OPEN ACCESS

Saudi Journal of Civil Engineering
Abbreviated Key Title: Saudi J Civ Eng
ISSN 2523-2657 (Print) |ISSN 2523-2231 (Online)
Scholars Middle East Publishers, Dubai, United Arab Emirates
Journal homepage: https://saudijournals.com/journal/sjce/home

Original Research Article

Sustainable Precast Concrete Technologies for Climate-Resilient Buildings and Infrastructure in Saudi Arabia

Khalid Mumtaz Bhambhro[1]*

[1]Quality Assurance and Quality Control Department, Al Kifah Precast, Dammam, Kingdom of Saudi Arabia

DOI: https://doi.org/10.36348/sjce.2026.v10i11.003 | **Received:** 22.09.2026 | **Accepted:** 13.11.2026 | **Published:** 18.11.2026

***Corresponding author:** Khalid Mumtaz Bhambhro
Quality Assurance and Quality Control Department, Al Kifah Precast, Dammam, Kingdom of Saudi Arabia

Abstract

Saudi Arabia's is big country that require concrete systems that can endure severe heat, chloride-bearing coastal conditions, intermittent intense rainfall and long service periods while reducing embodied emissions. This critical integrative review examines sustainable precast concrete technologies through the combined lenses of climate exposure, material performance, factory quality control and whole-life environmental accounting. Evidence published during 2020–2025 is organised around supplementary cementitious materials, ultra-high-performance concrete, carbon dioxide mineralisation, production control and implementation constraints. The synthesis distinguishes demonstrated material mechanisms from site-specific assumptions and proposes a stage-gated decision framework for Saudi precast applications. Silica fume and carefully selected pozzolans can refine pore structure, while fly ash performance depends strongly on curing and supply consistency. Ultra-high-performance concrete offers demanding durability applications but cannot be presumed low-carbon without mix-specific assessment. Carbon mineralisation may provide measurable storage and process benefits, yet gross injected carbon dioxide must not be confused with net avoided emissions. The review concludes that climate resilience is an evidence-based combination of exposure-specific qualification, reproducible production, service-life design and transparent life-cycle accounting, rather than a property conferred by any single additive.

Keywords: Precast Concrete, Climate Resilience, Supplementary Cementitious Materials, Ultra-High-Performance Concrete, Carbon Mineralisation, Saudi Arabia.

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1. INTRODUCTION

Precast concrete occupies an important position in rapid infrastructure delivery because controlled manufacturing permits repeatable batching, dimensional checks, accelerated assembly and systematic traceability. These advantages are especially relevant to Saudi Arabia, where construction programmes span coastal corridors, inland urban developments and industrial facilities. Yet a prefabricated component is not inherently resilient: long-term performance depends on its binder chemistry, curing history, reinforcement protection, joints, handling damage and environmental exposure. The climate challenge is therefore simultaneously a materials problem and a production-systems problem [9-12].

1.1 Problem Statement and Knowledge Gap

Much concrete sustainability research reports compressive strength or binder replacement percentages without linking these outputs to transport properties, exposure classes and expected maintenance. Conversely, resilience discussions may address hazards and governance without considering how an actual precast plant controls moisture, curing temperature or batch variation. A Saudi-focused synthesis must join these perspectives, including the interaction between high ambient temperature, saline aerosols, sulphate-bearing soils and rapid construction schedules. The resulting knowledge gap concerns selection under multiple constraints, not the absence of another high-strength mixture [1-9]. For practical adoption, each candidate should be documented as a complete production recipe rather than a binder percentage. Aggregate grading, moisture compensation, mixing sequence and curing regime determine whether the proposed sustainability advantage survives industrial manufacture. Evidence should be captured before a project commits to procurement volumes.

1.2 AIM AND OBJECTIVES

The aim is to critically evaluate how sustainable precast concrete technologies can improve climate

resilience in Saudi buildings and infrastructure while maintaining verifiable engineering performance. Four distinct objectives guide the review: first, map locally relevant climate exposures to concrete deterioration pathways; second, compare supplementary cementitious materials, ultra-high-performance formulations and carbon mineralisation on durability and carbon-accounting grounds; third, identify manufacturing and quality-assurance controls needed to translate laboratory findings into dependable precast products; and fourth, develop a practical evidence-based framework for specification, procurement and future field validation. The study asks what is technically supported, what remains conditional and what must be measured before a technology is adopted considering local sourcing of materials.

