

UDC: 691.3

**LOW-IMPACT CONSTRUCTION MATERIALS
FOR KARAKALPAKSTAN: DURABILITY-
FIRST, LOW-CARBON CHOICES FOR SALINE
AND ARID CONDITIONS**

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***Abstract:** Karakalpakstan combines two pressures that rarely appear together in mainstream low-carbon construction guidance: a harsh arid climate with large temperature swings, and widespread soil and groundwater salinity that can accelerate concrete deterioration. This paper develops a durability-first, low-carbon selection framework for building materials suitable for Nukus and surrounding districts. The method integrates (i) a simplified cradle-to-gate embodied-carbon screening of binder pathways, and (ii) a chemical-exposure screening for sulfate and salt environments based on durable-concrete guidance and exposure-class concepts. Results indicate that clinker substitution pathways such as LC3 and locally feasible supplementary cementitious material (SCM) blends can reduce embodied carbon while maintaining, and in some cases improving, durability when permeability is controlled. The practical output is a decision matrix and mix-design guidance that prioritizes low water-to-binder ratio, sulfate resistance and curing quality, with recommendations tailored to saline soils in the Southern Aral Sea region.*

***Keywords:** Karakalpakstan; low-carbon concrete; LC3; supplementary cementitious materials; sulfate attack; saline soils; durability; embodied carbon*

1. Introduction

The construction sector in Uzbekistan is growing, and Karakalpakstan has an additional infrastructure demand linked to urban development and adaptation in the Aral Sea region. At the same time, cement production is one of the largest industrial sources of CO₂ emissions globally, primarily due to clinker production [1]. International roadmaps emphasize multiple levers to reduce cement-related emissions, including lowering the clinker-to-cement ratio through substitution and improving efficiency [2].

However, low-carbon material substitution cannot be evaluated on emissions alone in Karakalpakstan. Soil and groundwater salinity, often dominated by sulfate and chloride ions in the Southern Aral Sea region, is widely documented in recent studies [8,9]. Salts can drive chemical sulfate attack, physical salt crystallization and reinforcement corrosion, which means that a 'green' mix that is permeable or poorly cured may fail prematurely and lose its environmental advantage through repair and replacement.

The aim of this paper is to propose a materials-selection framework that treats durability under salinity as a primary constraint while still delivering meaningful embodied-carbon reductions. The objectives are: (i) compare common binder pathways using a simplified cradle-to-gate screening; (ii) map those pathways to durability requirements relevant to saline soils; and (iii) provide practical mix-design and specification guidance for typical applications in Nukus and nearby districts. Scientific novelty is the explicit coupling of low-carbon binder selection with saline-exposure screening using sources that are directly relevant to the Aral Sea region.

2. Materials and Methods

System boundary and functional unit. The embodied-carbon screening uses a cradle-to-gate boundary (A1-A3) and a functional unit of 1 m³ of structural concrete of comparable strength class. Because the exact mixture proportions depend on local materials and target strength, we use a scenario approach with representative mid-range values from peer-reviewed synthesis and widely cited references on binder substitution [2-4]. The purpose is to compare pathways, not to claim project-specific life-cycle values.

Binder pathways considered. Four representative pathways were screened: (a) ordinary Portland cement (OPC) baseline; (b) limestone calcined clay cement (LC3) with around 50% clinker, supported by evidence that such blends can deliver similar performance with lower environmental impact [3]; (c) an SCM blend with about 30% replacement using materials available regionally or through supply chains (for example, slag, pozzolans or silica-containing additives); and (d) a waste-based geopolymer pathway as a long-term option where suitable feedstocks and quality control exist [4].

Durability screening for saline environments. We used durable-concrete guidance emphasizing low permeability, appropriate cementitious composition and curing as key defenses against sulfate and salt attack [5]. Exposure-class concepts were used to translate soil and groundwater aggressiveness into practical specification constraints (maximum water-to-binder ratio, minimum binder content and material restrictions) [6]. Evidence on salinity type and prevalence in Karakalpakstan was taken from recent regional studies in the Southern Aral Sea zone [8,9].

