

Can low-carbon concrete technologies simultaneously reduce emissions and improve arid-climate structural integrity in Egypt?

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ABSTRACT

Egypt is going through a period of rapid urban expansion, requiring enormous quantities of concrete to sustain. Yet, Ordinary Portland Cement (OPC) presents two significant problems. The first is environmental; OPC accounts for roughly 7-8% of global CO₂ emissions. The second is technical: in Egypt's hot desert climate, concrete is prone to plastic shrinkage cracking, thermal cracking, and sulphate attack, all of which compromise structural integrity over time. This literature review examines whether low-carbon concrete technologies can address both environmental and durability issues simultaneously.

Research conducted with peer-reviewed literature across Web of Science, Google Scholar and ScienceDirect showed five main low-carbon concrete formulations to be evaluated against Egyptian specific criteria: carbon reduction potential, early-age strength development, resistance to sulphate attack, curing requirements, and local material availability. The formulations compared include high-volume fly ash concrete, slag-blended concrete, limestone calcined clay cement (LC³), ternary blends with silica fume, and geopolymer concrete.

Findings declare that no single formulation is optimal for every situation. Rather, for general construction, LC³ appears the most promising. It relies on limestone and clay abundant in Egypt, achieves early-age strength comparable to OPC which aids mitigation of plastic shrinkage, and reduction of emissions by 30-40%. Slag-blended concrete is well-suited for aggressive environments like saline soils and coastal areas. This is due to its excellent sulphate resistance and availability from Egypt's steel industry. For signature structures requiring very high performance, ternary blends are appropriate, though their cost and imported materials limit them to premium applications. Geopolymers and fly ash concretes face significant challenges with availability and curing temperature sensitivity, making them practical only for precast elements.

The review concludes that low-carbon concrete can reduce emissions and improve structural integrity in Egypt, but success is dependent on formulation selection aligned with each practical requirement.

INTRODUCTION

Concrete is the most consumed man-made material globally. This is a testament to its low cost, versatility, and, advantageous mechanical properties when working in compression, helping it withstand vertical loads. (Monteiro et al., 2017). However, this widespread reliance presents significant challenges that are often treated like an occupational reality than fundamental shortcomings.

Its primary binder, Ordinary Portland Cement (OPC) is a significant source of CO₂ emissions, responsible for an estimated 7-8% of the global total, and with the escalating infrastructure needs driven by global population, OPC production is projected to increase by about 12–23% by 2050. This stems from both the energy-intensive calcination process, which heats limestone to over 1400°C, and, the chemical reaction itself, which releases CO₂ during clinker production. (IEA, 2021). Despite this, the cement and concrete industry must reduce its annual CO₂ emissions by 4% by 2030 to meet the Net Zero Emissions by 2050 scenario (Lim et al., 2025).

Furthermore, Egypt's climate, a hot desert climate characterized by high temperatures, low humidity and wind, is prone to experiencing multiple setbacks both in the building process and throughout its lifetime. The desert climate causes accelerated evaporation, leading to increased plastic shrinkage cracking that, if not addressed, can reduce longevity and durability. High temperatures also speed up the curing process, causing the concrete to set too quickly preventing it from reaching its maximum strength. And, because of the extreme temperature variation between days and nights, the concrete is subjected to significant expansion and contraction which may cause cracking. A phenomenon that also challenges the structural integrity of concrete is the high soil salinity. The wind picks up the salt particles and if the sulphates penetrate the concrete, they cause internal expansion and damage. (Al-Saleh, 2016).

Consequently, any viable path taken to amend these issues should address the dual challenges of decarbonization and durability. This defines the core research of low carbon concrete. Low-carbon concrete technology is focused on reducing the clinker factor in cement. Therefore, the development of innovative production technologies for carbon-neutral concrete is imperative to achieve a more sustainable environment. This is also increasingly reinforced by both domestic regulations and international trade policies.