2. RESEARCH DESIGN AND SECONDARY-EVIDENCE METHODOLOGY

This manuscript presents a secondary-evidence analytical framework for comparing sustainable precast concrete technologies. It does not report new laboratory experiments or claim a completed statistical meta-analysis. Published studies from 2020–2025 provide the evidentiary basis for a proposed comparative assessment of durability, embodied-carbon accounting, manufacturability and Saudi climate exposure. The analytical workflow specifies common functional units, exposure categories, material-system descriptors and evidence-quality criteria. A journal submission claiming original quantitative results will require a documented study-level extraction sheet, verifiable source measurements and reproducible calculations; the present draft does not yet satisfy that requirement.

2.1 Evidence Extraction and Comparative Assessment

Priority is assigned to traceable peer-reviewed publications reporting material compositions, test conditions, comparison groups and measurable outcomes. Secondary reviews are used to locate mechanisms and conflicting results, not to create artificial numerical consensus. Findings are grouped by exposure mechanism, material technology, factory process and life-cycle boundary. Each claim is interpreted with attention to specimen scale, curing regime, reference mix, exposure duration and whether performance concerns a paste, mortar, concrete element or operating structure. Saudi relevance is assessed through climatic and procurement transferability rather than geographic publication alone [1–8]. For each binder candidate, laboratory records should include oxide composition, loss on ignition, particle-size distribution, density and batch-to-batch variability. These descriptors allow reviewers to interpret divergent outcomes and permit a plant to detect changes before they affect structural production. Without them, nominal replacement percentages offer little reproducibility.

2.2 Data Availability and Reproducibility Limitations

The framework is an original synthesis and research design, not a substitute for a completed quantitative secondary-data study. Cross-study comparisons are limited by inconsistent mixture proportions, curing regimes, exposure durations, carbon-accounting boundaries and reporting conventions. No pooled effect sizes, numerical rankings or experimental measurements are presented as original findings. Before submission as an original research article, the authors must populate a traceable dataset, perform the specified analysis and update the results and discussion accordingly.

3. Climate Exposure in Saudi Arabia

Saudi exposure conditions are diverse rather than uniformly desert-like. Inland components may experience strong daily temperature gradients, rapid surface drying and dust deposition. Coastal elements face airborne chlorides, saline groundwater and, in some locations, wetting and drying cycles that increase ionic transport. Buried infrastructure can encounter sulphate-bearing soils and variable moisture. Short-duration heavy rainfall creates drainage and joint-performance demands even in arid regions. Each mechanism requires an exposure-specific design response, and the response may vary between structural walls, façade panels, bridge elements and buried utility components [12-21].