Decision matrix and performance scoring. Each pathway was ranked using two parallel scores: an embodied-carbon score based on the scenario GWP values, and a durability suitability score based on resistance to sulfate attack, expected permeability control and local feasibility of materials and curing.

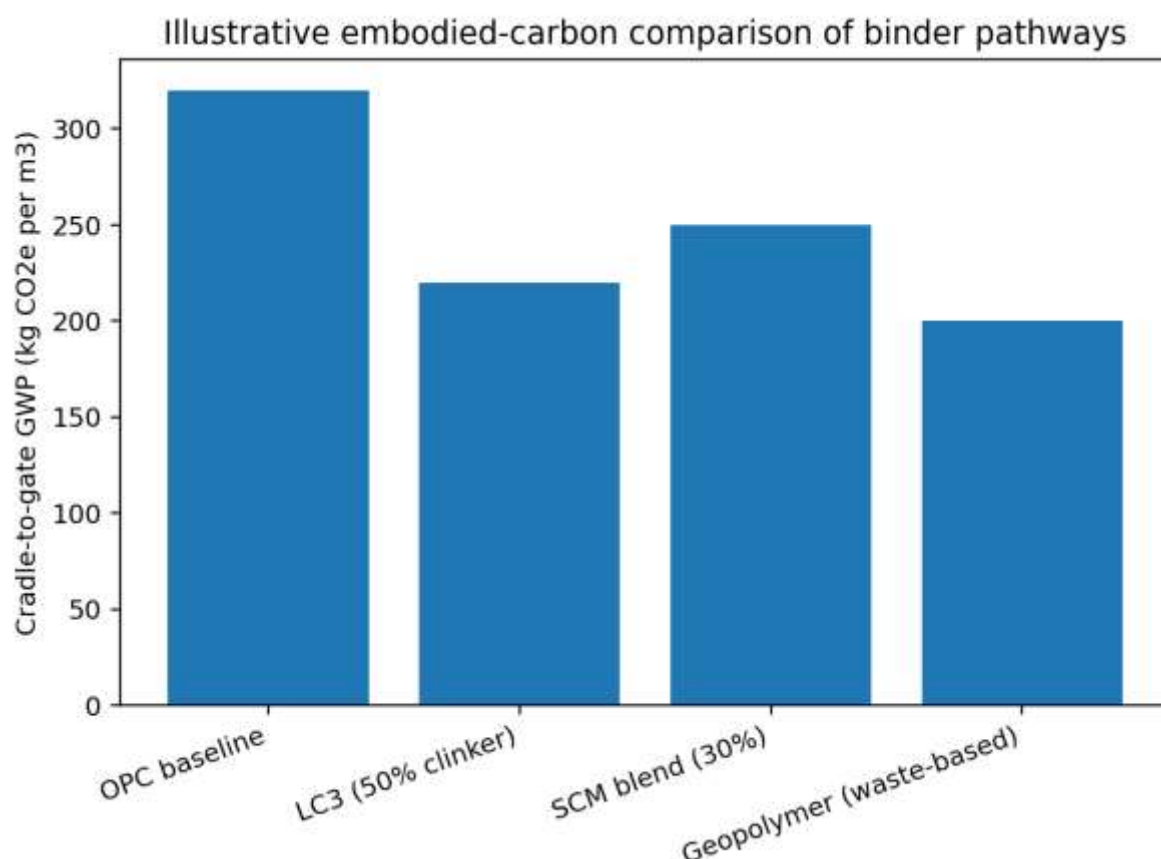


Figure 1. Illustrative cradle-to-gate embodied-carbon comparison of binder pathways. Values represent mid-range scenarios from published literature and roadmaps [2-4].

