Materials Research Proceedings 67 (2026) 832-839 https://doi.org/10.21741/9781644904176-115

Breaking the 25% barrier: Evaluating high-volume slag concrete for sustainable UAE infrastructure

Ahmed Bediwy[1,*], Moustafa Basha[2], Mohamed Mekky[1], Farah Alnuaimi[1], Noora Alsayed[1], and Shaikha Rashed[1]

[1]UAEU, Civil and Environmental Engineering Department, Al Ain, UAE

*abediwy@uaeu.ac.ae

Keywords: Slag, Decarbonization, Optimization, Sustainability, Infrastructure

Abstract. As the United Arab Emirates forges ahead with its ambitious 2050 Net-Zero Initiative, a direct response to its national strategy and the UN Paris Agreement, the construction sector faces a critical challenge: decarbonizing one of its most fundamental materials, concrete, without compromising the longevity of its vast infrastructure1. Concrete is the second most consumed material on earth, and its key binder, cement, is responsible for 8–9% of global CO_2 emissions2. The use of Supplementary Cementitious Materials (SCMs), like slag, a byproduct of steel production, is a cornerstone of sustainable concrete design, reducing the carbon footprint and enhancing durability. In alignment with national sustainability goals, the UAE is actively promoting such practices, as outlined in national roadmaps like "Concrete Zero"2. However, a significant regulatory limitation persists, as current specifications often restrict slag content to a maximum of 25% due to concerns over its long-term durability in harsh environments, particularly regarding carbonation3. This precautionary cap, implemented in the absence of conclusive data, potentially limits the full environmental benefits of slag utilization. This research directly addresses this knowledge gap by experimentally investigating the feasibility and performance of concrete mixes incorporating slag content significantly beyond the conventional 25% limit. The primary objective is to comprehensively evaluate the effect of high-volume slag replacement (0%, 25%, 40%) on the key properties of concrete. The experimental program included a full suite of tests to assess fresh properties (workability, air content), mechanical properties (compressive, tensile, flexural, and shear strengths and modulus of elasticity), and durability properties (Abrasion, absorption and electrical resistivity). To interpret macro-scale performance, microstructural analysis using Scanning Electron Microscopy (SEM) and X-Ray Diffraction (XRD) were conducted to examine the hydration products and pore structure. The ultimate objective is to establish a scientific foundation for revising the current 25% slag restriction, enabling the UAE construction sector to adopt higher slag volumes without compromising concrete quality. By doing so, the project directly supports the UAE's climate action goals by facilitating a substantial reduction in the embodied carbon of its future infrastructure.

Introduction

The United Arab Emirates (UAE) has embarked on a transformative journey towards sustainable development, crystallized by its national mandate to achieve net-zero emissions by 2050 in alignment with the UN Paris Agreement [1]. This ambitious commitment must be reconciled with the pressing need for significant infrastructure modernization and expansion, a sector currently facing an estimated deficit of $125 billion. Concrete, the most widely used human-made material on earth, is indispensable for this build-out. Yet, the environmental footprint of its production presents a profound paradox: the cement industry alone is responsible for 8-9% of global CO_2 emissions. With annual cement production anticipated to grow by 50% by 2050, driven by regional urbanization and economic development, the urgency to decarbonize the construction sector has

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 license. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI. Published under license by Materials Research Forum LLC.

never been greater. In a strategic move to address this challenge, the UAE, in partnership with the Cement Association of Canada, launched the "Concrete Zero" action plan, providing a comprehensive roadmap to navigate the construction sector towards a net-zero future [3,4].

A critical pathway outlined in this roadmap is the efficient use of supplementary cementitious materials (SCMs) to reduce the clinker factor of cement. The partial replacement of cement with industrial by-products such as fly ash and slag has long been recognized for its dual benefit of enhancing durability while conserving natural resources and reducing energy consumption. However, the sustainability landscape for these materials is shifting rapidly. The UAE's commendable and codified commitment to phasing out coal-fired electricity generation by 2030, as detailed in the Cessation of Coal Use Regulation, directly impacts the availability of conventional fly ash [1]. This necessary energy transition inadvertently creates a supply crisis for a key component of low-carbon concrete, compelling the industry to seek and validate alternative SCMs that are both sustainable and readily available.