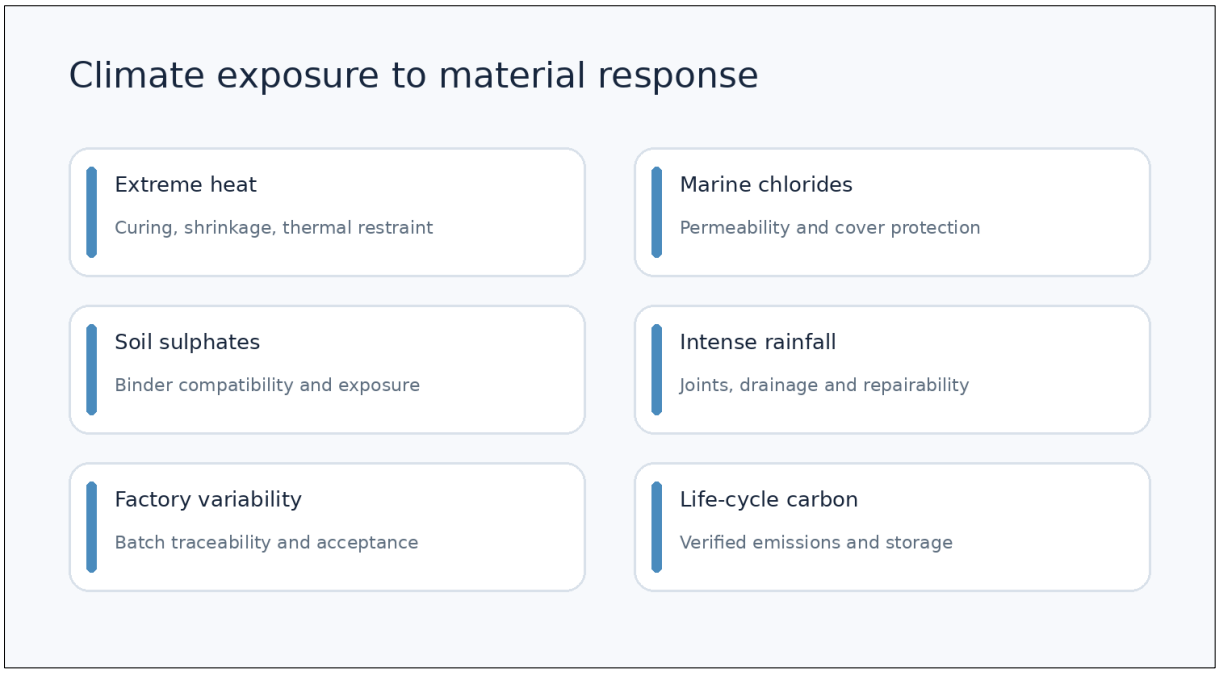


Figure 1: Climate stressors and associated precast-concrete performance responses (original conceptual illustration)

3.1 Heat, Curing and Thermal Gradients

High temperature can accelerate early hydration but also intensify evaporation, plastic shrinkage and differential temperature development. For precast production, early strength targets should not justify uncontrolled steam or thermal curing. A curing cycle must balance stripping time against moisture retention, microcrack risk and subsequent permeability. Thermal movement also concentrates stress at connections and interfaces between panels. The critical assessment therefore extends beyond cylinder strength to dimensional stability, crack control and connection detailing. Environmental adaptation begins with realistic manufacturing and service temperature histories. Accelerated durability tests are valuable for screening, but their boundary conditions should be stated explicitly. Temperature, electrolyte concentration, preconditioning, specimen geometry and curing age may all alter transport measurements. Results should be presented with dispersion and an explanation of how laboratory acceleration relates to service exposure. The engineering value of prefabrication also depends on logistics. Transport restraint, lifting points and temporary storage may introduce cracks or edge damage before installation. Sustainable material selection should be accompanied by handling plans and inspection criteria that prevent avoidable waste and replacement. A chloride-exposure validation programme should compare surface and internal transport measurements at defined ages. Reinforcement condition, cover tolerance and visible cracking should be documented together. This helps prevent a laboratory permeability improvement from being mistaken for a complete corrosion-control strategy. The field component, rather than the isolated paste, remains the relevant unit of resilience.

3.2 Chloride Ingress and Reinforcement Corrosion

In coastal structures, chloride transport and the resulting risk of steel corrosion are major service-life considerations. A dense matrix can delay ingress, but the protective system also depends on cover depth, crack width, curing, workmanship and connection details. Laboratory migration tests provide comparative information; they do not automatically predict decades of field exposure. Silica-fume and pozzolan blends in certain proportions based on trials can reduce connected pore pathways under suitable curing, whereas insufficient curing may diminish the expected benefit. A climate-resilient specification should therefore include durability testing alongside conventional strength acceptance [1-12].

3.3 Sulphates, Moisture and Combined Hazards

Sulphate exposure is influenced by the chemistry of the soil or water, binder composition, permeability and the frequency of moisture movement. Concrete subjected to both heat and salts may deteriorate differently from specimens tested under one laboratory condition. Flooding can transport contaminants through joints, while drying can concentrate dissolved salts near exposed surfaces. Resilience assessments should consider combinations of hazards and the accessibility of components for inspection or replacement. Modular precast systems may support repair, but only when connection details and spare-component logistics are designed accordingly [10-24]. Quality-control indicators need to be actionable. A laboratory measurement is most useful when it can trigger a documented response, such as adjusting curing, quarantining a batch or repeating a qualification test. Monitoring without decision rules can

increase paperwork without improving structural reliability.

