MATERIALS TECHNOLOGY

Building in the Mountains: Quality and Durability Controls for Precast Accommodation and Infrastructure at Trojena, Saudi Arabia

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Published November 2026

Abstract

Trojena, the mountain destination planned within NEOM, places buildings and infrastructure between roughly 1,500 and 2,600 m above sea level, where winters fall below freezing, air pressure is markedly lower than at the coast and remote access favours factory-made components. Precast and modular construction suits such a site, but the conditions that make it attractive also threaten the durability of concrete and of the joints that hold precast elements together. This paper pairs a systematic integrative synthesis of thirty peer-reviewed sources dated 2020–2025 with a disclosed set of public documents on the project to develop a quality and durability control framework for precast accommodation and infrastructure at Trojena. The review groups the evidence into six themes: factory inspection, connections and grouting, air entrainment under reduced pressure, combined frost and salt attack, cold-weather strength verification, and thermal and shrinkage cracking at altitude. Evidence on the effect of low pressure on entrained air is mixed, with the clearest losses reported at pressures lower than those expected at Trojena, whereas evidence that early frost exposure and inadequate curing degrade strength and frost resistance is consistent. The resulting framework assigns hazard-specific controls to four gates, from factory release to in-service monitoring, and identifies maturity-based strength release, site-calibrated air content limits and connection grouting under temperature control as the highest-priority measures. The study relies on published evidence alone; neither project records nor field measurements from Trojena were available, so the framework should be calibrated through trial production before adoption.

1 Introduction

Mountain construction compresses a set of difficulties that lowland projects meet one at a time. Haul routes are long and steep, working seasons are interrupted by cold, skilled labour must be housed on site, and the concrete itself behaves differently when it is mixed in thin air and cured through freezing nights. Trojena, the mountain tourism component of NEOM in north-west Saudi Arabia, is being developed in the Jabal Al Lawz mountains at altitudes publicly reported as 1,500 to 2,600 m, with winter temperatures below zero and a year-round climate about 10 °C cooler than the surrounding region (Table 1, D1–D2). Its planned programme includes a ski village, chalets, hotels and supporting roads and structures, a mix that relies heavily on repeatable building elements.

Precast and modular methods are a natural response to such a setting because they shift work from an exposed hillside to a controlled factory. Reviews report that modular construction can shorten schedules substantially and reduce material waste (Zohourian et al., 2025), and a Saudi life-cycle model found that construction costs dominated the life-cycle cost of building systems while operation and maintenance over 50 years formed about a quarter of the total (Alshamrani, 2022). Yet the same reviews identify transport complexity, design constraints and high initial cost as persistent obstacles,

and a study of factory production risks placed dimensional conflicts between modules and defective design among the most critical (Wuni & Shen, 2023). The advantages of precast production at altitude therefore depend on quality controls that anticipate both factory risks and mountain exposure.

Research on high-altitude and cold-weather concrete has grown, largely through work on the Tibetan Plateau and in cold continental climates, while research on precast quality control has advanced through statistical inspection, automation and digital tracking. The two bodies of work are rarely brought together, and neither addresses the specific combination found at Trojena: moderate altitude, mild but recurrent frost, arid conditions and a precast-heavy delivery model. This gap matters for owners and contractors who must write specifications, inspection and test plans and acceptance criteria before field performance data exist.

This paper seeks to close part of that gap by developing an evidence-based quality and durability control framework for precast accommodation and infrastructure at Trojena. Its objectives are, first, to synthesise recent evidence on how altitude and low temperature affect the production, connection and long-term durability of precast concrete; second, to translate that evidence into hazard-specific controls organised by stage of delivery; and third, to indicate how firmly each control is supported by the literature. The study is guided by three questions. RQ1 asks which mechanisms associated with altitude and cold most threaten the quality and durability of precast elements and their joints. RQ2 asks which controls, at which stage from factory to service, can mitigate those mechanisms. RQ3 asks where the evidence is strong enough to justify immediate adoption and where trial calibration is needed.

After this introduction, Section 2 describes the site and its exposure, and Section 3 sets out the review and framework method. Section 4 reports the review findings in six themes, Section 5 presents the control framework, Section 6 discusses its implications and limits, and Section 7 concludes.