Within this context, ground granulated blast-furnace slag (slag) emerges as a particularly promising candidate. As a by-product of the steel industry, its utilization in concrete represents a cornerstone of the circular economy, diverting industrial waste from landfills and reducing the reliance on virgin materials. Technically, slag contributes to a denser, more refined microstructure within the cement paste, leading to lower permeability and improved long-term resistance to chemical attacks, such as those from sulfates and chlorides. The strategic incorporation of high-volume slag thus represents a readily implementable and high-impact lever for drastically reducing the embodied carbon of concrete, directly supporting the objectives of the "Concrete Zero" initiative [3,4].

Despite its significant potential, the widespread adoption of slag-concrete blends beyond a nominal replacement level of approximately 25% is impeded by persistent conservatism in material specifications, particularly for critical infrastructure like transportation networks. These prescriptive limits are rooted in legitimate, yet manageable, concerns regarding the altered hydration kinetics and chemical composition of slag-blended systems. The slower rate of early strength gain can pose challenges for fast-track construction schedules, while the reduced alkalinity of the hydrated paste raises questions about the carbonation resistance and the subsequent risk of corrosion for embedded steel reinforcement, especially in the UAE's aggressive marine environment. The persistence of these specification caps is fundamentally a problem of insufficient long-term, field-validated performance data. Without conclusive evidence from real-world applications demonstrating that these potential drawbacks can be mitigated through optimized mix design and proper curing protocols, engineers and specifiers understandably default to conservative practices.

The central challenge, therefore, is not merely a material limitation but a critical knowledge gap. The transition to performance-based specifications, which would allow for higher slag content where its performance is proven, requires a robust and multi-faceted body of evidence. This evidence must span from fundamental material characterization to field-scale validation, explicitly quantifying the effects of high slag volumes on both fresh and hardened concrete properties under conditions representative of the local climate and construction practices. Research must systematically address the interplay between slag content, curing conditions, and long-term durability indicators, such as chloride diffusion coefficients and carbonation depth, to calibrate reliable service-life prediction models.

Accordingly, this research aims to systematically investigate the viability of high-volume slag concrete as a key enabler for sustainable infrastructure in the UAE. The study will pursue a comprehensive methodology that bridges the gap between laboratory mixtures and practical applications. The investigation will characterize early-age properties, including workability, setting time, and strength development, to establish practical constructability parameters.

Concurrently, a detailed analysis of long-term durability will be conducted, focusing on transport properties and microstructural evolution to assess corrosion initiation risks. The ultimate goal is to generate the necessary technical foundation to support the evolution of prescriptive standards into performance-based specifications. By providing the rigorous, exposure-specific data required to confidently deploy high-volume slag concrete, this work seeks to unlock a crucial decarbonization pathway, thereby supporting the UAE's strategic objectives of infrastructural resilience and environmental leadership.

Need for Research

The significance of this research lies in addressing the critical impediment posed by the conservative 25% cap on slag replacement in concrete specifications. While the UAE's "Concrete Zero" agenda and the phasing out of coal-fired power necessitate the rapid adoption of alternative supplementary cementitious materials like slag, this arbitrary prescriptive limit severely constrains the construction sector's ability to decarbonize. This cap, often rooted in dated concerns over carbonation and early-age performance, lacks validation from long-term, exposure-specific field data for modern mix designs. By systematically investigating the durability and constructability of high-volume slag concrete, this research will generate the essential evidence required to transition from restrictive prescriptive standards to performance-based specifications. Overcoming this barrier is paramount, as it would unlock a readily available, high-impact pathway to significantly reduce the embodied carbon of the UAE's essential infrastructure, directly supporting national net-zero ambitions while ensuring structural longevity and resilience.