4. Supplementary Cementitious Materials

Supplementary cementitious materials reduce reliance on Portland cement clinker and can change the hydration products and pore network of concrete. Their effects are not interchangeable: material fineness, glass content, chemical composition, replacement level and curing conditions govern outcomes. A sustainable mix should be judged against a reference mixture with equivalent functional performance, not merely a lower nominal cement mass. For precast applications, the trade-off between early release strength and later-age durability is especially important [1-3]. A realistic thermal assessment considers restraint, section thickness, hydration heat, ambient conditions and the timing of demoulding. Temperature differences within an element can generate early microcracking even when standard specimens achieve the specified strength. Instrumented pilot castings can reveal such effects before mass production. For inland projects, test planning should examine thermal gradients during curing and service. Full-scale panels can reveal restraint and warping effects that small laboratory specimens cannot reproduce. Monitoring surface temperature and internal temperature together provides a more defensible basis for specifying demoulding times, curing blankets and acceptable temperature differentials.

Table 1: Technology comparison for Saudi precast applications.

Technology	Potential contribution	Critical qualification issue
Fly ash / pozzolan	Clinker substitution; pore refinement	Early strength; reactivity; curing
Silica fume	Matrix densification; chloride resistance	Workability; dispersion; shrinkage
UHPC	Section efficiency; demanding exposure	Fibres; embodied carbon; repeatability
CO_2 mineralisation	Mineral storage; possible process benefit	Net balance; dose verification; LCA

4.1 Fly Ash and Natural Pozzolan

Fly ash may improve workability and later-age properties through particle packing and pozzolanic reactions, but early strength development can be slower, especially when replacement levels are high. Supply variability and changes in industrial fuel systems create procurement uncertainty. Natural pozzolans may offer regionally relevant alternatives, although mineralogy and reactivity require independent characterisation. Ahmad and colleagues examined UHPC containing fly ash and natural pozzolan, illustrating the value of evaluating both mechanical and durability outcomes rather than treating substitution as a single optimisation variable [2]. At the project level, resilience also includes recoverability. Standardised panel geometries, replaceable connections and accessible inspection points can shorten disruption after an extreme event. These system features may offer substantial value even when the underlying concrete mixture remains relatively conventional.

4.2 Microsilica and Pore Refinement

Microsilica, also called silica fume, is highly reactive and fine, making it useful for dense cementitious matrices when dispersion and water demand are controlled. Its potential to improve chloride resistance must be balanced against workability loss, admixture compatibility and shrinkage sensitivity. Alhajiri and Akhtar reviewed engineering and economic dimensions of silica-fume use, underscoring the importance of choosing replacement levels through performance and cost evidence rather than fixed recipes [3]. In factory production, consistent weighing, mixing energy and admixture sequencing are as important as the nominal proportion.

4.3 Blended Systems and Material Compatibility

Combining fly ash, natural pozzolan and silica fume can provide complementary particle-size and reaction effects, but the benefits depend on the complete binder system. Increased fines can raise water demand and complicate casting, while lower clinker content may change carbonation resistance. Blends should therefore be evaluated for fresh stability, early and later strength, shrinkage, permeability and long-term chemical resistance. An effective qualification programme compares alternative formulations under the same curing and exposure protocols, recording both successes and unacceptable trade-offs [1, 2]. Pilot production should use the actual mixer, aggregate moisture range, casting method and curing equipment planned for the project. Sampling across multiple production days is preferable to a single demonstration batch. The purpose is to establish process capability, not simply to reproduce a laboratory maximum. Future reporting should distinguish observations from recommendations. Measured strength, permeability and carbon uptake belong in results, whereas projected service-life or economic benefits require models and assumptions. Transparent separation would make comparative reviews more useful to designers, manufacturers and public clients. A practical natural-pozzolan qualification plan should record mineralogical variation between deposits and production lots. Reactive silica content alone may not predict water demand or admixture response. Trial mixes should also document consistency retention during casting, because a theoretically durable mixture that cannot be placed reliably is unsuitable for precast manufacture.