Domestically, Egypt's environmental law (Law 4 of 1994) and its amendments mandate emission controls for industrial facilities (Egyptian Environmental Affairs Agency, 1994), with government agencies monitoring compliance and enforcing pollution reduction plans. Specific to the cement sector, regulations require the use of emission control systems and set specifications for coal usage, with penalties for violations under the Environment Law (Egyptian Environmental Affairs Agency, 2015).

Egypt's updated Nationally Determined Contribution also explicitly references a Low-Carbon Roadmap for the cement sector, targeting a 15% reduction in CO₂ emissions (Government of Egypt, 2023).

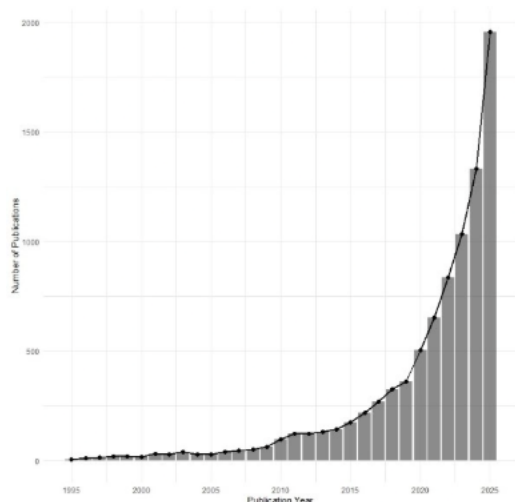


Figure 1: Number of publications from 1995-2025 using the search term "low carbon concrete" on Web of Science. Figure was made using the ggplot2 (Wickham, 2016) package in R studio (R Core Team, 2025).

But perhaps more pressing is the European Union's Carbon Border Adjustment Mechanism (CBAM), which entered full enforcement in 2026. It mandates that Egyptian exports of cement, steel, aluminum, and fertilizers to Europe now face carbon tariffs based on the emissions generated during production. These tariffs track EU carbon prices which have been hovering around €85-100 per ton of CO₂. Estimates suggest this could cost Egyptian exports between €7 billion and €29 billion annually unless domestic production emissions come down (El-Lethey, 2026), which poses a significant economic threat.

The government has responded by planning an industrial emissions registry for late 2025, developing national strategies for greener manufacturing, and securing around €62.6 million in financing from development partners like the French Development Agency and European Investment Bank to support industrial decarbonization (Ministry of Industry and Transport, 2025b). Companies are beginning to move as well. Arabian Cement Company secured financing to install Egypt's first hydrogen injection system and expand its alternative fuel capacity, aiming to cut about 130,000 tonnes of CO₂ annually (Arabian Cement Company, 2025). The Egyptian government has also started collaborating with state-owned enterprises to meet the technical requirements of the CBAM. Mohamed El-Shimy, the Minister of Public Enterprises Sector, has stressed the need for continuous monitoring of carbon emissions, and specialised task forces have been formed within companies to prepare carbon footprint reports and monitor emissions (Daily News Egypt, 2025).

Due to rigorous emergent climate policies and corporate net-zero pledges, low carbon concrete and its various methodologies have rapidly evolved into a major global research frontier. Academic publication rates have significantly exponentially increased over the past 3 decades (Figure 1: Number of publications from 1995-2025 using the search term "low carbon concrete" on Web of Science. Figure was made using

the ggplot2 (Wickham, 2016) package in R studio (R Core Team, 2025), and new industrial standards have been developed to facilitate its adoption.

A comprehensive review by D'Alessandro et al. (2017) classifies innovative concrete methodologies into three main lines. The first is concrete with improved physical and mechanical properties, which focuses on improving performance and durability to extend life cycle and reduce material needed. The second is concrete with reduced raw material, which focuses on reusing materials and replacing virgin materials with low-use alternatives. The third is concrete with increased energy efficiency, which has better thermal and optical properties. Together, these three categories provide a framework for understanding different approaches to sustainable concrete, from making it last longer to using less material to making buildings more energy efficient.