2 Site setting and exposure

Public descriptions place Trojena in the mountains of north-west Saudi Arabia, about 50 km inland from the Gulf of Aqaba, on a site of about 60 km^2 that rises from roughly 1,500 m to 2,600 m (Table 1, D2). The wider mountain region described by the developer covers about 1,400 km^2 of light-toned granite and volcanic rhyolite terrain (Table 1, D1). Reported climatic features include sub-zero winter temperatures, little rainfall and a climate cooler than the coast throughout the year. For concrete, three implications follow. Atmospheric pressure under the standard atmosphere is roughly 85 kPa at 1,500 m and 74 kPa at 2,600 m, compared with about 101 kPa at sea level, which may influence air entrainment. Frost exposure is likely to take the form of repeated mild freezing at night rather than the deep, prolonged cold of continental interiors. Low humidity and strong daytime sun on a high, arid site are likely to accentuate early drying and temperature gradients in fresh concrete.

The project's programme has changed since its announcement. Trojena was selected in 2022 to host the 2029 Asian Winter Games, but those Games were later postponed, and Almaty was named as the new host in February 2026 (Table 1, D2–D3). Public reporting in 2026 also noted the termination of a structural steel contract for the ski village and a shift in the delivery model for NEOM as a whole towards phased, commercially prioritised implementation (Table 1, D4–D5). These developments do not alter the physical exposure of the site, but they make it more likely that construction will proceed in stages over several winters, which raises the importance of controls that work reliably across seasons and of evidence that can be carried from one phase to the next.

Table 1. Public documentary sources used to describe the Trojena setting (not counted among the reference list)

Code	Source and date	Type	What the source states
D1	NEOM, Trojena destination page (accessed November 2026)	Developer web page	Mountain region of about 1,400 km^2 in the Jabal Al Lawz range, rising to 2,600 m, with subzero winter temperatures; light-toned granite and volcanic rhyolite terrain
D2	Arab News reports on the Asian Winter Games award (4–5 October 2022)	Press report	Site of about 60 km^2 at 1,500–2,600 m, about 50 km inland from the Gulf of Aqaba; sub-zero winters, little rainfall, about 10 °C cooler than the region; ski village, chalets, hotels and a lake planned; completion then targeted for 2026
D3	International press reports (January and February 2026)	Press report	The 2029 Asian Winter Games at Trojena were postponed, and Almaty was later named as the new host
D4	Dezeen, report on cancelled NEOM contracts (26 March 2026)	Trade press	A structural steel contract for the Trojena ski village was terminated while the site was under construction
D5	Press report of the Public Investment Fund annual report for 2025 (2026)	Press report of fund report	NEOM ambitions, including Trojena, retained with delivery moved to phased implementation and commercial prioritisation

3 Method

3.1 Search and selection

The study adopts a systematic integrative review, a design suited to questions that span different methods and disciplines, here combining materials testing, structural experiments, surveys and reviews. Searches were run during November 2026 using an open bibliographic index and checked against registration records held by publishers. Search strings combined precast, prefabricated, modular or offsite with quality control or inspection, and combined concrete with high altitude, low atmospheric pressure, air entrainment, freeze–thaw, cold weather, maturity, thermal cracking and shrinkage. Two seed studies anchored the search: a statistical quality inspection methodology for precast production (Skrzypczak, 2023) and an on-site investigation of how reduced barometric pressure influences entrained air (Chen et al., 2020). Forward and backward reference tracing from these studies identified further candidates.

The final set was limited to thirty refereed journal or conference journal studies published between 2020 and 2025, each with a registered digital object identifier. Studies were included when they reported experimental, field, survey, modelling or review evidence on precast quality, connections, or the behaviour of concrete under low pressure, low temperature or freeze–thaw exposure. Studies of non-cementitious materials, purely architectural design and non-engineering aspects of mountain tourism were excluded. Each study was coded for theme, mechanism, setting, method and the control it implies.