5. Ultra-High-Performance Concrete

Ultra-high-performance concrete offers high mechanical capacity and a refined matrix, often with

fibre reinforcement and tightly controlled granular packing. These properties can be attractive for slender precast elements, connection zones and components exposed to severe service conditions. However, high binder and fine-material contents can increase embodied impacts, and fibre dosage affects cost and processing. UHPC should be selected where its structural efficiency, durability or reduced replacement frequency justifies the additional manufacturing burden. Its use as a blanket substitute for ordinary precast concrete would ignore functional optimisation [2].

5.1 Structural Efficiency and Durability

The value of UHPC is best assessed at element or system level. A smaller section may reduce material volume, lifting demand or foundation load, but these savings depend on the structural design and connection scheme. Fibre orientation, casting direction and curing influence tensile response and crack behaviour. The relevant comparison is therefore not simply strength per cubic metre; it is a verified component meeting the same design life and reliability requirements. Long-term chloride and shrinkage behaviour deserve particular attention in Saudi coastal applications. Environmental assessment should account for production rejects and rework. A mixture with low theoretical embodied carbon may perform poorly if unstable workability or curing defects cause frequent scrapping. Yield and process capability are therefore relevant environmental indicators, not merely factory management statistics.

5.2 Practical Barriers to UHPC Deployment

Industrial UHPC requires disciplined material storage, moisture correction, mixing time, temperature control and fibre distribution. Tight tolerances can be difficult to maintain when raw materials change between suppliers. Quality assurance must cover flow, air content, strength, dimensional accuracy and relevant durability indicators. Training and trial production are necessary before large-scale specification. A plant should demonstrate reproducibility over multiple batches and shifts rather than relying on one successful laboratory mixture. Carbon accounting should identify the origin of carbon dioxide, delivery losses, mineralised fraction and the treatment of any remaining gas. Emissions associated with equipment and additional energy must be included in the same boundary. A claim of permanent storage should be supported by a measurement or justified calculation method. For carbon-mineralised products, environmental reporting should distinguish injected gas, reacted gas and avoided cement-related emissions. These are separate quantities with different evidence requirements. A third-party reviewer should be able to reconstruct the calculation from delivery records, equipment measurements, mixture changes and the declared life-cycle boundary without relying on confidential marketing claims.

6. Carbon Dioxide Mineralisation

Carbon mineralisation introduces carbon dioxide into reactive cementitious systems so that some carbon can form stable carbonate products. Available approaches include early-age carbonation curing, carbonated aggregates and carbon dioxide addition during mixing. Their reaction pathways and practical operating conditions differ substantially. Reviews by Ahmed and colleagues and Kazemian and Shafei show that storage potential, microstructure and mechanical outcomes depend on material composition and process conditions [5, 6]. The term carbon utilisation alone does not demonstrate net climate benefit. The selection of reference scenarios deserves particular care. Conventional concrete, blended concrete and UHPC may require different section sizes to deliver the same function. A component-level functional unit reduces the risk of drawing misleading conclusions from simple material-volume comparisons.

6.1 Carboncure-Type Mixing Processes

Commercial systems that introduce carbon dioxide during concrete mixing should be evaluated separately from enclosed-chamber carbonation curing. Early mineral formation can influence hydration and nucleation, as explored in mechanistic work on in-situ calcium carbonate formation [8]. However, the amount of injected gas is not equivalent to the mass permanently stored, and any cement reduction enabled by strength optimisation requires separate proof. Plant-level monitoring should document delivered carbon dioxide, dosing records, rejected batches, energy use and changes to the reference formulation.