Objectives

This paper is a part of an ongoing project that comprehensively aim to evaluate the mechanical and durability properties of concrete mixtures incorporating high volumes of slag (ranging from 25% to 70% cement replacement) compared to conventional concrete with no slag and ordinary Portland cement (OPC) concrete under harsh environment (e.g., high temperature). The specific objectives of this paper are:

1- To design and produce concrete mixtures with varying slag contents (0%, 25% and 40%).
2- To investigate the fresh properties of these mixtures, including Air content and slump to assess workability and its impact on practical construction applications.
3- To determine the mechanical properties, including compressive strength, splitting tensile strength, and flexural strength, at 28 days to understand strength development patterns.
4- To evaluate key durability indicators, with a focus on electrical resistance of concrete.

To analyze the results to identify an optimal range of slag content that balances environmental benefits with performance requirements for highway infrastructure applications in the UAE's specific climate.

Methodology

During the initial phase of this project, the completion of an extensive literature review was conducted. In addition, a generic bibliometric analysis was performed using the software VOSviewer to identify the most relevant and influential literature in the research domain of the use of high volume of slag as a construction material under harsh environment to increase its practicality in field application. Subsequently,



Figure 1: Compressive strength set-up

This phase explores the potential role of high volume of slag on the fresh and hardened characteristics of concrete. General use (GU) and slag that meet the requirements of CAN/CSA - A3001 standard will be used [9]. In comparison to control mixtures without slag, a wide range of novel concrete mixtures will be designed and manufactured with a water-to-binder ratio of 0.42 and dosages of cement (35-75% by mass of binder) and slag (25-65% by mass of binder). The binder content will be kept constant (450 kg/m3). A set of trial experiments was conducted to adjust the dosage of superplasticizer and air-entrainment admixture to achieve acceptable criteria set by different standards for structural concrete. A total of 26 mixtures was designed to prepare concrete with high volume of slag. The number of mixtures can be adjusted accordingly based on the availability of slag grades. The experimental work was based on a factorial design approach to verify statistical significance of results and detect individual and interaction effects of key mixture design parameters on fresh (air content, workability, heat of hydration, setting time, plastic shrinkage) and hardened (strength development, modulus of elasticity, drying shrinkage) properties of these novel concretes. For each mixture replicates of 100×200 mm cylinders, and 75×75×285 mm prisms were cast [10-15].

The consistency of the mixtures will be performed using the truncated cone method according to CSA A23.2-5C [16]. In addition, the setting time of the mixtures will be determined following ASTM C403/C403M [17], fresh mortar without coarse aggregate will be placed in a container at room temperature, and the penetration resistance was determined by standard needles at regular time intervals. Also, the air content of the fresh mixtures was measured according to CSA A23.2-4C [16]. The compressive and splitting tensile strengths were determined according to CSA A23.2-14C (see Figure 1) and ASTM C496, respectively [15-16]. Following the guidelines of ASTM C78, four-point bending tests will be carried out to evaluate the flexural performance of the mixtures [15]. The air content and spacing factor of the hardened specimens was determined following ASTM C 457 [11]. For the concrete under ambient temperature, the interconnectivity of pore system of the composites was assessed by bulk resistivity to simulate non-destructive testing approach [18].

The results of fresh and hardened properties were corroborated with analyses from characterization techniques (e.g., SEM, TGA, XRD) to interpret the trends observed and describe the evolution of the microstructure versus time. This approach will capture most efficient type and replacement level of the slag without impairing the development of microstructure and stability of the air void system within the matrix.

Materials Research Proceedings 67 (2026) 832-839 https://doi.org/10.21741/9781644904176-115

Results and Discussion

Fresh properties

Fresh properties, slump and setting time. Increasing slag content was associated with a progressive loss in workability under a constant w/c of 0.42 and no superplasticizer dosage. The slump decreased from 55 mm at 0% slag to 45 mm at 25% and 35 mm at 40%, corresponding to reductions of about 18% and 36% relative to the control. The setting-time response showed a more complex pattern. The initial setting time was essentially unchanged at 25% slag (approximately 151 min versus 151 min for the control), but it shortened at 40% slag to 111 min (27% lower than the control). In contrast, the final setting time increased monotonically with slag content, from 225 min (0%) to 250 min (25%) and 308 min (40%), yielding an extended setting interval (final–initial) from 74 min at 0% to 99 min at 25% and 197 min at 40%. Practically, this means that while the 40% slag mixture reached the initial-set criterion earlier, it required substantially longer to attain final set, widening the finishing and curing window. The joint effect of lower slump and a longer final setting at 40% suggests that, in the absence of chemical admixtures, placement and finishing would benefit from more deliberate curing management to avoid premature drying while ensuring adequate surface quality.