3.2 Synthesis and framework construction

Findings were synthesised thematically and then mapped onto a delivery sequence of four gates: factory release, transport and storage, erection and connection, and service. For each hazard, controls were drawn from the studies and assigned to the earliest gate at which they can act. Each control was

given an evidence grade. A grade of supportive denotes at least two concordant studies whose conditions resemble those at Trojena; mixed denotes concordant evidence obtained under conditions that differ materially, or studies that disagree; limited denotes a single study or a conceptual argument. The grading is the author's judgement and is reported so that readers can challenge it.

3.3 Documentary sources

Site facts are taken from public documents listed in Table 1. They comprise the developer's description of Trojena, press reports of the 2022 hosting decision and of its later reversal, a press report of a contract termination and a press report of the national investment fund's annual report. These documents describe context only; they are not part of the review corpus and are not counted among the thirty references. No project specifications, inspection records or field measurements from Trojena were available to the study.

4 Review findings

4.1 Factory quality control of precast and modular elements

The factory is the stage at which precast quality can be controlled most tightly, yet practice is uneven. A review of automation in precast production found a generally low level of automation despite a growing range of robotic and automated applications, and argued that labour scarcity is pushing the industry towards automated processes (Reichenbach & Kromoser, 2021). Statistical acceptance sampling has seldom been applied to precast elements; an analysis based on operating characteristic and average outgoing quality curves showed that the probability of accepting a lot depends strongly on production defectiveness, and that the current average defectiveness should govern switching between normal, tightened and reduced inspection (Skrzypczak, 2023). For a remote site, such switching rules offer a disciplined way to intensify inspection when a factory begins to drift.

Digital tools extend factory control. A quality information system for modular factories standardised quality data across module information, materials and production and was judged practicable by accredited users (Shin & Choi, 2022). A digital twin framework for mobile factories producing precast tubes linked quality requirements to measurable indicators and recorded both automated and manual inspections (Tripathi et al., 2025). Field-oriented tracking also exists: fiducial markers read by an ordinary phone camera were used to identify modules and to compare their as-built position with the design model at lower cost than laser scanning (Liu et al., 2024). Mobile or near-site factories are of particular interest at Trojena, because they shorten haul distances on mountain roads and allow production to be controlled close to the point of use.

Risk studies explain why factory control alone is insufficient. Experts in eighteen countries ranked dimensional conflicts between modules, delays in material procurement, defective design, information gaps between designer and manufacturer and limited manufacturer capacity as the leading production risks for modular projects (Wuni & Shen, 2023). A Bayesian network study of the Saudi precast industry found erection productivity to be the highest risk, with design schedule problems propagating to production capacity (Al-Gahtani et al., 2024). An analysis of modular adoption highlighted that its benefits depend on careful decisions by senior authorities on when and where to apply it (Tsz Wai et al., 2023). Taken together, these studies indicate that the interfaces between design, factory and site are where quality is most often lost.

4.2 Connections, joints and grouting

Precast structures depend on their connections. A review of mechanical performance found that connections, whether dry, wet or hybrid, govern the overall behaviour of precast buildings and require particular attention in design and execution (Chang et al., 2023). For bridges, cracking and water infiltration in normal-strength joints between deck panels are a known weakness, and ultra-high-performance fibre-reinforced concrete joints of several shapes have been shown to perform effectively as replacements for conventional grout (Zhang et al., 2022). A grout designed on closest-packing principles met flowability and twelve-hour strength targets for sleeve connections, with failures occurring in the bars outside the sleeve rather than within the grout (Jiang et al., 2023). For pavements, precast slab systems with two-direction dowels, flexible bases, secondary levelling and sealed joints were reported to approach the performance of cast-in-place pavements (Fang et al., 2022).

None of these connection studies was conducted at low temperature or reduced pressure. Grouts and joint concretes are typically placed in small volumes, so they lose heat quickly and are vulnerable to early freezing, and their air content is rarely specified. The connection literature therefore supports the choice of high-performance joint materials but leaves open how they should be placed and cured on a cold mountain site.