6.2 Accelerated Carbonation Curing

Early-age carbonation curing can promote carbonate formation in suitable materials under controlled humidity, pressure and exposure duration. The response depends on the available reactive calcium phases and the degree of prior hydration. Zhang and co-authors summarised process variables and applications, while Al Salaheen and colleagues considered waste-based materials and the influence of curing conditions [4-7]. A factory evaluating this route must also assess chamber throughput, operational safety, moisture conditioning and whether surface carbonation produces uniform component properties. Joint detailing should account for installation tolerance, differential movement, water drainage and sealant replacement. These features may determine service continuity more directly than modest differences in concrete compressive strength. A component-based review therefore needs to assess interfaces as well as the constituent material. Local testing programmes could prioritise coastal precast beams, buried utility structures and exposed façade units because their degradation mechanisms differ substantially. Such programmes would create practical design data while helping factories develop specialist product families suited to clearly defined exposures. UHPC adoption should begin with a component-level

design comparison. The analysis ought to examine material quantities, reinforcement details, fibre distribution, casting practicality and transport constraints. If the advanced mixture does not reduce maintenance, component dimensions or another relevant burden, its higher binder intensity may undermine the proposed environmental advantage.

6.3 Environmental Accounting and Additionality

A credible carbon claim requires a transparent functional unit, defined life-cycle boundaries and consistent allocation of upstream impacts. Carbon dioxide capture, purification, transport, compression and injection consume resources. Avoided clinker emissions, permanent mineral storage and any change in service life should be reported as distinct contributions to prevent double counting. Comparisons must also consider equivalent strength and durability. For public procurement, independently reviewed environmental product declarations or equivalent documentation offer more useful evidence than promotional sequestration totals [5-18].

7. Factory Quality Assurance and Traceability

Precast manufacturing provides opportunities for reliable monitoring that are harder to reproduce on open construction sites. Each production batch can be linked to cement and SCM certificates, moisture adjustments, admixture additions, mixing duration, temperature, curing history and test results. Such traceability helps identify whether an unexpected durability outcome reflects the material formulation or a process deviation. A robust quality plan includes incoming inspection, trial mix approval, production sampling, non-conformance response and periodic requalification when sources change. For independent review, researchers should archive the test matrix, exclusion decisions and source data wherever permissions allow. This would enable future evidence synthesis and reduce the risk that only favourable results are reported. Reproducibility is especially important when new products are promoted for public infrastructure.

7.1 Performance-Based Acceptance

A performance-based specification defines required outcomes while allowing more than one qualified material route. For ordinary and advanced precast mixes, acceptance may include compressive strength, surface finish, permeability-related indicators, shrinkage, chloride transport and exposure-specific resistance. UHPC also needs appropriate tensile or flexural characterisation. Carbon-mineralised products require documentation of the carbon-accounting method. Test methods and acceptance limits should follow the governing project code and be agreed before production, rather than selected retrospectively to favour a technology. Natural pozzolans should be screened for reactive mineral phases, soluble salts, grinding demand and compatibility with admixtures. Local availability is not itself proof of environmental superiority; extraction, processing and transport must also be considered. A locally sourced material may nevertheless improve supply security when quality is consistent. Climate-resilience procurement should explicitly require documented assumptions about maintenance and replacement. A service-life model becomes misleading when it silently assumes perfect joints or unlimited inspection access. Sensitivity tests covering sealant replacement, local chloride intensity and component accessibility can show which conclusions remain robust under realistic operating conditions.

7.2 Connections, Joints and Repairability

A durable panel can still form part of a vulnerable building if water penetrates its joints or reinforcement corrodes at connections. Resilience assessment must include seals, embedded plates, tolerances, drainage paths and maintenance access. Prefabrication can enable rapid replacement after damage, but replacement is only practical when standardisation and documentation are maintained. This shifts attention from isolated material strength toward continuity of service at the assembled-system level [11-17]. Implementation should proceed through staged authorisation. Laboratory success can justify a factory trial; a factory trial can justify limited monitored deployment; only accumulated performance evidence should justify broader standardisation. This progression protects public safety while preserving opportunities for innovation.

8. Whole-Life Sustainability

Embodied carbon comparisons should use the same functional unit, such as a component satisfying a specified load, exposure class and design life. Comparing mixtures only per cubic metre can unfairly favour or penalise UHPC and high-replacement binders. Whole-life evaluation should include production, transport, installation, maintenance, replacement and end-of-life assumptions. Where long-term field evidence is limited, sensitivity analyses should vary service-life assumptions rather than asserting a single precise outcome. Circular economy benefits also depend on practical recovery and recycling pathways [13-22].