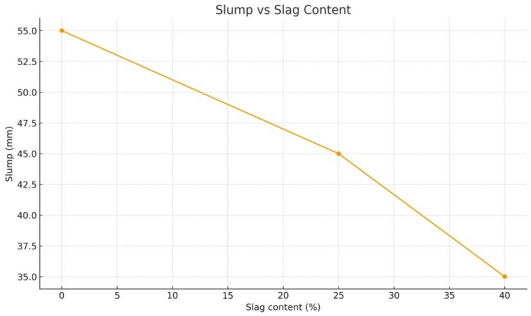


Figure 1. Slump versus slag content.

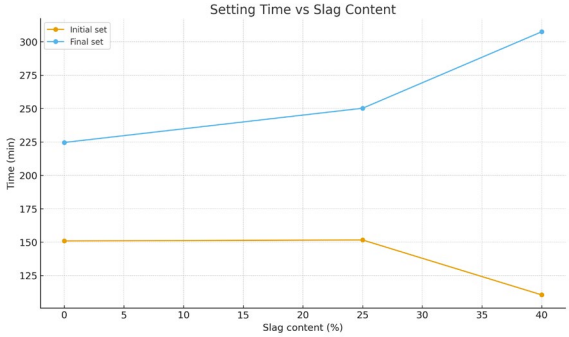


Figure 2. Initial and final setting time versus slag content.

Mechanical properties

Mechanical properties, compressive, splitting tensile, and flexural strength. The compressive strength at 28 days decreased modestly with slag addition, from 45.9 MPa (0%) to 43.0 MPa (25%) and 42.3 MPa (40%), representing reductions of about 6% and 8% relative to the control. By 56 days, however, both slag mixtures slightly exceeded the control, reaching 47.9 MPa at 40% and 47.9 MPa at 25% compared with 46.3 MPa at 0% (3-3.5% gains). This evolution indicates a familiar kinetic trade-off: slower early hydration and strength gain at 28 days followed by partial recovery and mild overperformance at 56 days, consistent with latent hydraulic activation over time. The 28-day splitting tensile strength also trended downward with slag content, from 3.73 MPa (0%) to 3.46 MPa (25%) and 3.19 MPa (40%), equivalent to decreases of roughly 7% and 15%. Flexural strength at 28 days showed a similar early-age penalty, dropping from 5.55 MPa (0%) to 5.34 MPa (25%) and 4.80 MPa (40%), or about 4% and 14% lower than the control. Notably, flexural strength at 56 days reversed this trend and increased with slag, reaching 5.91 MPa at 25% and 6.75 MPa at 40% compared with 5.63 MPa at 0% (5% and 20% gains). Taken together, the mechanical results show that higher slag contents impose a measurable early-age penalty in both compressive and tensile-related properties at 28 days, but that penalty is largely mitigated, and in flexure substantially offset, by 56 days. From a structural scheduling perspective, mixtures with 25-40% slag would benefit from construction sequencing that either allows additional curing time before load application or uses maturity-based opening criteria; conversely,

for applications where 56-day performance governs, the 40% slag mixture offers a clear flexural advantage.

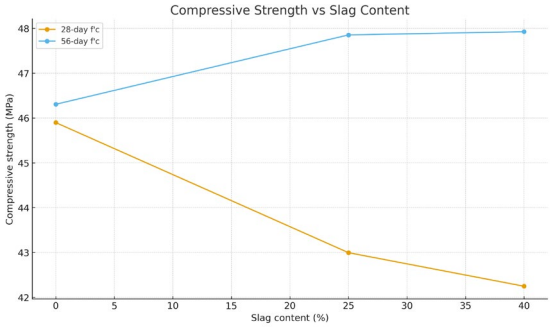


Figure 3. 28-day and 56-day compressive strength versus slag content.

