing only 6% Portland cement and 92.5% EAF slag, achieved 80.89 MPa.**

The **density target (>2,600 kg/m³) was met across all recipes**, with measured densities between **2.85 and 3.01 g/cm³**. UPV results indicated **no detectable internal microcracking** within the sensitivity limits of the method, while the angular slag morphology promoted strong mechanical interlocking within the cementitious matrix.

The results show that **substantial Portland cement reduction can be achieved without compromising the required mechanical performance** of counterweight concrete.

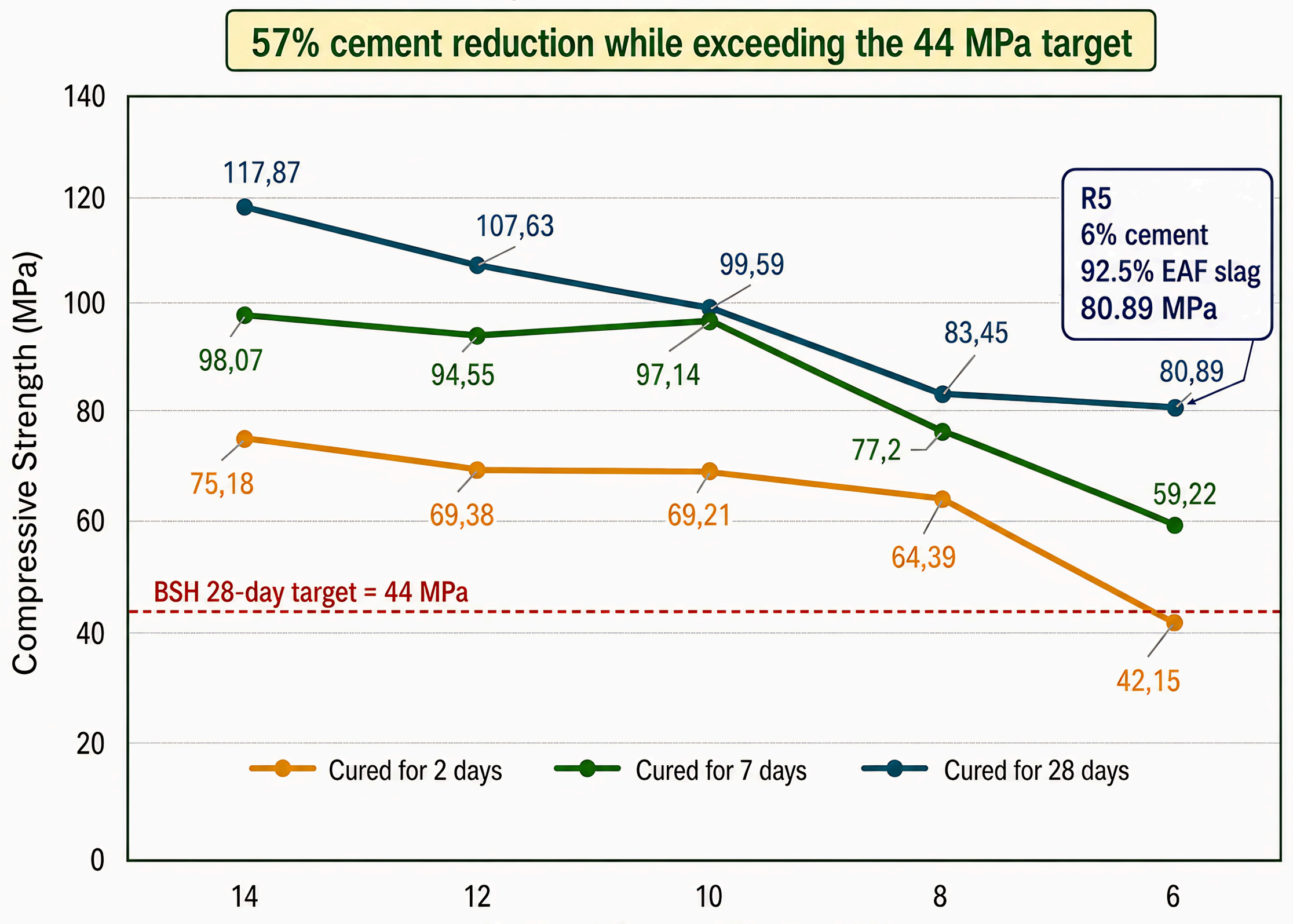
57% cement reduction while exceeding the 44 MPa target

Figure 1: Compressive Strength Development of R1–R5 Mixes

PILOT-SCALE PRODUCTION

A **full-scale oven counterweight (2,956 g)** was successfully produced using the **R5 formulation (6% cement)**. Post-production testing confirmed **internal structural integrity** and **compliance with BSH weight specifications.**

Figure 2: Pilot-Scale Oven Counterweight Block Views

CONCLUSIONS

- **EAF slag successfully replaced conventional aggregates** in high-density counterweight concrete.
- The apparent density of EAF slag, ranging from 3.15 to 3.20 g/cm³, enabled the production of high-density concrete **without supplementary weighting additives.**
- Portland cement content was **reduced from 14% to 6%**, while the optimized R5 formulation **still achieved 80.89 MPa compressive strength at 28 days.**
- **All formulations exceeded the 44 MPa 28-day compressive strength** target specified for the application.
- UPV and visual inspection results indicated **no detectable internal microcracking** in the pilot-scale counterweight block.
- The approach supports EAF slag valorization, **reduced cement use,** and circular-economy-oriented production in the white goods industry.

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