8.1 Supply-Chain Resilience

Material sustainability is constrained by reliable access to constituents. Fly ash characteristics can change, high-grade silica fume may be imported and specialised UHPC fibres can have concentrated supplier networks. Regional pozzolan evaluation may reduce some dependencies but creates new testing obligations. A resilient procurement strategy qualifies alternative suppliers, sets chemical and physical acceptance criteria and records transport-related impacts. It should also distinguish laboratory feasibility from sustained industrial availability [16-22]. UHPC qualification should specify the mechanical property used in design and the test configuration that measures it. Fibre

orientation and specimen size can affect tensile or flexural response, especially in thin cast elements. Transfer from laboratory coupons to full components requires explicit engineering judgement. Manufacturers can improve research transfer by recording failed trials as carefully as successful ones. Rejected formulations reveal thresholds for workability, segregation, curing sensitivity and quality variation. Publishing such constraints, where commercially permissible, would help other producers avoid repeating costly mistakes and would strengthen the external validity of academic reviews.

8.2 Economic and Operational Feasibility

Initial material price is only one component of value. Factory throughput, curing energy, rejected units, transport weight, erection time, inspection access and maintenance frequency can dominate project economics. An advanced formulation may be justified for a coastal bridge component but unnecessary for a replaceable internal partition. Decision-makers should therefore compare scenarios with consistent service requirements and transparent uncertainty. The cost of additional testing is not waste; it is part of controlling technical and commercial risk.

9. Integrated Decision Framework

The proposed framework begins with an exposure profile for each component and a functional specification defining structural performance, durability and service life. Candidate mixtures are then screened for material availability and manufacturing compatibility. A qualification stage assesses fresh properties, strength, transport, shrinkage and relevant chemical resistance. A separate environmental stage calculates whole-life impacts and substantiates any carbon-storage claim. Only mixtures meeting both technical and environmental thresholds proceed to controlled pilot production, followed by monitored deployment and periodic review [9-26].

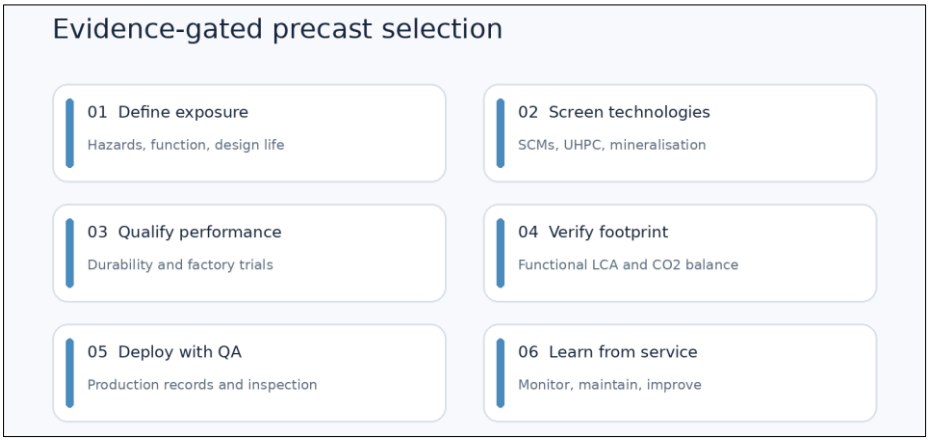


Figure 2: Proposed evidence-gated selection and monitoring framework (original conceptual illustration)

9.1 Multi-Criteria Evaluation

Decision weights should be established before comparing technologies and reflect the project's actual hazards. A chloride-exposed marine element may prioritise ingress resistance and connection protection, whereas an inland façade may emphasise thermal movement, dimensional stability and maintenance. Embodied carbon and cost remain important in both cases but cannot compensate for failure to meet mandatory safety thresholds. Multi-criteria scoring should be used after pass–fail engineering requirements, not as a substitute for them. When comparative evidence is incomplete, decision-makers should report uncertainty rather than force a precise ranking. Scenario analysis can show whether a preferred option changes when service life, energy intensity or transport distance varies. Robust selections are those that remain acceptable across plausible assumptions. The principal contribution of this synthesis is a disciplined comparison framework rather than a universal optimum mixture. Its application requires project-specific hazards, transparent engineering thresholds and independent environmental verification. Future researchers can test whether the proposed gates improve procurement decisions by comparing pilot projects with conventional specification practices.