Within the first category, high-strength and ultra-high-performance concretes use optimized particle packing, low water-to-binder ratios, and additions of fiber or silica to achieve noticeably higher compressive strength, leading to sustainable constructions with increased long-term serviceability and reduced overall material volume. Zhang et al. (2016) demonstrated that optimal cement compositions of silica fume, slag, and fly ash in 0.7:0.1:0.1 can achieve 100 MPa at 28 days, yielding strength increases from 77.9 MPa to 108.0 MPa in OPC mortars. Al-Saleh (2016) points out that dense microstructures trap pore pressure, making high-strength concrete more prone to explosive spalling under fire. Higher-durability concretes also fall under this category: SCM-blended concrete, especially those containing slag or calcined clay, develops refined pore structures that greatly improve resistance to sulphate attack and chloride ingress (Barbhuiya et al., 2024). Blends containing calcined clay and rice husk ash have shown a 33% increase in compressive strength and up to 32% reduction in porosity (Marangu et al., 2024). Self-sensing and self-healing concretes also sit within this category, offering smart-infrastructure monitoring and autonomous crack repair respectively, though both remain emerging technologies.

Within the second category, fly ash is a pozzolanic material recovered from coal combustion, with replacements typically ranging from 15% to 35% (Barbhuiya et al., 2024), though high-volume fly ash (HVFA) formulations can exceed 50%. Ground granulated blast furnace slag (GGBFS) is a by-product of iron manufacturing with both hydraulic and pozzolanic properties, with replacement levels from 30% to 80% (Althoey et al., 2023). Silica fume, a fine byproduct of silicon production, boosts performance when present at around 5–10% (Althoey et al., 2023; Zhang et al., 2016). Calcined clay becomes a reactive pozzolan when heated between 600 and 850°C, with optimum reactivity depending on kaolinite content; for low kaolinite content of 27%, the optimum clay-to-limestone ratio is 2:1, while for high kaolinite content of 80%, it should be 1:2.5 (Almada et al., 2025). Novel cements including limestone calcined clay cement (LC³), alkali-activated materials (AAMs), and geopolymers further reduce or eliminate clinker. LC³ contains roughly 50% clinker, 30% calcined clay, 15% limestone, and 5% gypsum, achieving performance similar to OPC while reducing CO₂ by 40% (Scrivener et al., 2018). Geopolymers can achieve very low carbon footprints because they use no clinker (Guo et al., 2024), though they face

challenges with activator cost and safety, precursor variability, limited durability data, and lack of standard mix designs.

The third category, concretes with increased energy efficiency, including insulation, optical, and thermal storage approaches addresses operational energy rather than the embodied carbon of concrete itself and is therefore outside the scope of this material-selection review.

Egypt's abundant limestone, clay, and steel-industry slag position it favorably relative to Gulf countries that rely more heavily on imported materials, and the adoption trajectories in Cuba, India, and parts of Africa provide useful precedents for LC³ deployment. But Egypt's water scarcity leads to curing challenges that are less acute in more humid MENA climates. The regional research gap identified by Al-Saleh (2016) remains: few studies systematically evaluate low-carbon formulations under the combination of high temperature, low humidity, and saline conditions found in Egypt. This paper addresses the gap by evaluating five low-carbon concrete formulations against Egyptian-specific criteria.

METHODOLOGY

Search strategy

This review was compiled from three different literature search databases: Web of Science, Google Scholar, and ScienceDirect. Web of science was used for peer-reviewed journal articles covering most of the major research topics. Google Scholar was employed to ensure broader literature coverage. Science Direct was utilized to search for more subject specific material. Organization websites including the International Energy Agency, United Nations Environment Programme, and Egyptian government agencies were consulted for policy documents and technical reports.

Keyword search terms were organized into five main groups:

- Low-carbon concrete, sustainable concrete, green concrete, and eco-efficient concrete.
- Supplementary cementitious materials, SCMs, fly ash, slag, GGBFS, silica fume, calcined clay, LC³, geopolymer, and alkali activated.
- Performance-related words like durability, compressive strength, early strength, sulphate resistance, chloride resistance, plastic shrinkage, and curing were also used.
- For climate context, keywords included arid climate, hot climate, desert environment, high temperature, Egypt, and MENA region.
- For sustainability, keywords included carbon footprint, embodied carbon, life cycle assessment, Egypt 2030 Vision, and climate strategy.