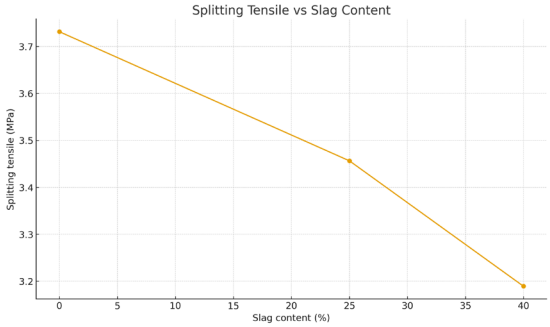


Figure 4. 28-day splitting tensile strength versus slag content.

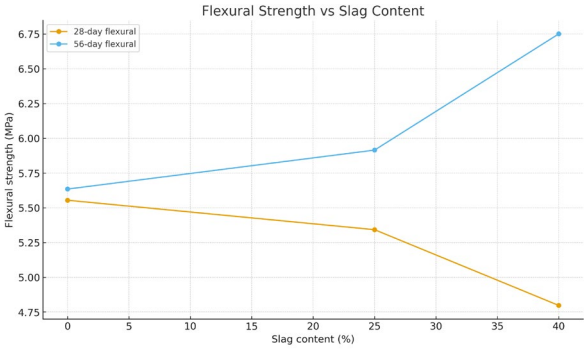


Figure 5. 28-day and 56-day flexural strength versus slag content.

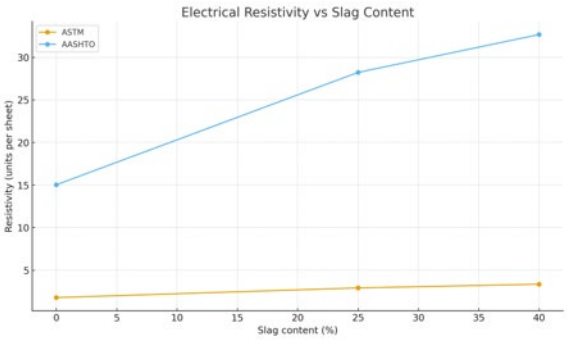


Figure 6. Electrical resistivity (ASTM and AASHTO) versus slag content.

Electrical resistivity

Electrical resistivity. Both measurement methods exhibited strong, monotonic increases in resistivity with slag addition. Using the ASTM protocol, resistivity rose from 1.77 (0%) to 2.91 (25%) and 3.34 (40%), corresponding to increases of approximately 64% and 89% relative to the control. Using the AASHTO method, values increased from 15.03 (0%) to 28.23 (25%) and 32.68 (40%), i.e., about 88% and 117% higher than the control. Although the two test methods yield different absolute magnitudes, the directional agreement is clear: higher slag contents substantially elevate resistivity. Because electrical resistivity is a well-established proxy for ionic transport, these data indicate a marked reduction in permeability-related transport processes as slag replaces clinker, consistent with microstructural refinement and pore-solution changes. The combination of modest 56-day strength gains and large resistivity increases at 25-40% slag suggests a favorable durability-strength balance at later ages, particularly for chloride-laden or marine exposures in

which reduced ingress is paramount. Overall, the dataset delineates a coherent performance envelope driven by slag dosage. At constant w/c and without chemical admixture, increasing slag from 0% to 25% to 40% reduces slump and slightly penalizes 28-day mechanical properties, while extending the time to final set; by 56 days, compressive strength is neutral-to-positive and flexural strength is notably improved at 40%. In parallel, both ASTM and AASHTO resistivity nearly double across the range, signaling significantly enhanced resistance to ionic transport. For practice, these results argue for tailored construction logistics at higher slag contents, particularly attention to curing and opening times, so that the early-age penalties do not offset the measurable durability gains evident at later ages.