Pathway	Embodied carbon (relative)	Salinity durability potential	Key specification controls	Local feasibility notes
OP C baseline	High	Moderate (depends on SR cement class)	Low w/b; sulfate-resistant cement where	Well established supply chain; carbon

			needed; curing quality [5,6]	intensive [1,2]
LC3 (limestone + calcined clay)	Medium	High potential (lower clinker, refined pore structure)	Controlled calcined clay quality; low w/b; curing; verify sulfate resistance [3,5]	Requires calcination capacity and quality control; promising where clays exist [3]
SC M blend (about 30%)	Medium-high	High if permeability controlled; can improve durability	Select SCM type; verify compatibility ; limit w/b; ensure curing [2,5]	May use industrial by-products or mineral additives; depends on supply
Was te-based geopolymer	Low	Potentially high but variable; sensitive to feedstock and curing	Strict material characterization; curing regime; field trials [4]	Long- term option; requires strong QA/QC and stable supply

3. Results

Embodied-carbon screening. The scenario results (Figure 1) show a clear ordering: clinker-reduction strategies dominate embodied-carbon performance, with LC3 and geopolymer pathways achieving the largest reductions relative to an OPC baseline. This aligns with international roadmaps emphasizing clinker substitution as a major mitigation lever [2].

Durability screening. For Karakalpakstan, the decisive factor is permeability control. Durable-concrete guidance stresses that low water-to-binder ratio, appropriate binder composition and adequate curing reduce the ingress of aggressive ions and slow sulfate and salt attack mechanisms [5]. Regional evidence indicates that soils and groundwater in the Southern Aral Sea region frequently exhibit high salinity and sulfate dominance [8,9], so durability margins must be built into specifications rather than treated as optional upgrades.

Decision matrix. Table 1 summarizes the integrated decision view. LC3 and well-designed SCM blends offer the most balanced near-term option: they reduce embodied carbon while maintaining durability potential, provided that the city and contractors enforce curing and quality control. Geopolymer materials can deliver very low embodied carbon, but field reliability depends on stable feedstocks and rigorous quality assurance [4].

Application in Nukus region	Recommended durability controls	Low-carbon options	Notes for saline soils
Foundations and basements	Low w/b; dense concrete; continuous curing; consider waterproofing layer [5,6]	LC3 or SCM blend with verified performance [2,3]	Check soil/groundwater for sulfate and chloride; avoid poor curing which increases permeability [8,9]
External walls (masonry or blocks)	Limit capillary absorption; use breathable yet water-shedding finishes	Low-clinker binders; locally produced blocks with	Salt crystallization can damage porous units; detailing and

		optimized binder content	coatings matter [5]
Water and sanitation structures	Strict permeability and crack control; sulfate resistance; robust curing	LC3 or SCM blends with tested sulfate performance; avoid unverified binders	Aggressive water chemistry can accelerate attack; prioritize testing and QA/QC [5,6]

4. Discussion

A key implication for Karakalpakstan is that low-carbon material selection must be embedded in specification culture. Without curing discipline and permeability targets, any binder pathway can underperform in saline environments. This is particularly important for municipal procurement where short construction schedules can tempt under-curing.

Local raw materials and industrial additives matter. Recent regional studies discuss the use of Karakalpakstan mineral resources and silica-containing additives in cement and binder production, suggesting pathways for local value creation if quality control is maintained [7,10]. Such local sourcing can reduce transport emissions and support economic resilience, but only if material characterization and standard compliance are enforced.

Limitations. The embodied-carbon values are scenario-based and should be replaced by local environmental product declarations or plant-specific data as they become available. Similarly, salinity conditions vary by site; therefore, soil and groundwater testing is essential for assigning the correct exposure class and selecting sulfate-resistant solutions.

5. Conclusion

In Karakalpakstan, durability under salinity and embodied-carbon reduction must be optimized together. This paper provided an IMRAD-structured framework linking binder pathway selection to sulfate and salt exposure constraints, supported by international roadmaps and regional salinity evidence. LC3 and well-designed SCM blends appear to offer the most practical near-term pathway, while geopolymers merit targeted pilot projects with strong QA/QC. For municipal implementation, the highest-impact actions are specification of low permeability (low w/b), verification of sulfate resistance, and enforcement of curing and construction quality.

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DOI: 10.1051/e3sconf/202449104001.

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