Search criteria

Only peer-reviewed journal articles or authoritative reports from industry or government were included. Sources with publication dates between 2010 and 2025, to ensure relativity. Content addressing low-carbon concrete materials, performance, and reporting on emissions reductions or mechanical properties. They also had to address concrete performance in challenging environments like arid or hot or chemically aggressive conditions. Sources relevant to Egypt or similar places like the Middle East or North Africa were prioritized.

Sources not in English were excluded due to accessibility limitations. Opinion pieces or editorials without original data were also left out. Research on materials that are not commercially available or scalable were excluded due to impracticality of implementation in Egypt.

Selection of formulations

To ensure proper contextuality and relevance this review focuses on five main formulations which were evaluated against five criteria. Prevalence in literature, meaning the formulation appears frequently in peer-reviewed research and has been studied by multiple independent groups so the findings are more reliable. Technical maturity, meaning the formulation has moved beyond just lab experiments to actual field trials or commercial use. Carbon reduction potential, requiring documented CO₂ reductions of at least 30% compared to OPC concrete which is vital to reach Egypt's targets. Arid climate relevance, requiring literature on how the formulation performs in conditions like Egypt's, high temperature, low humidity, and saline exposure. Material availability, meaning the materials are either available in Egypt or could reasonably be produced or imported.

The five formulations selected are high-volume fly ash concrete because it is the most studied SCM globally and works as a benchmark. Slag-blended concrete because it is widely used, has excellent durability, and comes from Egypt's steel industry. LC³ because it is an emerging technology that uses local materials and was developed for places without industrial SCMs. Ternary blended concrete because it is a high-performance option for premium applications. Geopolymer concrete because it is a zero-clinker option with maximum carbon reduction potential.

Evaluation framework

To assess which formulations are best suited for Egyptian application, a set of criteria was developed based on the literature to be applied qualitatively: The environmental stressors that Al-Saleh (2016) identifies for arid climates. Performance requirements from durability literature like Barbhuiya et al. (2024) and Scrivener et al. (2018). Policy priorities from Egypt's 2030 Vision and 2050 Climate Strategy that Fouly and Abdin (2024) and Hagag et al. (2022) discuss. Practicality like material availability, cost, and whether concrete can be properly cured in Egypt were also considered.

The criteria include carbon reduction potential, which compares the CO₂ reduction to OPC concrete in alignment with Egypt's 2030. Additionally, technical maturity distinguishes between established technologies and emerging alternatives. Early-age strength development and heat of hydration are performance related criteria which are both critical qualities due to the rapid setting and thermal cracking risks associated with hot arid climates. Sulphate and chloride resistance and workability are essential for structures exposed to aggressive soils and saline ground water common in Egypt and influence placement and compaction. Curing requirements, local material availability, cost competitiveness are practicality criteria which address domestic implementation.

RESULTS

Understanding the most widely researched and used low-carbon concrete technologies worldwide is vital to evaluating formulations against Egypt-specific standards. Literature indicates that there are five formulations that dominate current research and practice.

Formulation 1: high-volume fly ash (HVFA) concrete

High-volume fly ash concrete replaces 40% to 60% of OPC with fly ash, this formulation has been extensively studied since the 1980s and is one of the most well-known low-carbon concrete technologies (Habert et al., 2020). Fly ash particles are spherical and glassy; by reacting with calcium hydroxide, they form additional calcium silicate hydrate (C-S-H). However, this reaction occurs more slowly than cement hydration which leads to slower early-age strength gain than typical OPC concrete (Barbhuiya et al. 2024). Depending on replacement level and transportation distance, there could be a 30–50% decrease in embodied CO₂ when compared to OPC concrete (Habert et al., 2020).

When evaluated against Egypt's environment, HVFA offers both benefits and drawbacks. Its low heat of hydration is applicable to the massive concrete foundations built in new cities and avoids thermal stress. High workability is also beneficially exhibited in this formulation; it eases the pumping and construction process due to its low viscosity. Finally, the high sulphate resistance of HVFA is crucial in Egypt due to the presence of highly aggressive soils.