Conclusions

The research is focusing on evaluating the behaviour of concrete containg high volume of slag, and the following concluion can be drawn based on the experimetnal work introduced in this paper:

- Increasing slag from 0%-25%-40% reduced slump and widened the setting window; initial set was unchanged to slightly faster, while final set was noticeably longer, requiring stricter curing/finishing control.
- Early-age mechanical performance showed a modest 28-day penalty in compressive, splitting, and flexural strengths, but 56-day results recovered; flexural strength notably improved at 40% slag.
- Electrical resistivity rose substantially with slag content (ASTM and AASHTO), indicating markedly lower ionic transport and improved durability potential in chloride- and moisture-driven exposures.
- Overall, 25-40% slag is viable for durability-critical infrastructure when construction sequencing and curing are adjusted; results support moving from prescriptive limits to performance-based specifications.

References

[1] ADCEB 2021 "Abu Dhabi economic vision 2030."

[2] ECC (Environment and Climate Change). (2019). Government of UAE releases emissions projections, showing progress towards climate targets. https://u.ae/en/about-the-uae/strategies-initiatives-and-awards/strategies-plans-and-visions/environment-and-energy/the-uae-net-zero-2050-strategy

[3] Cement and Concrete Association (2022). "Roadmap to Net-Zero Carbon Concrete by 2050", https://ised-isde.use.ae/site/clean-growth-hub/en/roadmap-net-zero-carbon-concrete-2050.

[4] Cement and Concrete Association (2023). "Concrete Zero", https: //cement.ca/app/uploads/2023/05/ConcreteZero-Report-FINAL-reduced.pdf.

[5] Government of Fujairah, Mining and minerals, Hajar Mountains. https://fnrc.gov.ae:9044/portal/assets/pdffiles/brouchers/minning_book_en.pdf.

[6] Ghazi, A. B., Jamshidi-Zanjani, A., and Nejati, H. (2022). Utilization of copper mine tailings as a partial substitute for cement in concrete construction. Construction and Building Materials, 317, 125921. https://doi.org/10.1016/j.conbuildmat.2021.125921

[7] Market Research. Challenges to Tackle by the UAE Construction Sector. https://www.researchinuae.com/insight/challenges-to-tackle-by-the-uae-construction-sector

[8] Schuldt, S. J., Jagoda, J. A., Hoisington, A. J., and Delorit, J. D. (2021). A systematic review and analysis of the viability of 3D-printed construction in remote environments. Automation in Construction, 125, 103642. https://doi.org/10.1016/j.autcon.2021.103642

[9] CSA. (2018). "Cementitious materials for use in concrete." CSA-A3001-13, Canadian Standards 143 Association (CSA), Toronto, ON, Canada.

[10] ASTM, Standard Test Method for Slump of Hydraulic-Cement Concrete, in C143. 2015, ASTM International: West Conshohocken, PA.

[11] ASTM, Standard Test Methods for Time of Setting of Hydraulic Cement by Vicat Needle, in C191. 2013, ASTM International: West Conshohocken, PA.

[12] ASTM, Standard Test Method for Density, Absorption, and Voids in Hardened Concrete, in C642. 2013, ASTM International: West Conshohocken, PA.

[13] ASTM, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, in C39. 2015, ASTM: West Conshohocken, PA.

[14] ASTM, Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens, in C496. 2011, ASTM: West Conshohocken, PA.

[15] ASTM, Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading), in C78. 2016, ASTM International: West Conshohocken, PA.

[16] CSA. 2019. "Concrete materials and methods of concrete construction / test methods and 147 standard practices for concrete." CSA A23.1-19/A23.2-19, Canadian Standard Association 148 (CSA), Toronto, ON, Canada.

[17] ASTM C403. 2008. Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance. ASTM International, West Conshohocken, PA, 04.02

[18] ASTM, Standard Test Method for Bulk Electrical Conductivity of Hardened Concrete, in C1760. 2012, ASTM International: West Conshohocken, PA.