Table 2: Evidence required at each qualification gate

Gate	Evidence	Decision rule
Exposure	Site hazards; element function	Document governing mechanisms
Material	Batch chemistry; mix design	Meet fresh and structural limits
Durability	Transport; cracking; chemical resistance	Meet exposure-specific criteria
Carbon	Functional LCA; verified CO_2 balance	Demonstrate transparent net impact
Deployment	Factory trials; QA; monitoring	Approve only reproducible performance

9.2 Monitoring and Learning

Field monitoring should link design assumptions to observed performance. Useful records include crack mapping, joint condition, chloride profiles where relevant, corrosion indicators and repair interventions. Digital records can preserve the relationship between a component and its production batch, making it easier to investigate recurring defects. Periodic review should update specifications and supplier qualification as evidence accumulates. This feedback mechanism transforms resilience from a one-time material label into a measurable management process [20-24].

10. DISCUSSION OF SECONDARY EVIDENCE

The reviewed technologies address different parts of the sustainability–resilience problem. SCMs can reduce clinker demand and modify permeability, but their early-age behaviour and supply quality vary. UHPC can improve component efficiency and demanding durability performance, but its carbon advantage is conditional on system-level design. Carbon mineralisation can store carbon dioxide and alter hydration, yet claims require transparent mass balance and full-process accounting. None of these pathways removes the need for curing control, reliable joints or exposure-specific testing. Their greatest potential lies in deliberate combinations supported by reproducible evidence [1–8].

10.1 Implications for Saudi Vision 2030

For Saudi construction programmes, the immediate opportunity is to shift procurement language from named ingredients toward measurable outcomes. This would support innovation without relaxing safety and durability requirements. Precast manufacturers could develop validated mix families for inland, coastal and industrial exposures, with digital traceability and life-cycle declarations attached to each family. Such an approach supports industrial capability, resource efficiency and dependable infrastructure delivery. Vision 2030 alignment is a policy rationale, not evidence that any particular mixture has already achieved a quantified national benefit. Procurement documents should require auditable evidence while leaving space for equivalent innovative solutions. Manufacturers need clear change-control rules when replacing a cement source, SCM supplier or curing process. Regulators and owners can support adoption by defining transparent performance criteria instead of relying on unverified sustainability labels.

10.2 Research Agenda

Future studies should test Saudi-relevant combinations of high temperature, chloride exposure, sulphate conditions and wetting–drying cycles on full-scale or representative precast elements. Comparative work should report binder chemistry, curing histories and transport properties alongside strength. UHPC investigations should include connection performance and fibre orientation, while carbon-mineralisation trials should disclose verified storage and energy inputs. Long-term monitoring, local pozzolan characterisation and functional-unit life-cycle comparisons are especially valuable because they address current barriers to responsible specification. These requirements favour reproducible evidence, careful specification and transparent reporting across the entire precast value chain. A transparent pilot programme should include owners, designers, producers, testing laboratories and maintenance teams to document practical implementation risks and refine acceptance criteria before widespread adoption in Saudi infrastructure projects, including future maintenance and replacement.

11. CONCLUSION

Sustainable precast concrete is most convincingly defined by proven service performance with a reduced whole-life environmental burden. The literature supports the potential of pozzolanic blends, silica fume, UHPC and carbon mineralisation, but it also exposes important dependencies on curing, mixture compatibility, industrial repeatability and assessment boundaries. For Saudi Arabia, the strongest pathway combines hazard-specific material qualification, rigorous factory quality assurance, verified carbon accounting and monitoring of assembled infrastructure. The proposed framework is a practical synthesis rather than an experimentally validated prediction tool. Its next step is transparent pilot testing and long-term field evidence under the environmental conditions it is intended to address.

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