HVFA's main disadvantage is its slow early-age strength which heightens the threat of plastic shrinkage cracks appearing due to the rapid loss of moisture in the air. Furthermore, the cement requires moist curing for 7-14 days which is challenging in the hot seasons. Apart from that, HVFA is not produced locally anymore since the government ended production of coal, meaning that it must be imported from other countries.

Thus, it should be stated that HVFA is beneficial for projects with specific individual needs. However, for most construction sites, its application is complicated by the need for import and special curing conditions during the hot season.

Formulation 2: slag-blended concrete (OPC + GGBFS)

Slag-blended concrete uses ground granulated blast furnace slag, a by-product of making iron, to replace 30% to 80% of OPC. When activated, slag can react with water independently because it has both hydraulic and pozzolanic properties (Althoey et al., 2023). Slag particles are glassy and angular. Slag experiences a latent hydraulic reaction in the alkaline environment produced by cement hydration, forming C-S-H more slowly, but this reaction consumes less calcium hydroxide than pozzolanic reactions which creates a denser more durable structure (Barbhuiya et al., 2024). Using slag blended concrete decreases embodied carbon by 40-60%, with larger replacements resulting in larger savings (Guo et al., 2024).

Slag concrete is advantageous in a multitude of different ways. It exhibits outstanding sulphate and chloride resistance (Barbhuiya et al., 2024). It is a local product, the material is durable, and its long-term strength ensures extended service life. It also demonstrates moderate early-age strength compared to fly ash-blended cement.

Slag-blended concrete has significant disadvantages. The material requires proper curing to prevent early-age drying (Li et al., 2024), it has poor workability, especially in hot weather, and since slag production is tied to steel production levels, it is hard to meet the supply demands of the entire construction industry in Egypt.

Slag blended concrete is highly recommended for critical and high value infrastructure such as in marine structures, foundations in aggressive soils, water retaining structures and buildings with long design lives such as bridges or tunnels. Conversely, it is not cost-effective to use this concrete in general construction due to its limited supply and poor workability.

Formulation 3: limestone calcined clay cement (LC³)

LC³ is a ternary blended cement consisting of approximately 50% clinker, 30% calcined clay, 15% ground limestone, and 5% gypsum. It was developed specifically to address the limited availability of industrial SCMs in many developing regions (Scrivener et al., 2018). LC³ depends on the synergy between calcined clay and limestone. Calcined clay provides reactive alumina and silica, which react with calcium hydroxide from clinker hydration. The limestone then reacts with alumina to form carboaluminate phases which stabilize hydration products and refine pore structure Almada et al. (2025). Currently LC³ offers a 30-40% reduction in embodied carbon with higher potential as production efficiency improves (Scrivener et al., 2018; Yu et al., 2025). This type of cement is currently being adopted in countries like Cuba, India and parts of Africa due to the availability of local clay or lacking industrial SCMs.

Benefits of using LC³ include its early strength comparable to that of OPC, which decreases the risk of plastic shrinkage associated with fly ash and slag (Barbhuiya et al., 2024). Additionally, Egypt has ample supply of lime stone and clay that would be needed for production (Fouly & Abdin, 2024). Its fine pore structure ensures sulphate and chloride resistance, and its moderate curing requirements are easier to

meet in the water-scarce environment of Egypt. Finally, with its potential to reduce carbon emissions by 30–40%, LC³ is consistent with the goal of Egypt's 2030 Vision.

The main argument against adopting LC³ concerns the lack of existing infrastructure for clay calcination and the high capital expenditures needed to construct it. LC³ also has a moderate heat of hydration, which may need to be considered when designing large structures. Furthermore, there are variations in the quality of clay, and some deposits may be incompatible with the production process. Ultimately, while the initial cost of constructing LC³ production facilities may be expensive, the abundance of raw materials in Egypt suggests that the production costs of this cement should be comparable to that of OPC. In the long run, the carbon tax and the cost of importing fly ash will likely make LC³ more economical than OPC.

Overall, LC³ has the most potential to be a truly domestic cement replacement for OPC. It avoids the import dependance of fly ash and the supply constraints of Slag.

Formulation 4: ternary blended concretes (OPC + Slag + Silica Fume)

These blends combine three cementitious components such as OPC slag or fly ash and silica fume to take advantage of their strengths while also compensating for their individual weaknesses. In this example, silica fume provides high early strength along with denser packed concretes and rapid reactions; the slag provides long term durability and low permeability and the OPC provides primary activation and early hydration. Zhang et al. (2016) also demonstrated that optimized binder composition of cement: silica fume: slag: fly ash = 0.7:0.1:0.1:0.1 achieved compressive strength increases the pressure it can handle from 77.9 MPa to 108.0 MPa compared to OPC-only mortars. This cement formulation achieves a 40-50% reduction, though silica fume's high embodied carbon per ton (due to energy-intensive production) partially offsets slag's benefits. Net reduction depends on proportions.

Comparing to Egypt's standards, ternary blends are a high-performance, high-cost option. They have outstanding properties, including high workability, durability, and extremely high early strength, but this strength is almost exclusively due to the addition of silica fume, requiring import. Moreover, concrete is very challenging to process and requires very high levels of curing, which is a problem in the dry climate of Egypt.

This is the most versatile concrete so far but should preferably only be used in projects requiring the highest-grade material. Such as in high rise buildings, bridge decks, marine structures, industrial and chemical facilities and so on because of their mix of different abilities.

Formulation 5: geopolymer and alkali-activated concretes

Geopolymers and alkali-activated materials eliminate the use of a clinker entirely. They are produced in the reaction between aluminosilicate precursors (fly ash, slag, metakaolin) with alkaline activator solutions (sodium hydroxide, sodium silicate). When the precursor is fly ash or metakaolin, it is often called "geopolymer" (Al Khaffaf et al., 2024). The alkaline activator dissolves silica and alumina from the precursor, which then polymerize into a three-dimensional inorganic network (N-A-S-H gel in geopolymers, C-A-S-H in alkali-activated slag). This structure binds aggregate similarly to cement hydration but through different chemical mechanisms (Salihu et al., 2021). This blend creates up to an 80-90% reduction with zero clinker, though activator production (especially sodium silicate) can leave significant carbon footprint (Guo et al., 2024).

Geopolymers offers the most embodied carbon reduction and excellent chemical resistance properties (Bao et al., 2024). As well as good high-temperature performance (Salihu et al., 2021). Nevertheless, it is not applicable to significant commercial adoption due to challenges in standardization of mix design and lack of long-term performance data. Moreover, the activators used in the production of geopolymers have to be imported into Egypt, and the material requires highly stable temperatures for setting, which is difficult to meet in the local environment.

Based on this analysis, we can conclude that it is most suitable for niche applications such as chemical pipes and flooring. Further research and development of the technology might bring additional benefits, but it is unclear if they will be applicable in the local environment.

To determine which formulations are most suitable for Egypt, we apply certain criteria as an evaluation framework following Egypt's environmental conditions (Al-Saleh, 2016), its sustainability policy framework (Fouly & Abdin, 2024; Hagag et al., 2022) and material performance requirements (Barbhuiya et al., 2024; Scrivener et al., 2018).

Table 1: Comparison Table of five formulation candidates against criteria

Criteria	HVFA	Slag-Blended	LC ³	Ternary	Geopolymer
Carbon reduction potential	30-50%	40-60%	30-40%	40-50%	80-90%

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Early age strength development	Poor	Moderate	Good	Very High	Variable
Heat of hydration	Low	Moderate	Moderate	Variable	Low
Sulphate and chloride resistance	Good	Excellent	Good	Excellent	Excellent
Curing requirements	High	High	Moderate	High	Critical
Local material availability	Poor	Good	Excellent	Poor	Poor
Technical maturity	High	High	Growing	High	Low
Cost competitiveness	Moderate	Low	High (upfront)	High	High
Workability	Excellent	Moderate	Good	Challenging	Variable

Note: Carbon reduction values are relative to OPC concrete. Qualitative ratings (Poor, Moderate, Good, Excellent) are based on the synthesis of literature reviewed in this paper. Cost competitiveness ratings reflect upfront capital costs and long-term operational costs relative to OPC.

DISCUSSION

Findings show the potential for low-carbon concrete technologies to reduce emissions while simultaneously maintaining or improving structural performance in Egypt; however, the evidence is not universal across formulation types, and there are limitations.

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Carbon reduction and structural performance

The 30-60% emission reductions attributed to LC³, slag, and ternary mixtures are well-aligned with Egypt's 2030 Vision, but the studies are usually coordinated in temperate settings or controlled environments, and the actual reductions possible in Egypt will depend on several variables that are not typically explored in the literature, such as transport distances, local distribution, and calcination efficiency. As Habert et al. (2020) note, the environmental benefits of SCMs must be evaluated in the context of the local conditions in any given location. The claim that low-carbon formulations can enhance structural performance also needs qualification. The improved early-age strength characteristics of LC³, like that of OPC, offer benefits against plastic shrinkage (Barbhuiya et al., 2024), but there is limited information on the long-term durability (10-20+ years) of LC³ in the dry, hot, saline conditions of Egypt. Scrivener et al. (2018) acknowledge that LC³ has not had the benefit of decades of performance data as OPC has. Likewise, while the dense microstructure of slag concrete provides exceptional sulphate resistance, Li et al. (2024) highlight that high-temperature exposure could impact performance differently in arid environments with temperature swings.

Trade-offs and a portfolio approach

The analysis reveals a trade-off between formulations that offer the most carbon reduction (geopolymers) but face the most implementation barriers in Egypt, and those that offer only moderate reductions (LC³) but have the most viable pathway for application in the short term. As D'Alessandro et al. (2017) observe in their formulation of the optimization problem, there is rarely a universal best performer across all metrics of sustainability. The findings suggest that for Egypt, the most viable approach will involve a portfolio of materials, selecting individual formulations based on the requirements of individual applications rather than aiming for a single solution.

Local material availability emerged as a distinguishing factor. Hagag et al. (2022) find that material production dominates a building's initial carbon footprint, and steel and cement are the largest contributors. LC³ has the benefit of being able to utilize Egypt's abundant limestone and clay resources, which other imported material-based formulas cannot, and slag's abundance as a byproduct of Egypt's domestic steel industry addresses a critical need for materials capable of withstanding aggressive environments, although to a more limited extent in terms of supply.

This has implications for Egypt's broader strategies for emissions reduction. The country's emissions reduction strategies (Ministry of Industry and Transport, 2025a) focus on its existing cement production infrastructure. While this is the correct priority, it fails to consider the need for new infrastructure to be built using low-carbon concrete formulations. Fouly and Abdin (2024) make the compelling argument that utilizing local materials is the most effective way to reduce the total carbon footprint of buildings.

Economic pressures and policy

The implementation of the EU's CBAM creates an immediate economic incentive for Egypt to adopt low-carbon concrete blends, beyond the environmental and social benefits. El-Lethey's (2026) calculation of potential annual tariffs of €7-29 billion presents a significant threat to Egypt's cement export

competitiveness, but the CBAM may also create indirect benefits. Not all cement production in Egypt is directed toward export, and the domestic construction sector represents the majority of demand. Thus, the CBAM will likely have indirect effects by increasing production costs (by necessitating investments in emissions reduction) to maintain profitability on the global market due to the tariffs on exports.

CBAM's structure allows credit for carbon pricing already paid in the exporting country; this provides an economic incentive for Egypt to implement its own carbon pricing mechanisms. A 30–40% reduction in emissions through LC³ adoption would considerably offset the potential costs of the CBAM.

Limitations

Several limitations must be noted in this review. First, the nature of this review as one relying on previously published works means that some evidence may be subject to publication bias, studies reporting positive findings are much more likely to be published than those reporting negative results, potentially overstating the benefits of each blend. Second, the qualitative assessment framework does not incorporate quantitative multi-criteria decision analysis or life cycle assessment. Finally, the exclusion of non-English works represents a limitation, as it is possible that relevant findings have been published in other languages, from Arab countries or in China, major producers of concrete research. Furthermore, the rapidly evolving policy environment means that some of the findings related to policy may require updating in the future.

Implications for Practice

The findings have several implications for practice. For general construction, LC³ should be prioritized once infrastructure is in place due to the balance of its benefits in performance, carbon reduction, and availability of local materials. For aggressive environments, specifications should be changed to utilize slag-blended concrete in foundations on saline soils, marine works, and wastewater treatment works to take advantage of its sulphate resistance. For signature structures, ternary blends offer the most performance benefits for the cost (in terms of carbon reduction) assuming import costs are not a concern. For precast elements, geopolymers and HVFA concretes might be considered. For policymakers, incentives for LC³ production infrastructure investment are needed, and standards must be updated to accommodate low-carbon formulations.

Future Research Directions

Several areas of future research were identified during the review. First, there is a need for field durability studies on the long-term (10-20+ year) performance of LC³ and slag concretes in the Egyptian environment. Further, the characterization of Egypt's clay deposits is required before widespread utilization can begin. Water-efficient curing protocols should also be investigated. Additional work is required on life cycle assessments specific to Egypt, and the microstructural effects of high-temperature environments on the refined pore structures characteristic of LC³ and slag concretes should be studied.

CONCLUSION

The challenge that faces Egypt's construction industry is that it must balance the continuation of urban development with the need to reduce emissions and ensure structural integrity. With over 96% of Egypt's landmass classified as desert, the environmental stressors of high temperatures, low humidity, and saline soils will continue to test concrete performance. Additionally, the EU's Carbon Border Adjustment Mechanism and other international obligations make reducing emissions a priority. This paper aims to evaluate whether low-carbon concrete can simultaneously address these two pressing challenges.

For Egypt, it is concluded that no single formulation is specifically superior, but we may use different formulations for different approaches. The analysis supports a portfolio approach: LC³ for general construction once production infrastructure is established, slag-blended concrete for chemically aggressive environments, ternary blends for signature high-performance structures, and geopolymers for niche precast elements.

Low-carbon concrete technologies can reduce embodied carbon emissions in the Egyptian construction sector. Concrete production using alternative materials has the potential to reduce emissions by 30-90% compared to traditional OPC-based concrete. This directly supports the emissions reduction targets outlined in Egypt's 2030 Vision and 2050 Climate Change Strategy (Egyptian Environmental Affairs Agency, 2022). The most significant emission reductions are expected from geopolymers, with the potential reduction spanning 80-90%, while LC³ and slag blended concrete have reduction potential ranging from 30 to 60%.

The durability challenges identified by Al-Saleh (2016), such as plastic shrinkage, thermal cracking, and sulphate attack, are addressed in different ways depending on the formulation. LC³'s early-age strength comparable to OPC reduces the risk of plastic shrinkage. Slag concrete's dense microstructure provides strong resistance to the chemical attacks found in Egypt's saline soils and coastal zones. These benefits depend on proper curing and construction practices. Local material availability plays a decisive role.

However, not all low-carbon concrete options are equally viable in Egypt. Using alternative materials such as fly ash, silica fume, and geopolymer precursors requires import transportation and thus carbon emission costs. Moreover, it creates a dependency on foreign suppliers. Therefore, using domestic materials in concrete production, when possible, is better for reducing emissions and ensuring supply security. Substituting OPC with slag from domestic steel mills and using locally available limestone and clay for LC³ fits into Egypt's sustainable development strategy better.

Ultimately, the success of low-carbon concrete in Egypt depends on the strategic choice of formulation that serves the application requirements, supported by appropriate infrastructure investment, quality control, and construction practices. The technologies exist; the challenge lies in their adoption in Egypt's unique environmental and economic context.

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