4.3 Air entrainment under reduced pressure

Air entrainment is the principal defence of concrete against frost, and its behaviour at altitude is contested. Field experiments in Beijing and Lhasa found that reducing atmospheric pressure to about 64 kPa lowered the air content of fresh concrete by 9% to 39%, worsened bubble stability, and caused greater air loss with longer vibration, leading to larger spacing factors (Li & Yang, 2021). An on-site study with tight control of other variables, by contrast, found little effect of low pressure on air-entraining efficiency or bubble stability for the admixtures tested, and satisfactory air content in concrete, concluding that a suitable admixture removes most of the concern; it also observed that cold constituent materials held in storage at altitude markedly weakened air entrainment (Chen et al., 2020).

The pressure reported in the Lhasa experiments is well below the 74 to 85 kPa expected at Trojena, so the losses observed there probably represent an upper bound for the site. More general work confirms that pore structure determines frost resistance. Mercury intrusion tests showed that entrained air affects pore size distribution and the interfacial transition zone, with effects that depend on the presence of superplasticiser (Chen et al., 2021). Experiments over a range of admixture dosages found that higher dosage improved freeze–thaw resistance by refining pores below 0.3 mm while reducing compressive strength, with air content, specific surface and spacing factor correlating significantly with performance (Zalegowski, 2025). The implication is that the spacing and stability of air voids, not merely total air content at discharge, should be the controlled quantities.

4.4 Frost, salt and load interaction

Frost damage rarely acts alone. Tests in which concrete was first loaded and then exposed to freeze–thaw cycles in salt solution showed that initial load damage increased strength loss and that salt solution sharply increased deterioration compared with fresh water (Zhou et al., 2022). A study of concrete modified with nanoparticles and polypropylene fibre under combined freeze–thaw and sulfate attack found that fibre improved durability by about 67%, that nanoparticles helped only

during the first 120 cycles, and proposed a composite failure theory combining frost, salt heaving and corrosion (Ren & Lai, 2021). For Trojena, salt exposure could arise if de-icing salts are used on roads and walkways or if saline groundwater or wind-blown salts are present; neither possibility can be confirmed from public sources, but both would make the combined mechanisms relevant.

Early-age exposure compounds the risk. Concrete cured at −3 °C on permafrost reached only 57.8% to 86.4% of the strength of companion specimens cured normally, showed an age-lag effect, contained a higher share of harmful pores and had much lower frost resistance (Zhang et al., 2023). Elements that freeze before they gain sufficient strength may therefore carry a durability deficit for life, even if their later strength appears adequate.

4.5 Cold-weather placing and strength verification

Cold-weather practice depends on knowing when concrete is safe from frost and strong enough for the next operation. Tests linking early strength to frost resistance found that concrete reaching 5.0 MPa maintained its relative dynamic modulus above 90% over 18 freeze–thaw cycles, supporting 5.0 MPa as the minimum strength for safe cold-weather concreting at the locations examined (Cui et al., 2022). Instrumented slabs exposed to cold weather at early age showed that standard cylinders underestimated core strength by more than 40%, whereas the maturity method overestimated it by less than 10% with lower variation (Tekle et al., 2022). A complex maturity method that adds ambient temperature and humidity to the conventional calculation achieved a coefficient of determination of 0.976 against cube strengths, outperforming both the conventional method and rebound hammer testing (Utepov et al., 2021).

Survey evidence shows why rules on paper are not enough. In Ulaanbaatar, 71% of construction personnel reported placing concrete in winter at air temperatures between −10 and −20 °C, and 53% considered the national norms insufficient for cold-weather work, with gaps in planning, preparation, curing, protection against early freezing and quality control (Narantogtokh et al., 2022). The conditions at Trojena are milder, but the finding that winter concreting proceeds regardless of whether the rules are adequate is a warning for any schedule-driven mountain project.

4.6 Thermal and shrinkage cracking at altitude

Large temperature differences, low humidity and low pressure combine to raise the risk of early cracking. Low-heat cement mortars cured under low pressure with variable temperature gained strength faster at early age but less at later ages than mortars cured normally, and their drying shrinkage developed rapidly at first (Wang et al., 2023). For bridge piers at high altitude, a coupled hydration, temperature, humidity and restraint model identified cracking risk zones near the pile cap and at the centre of the pier face, and a micro-expansion admixture roughly doubled expansion at high temperature while reducing shrinkage at low temperature by about 11% to 12% (Hu et al., 2024).

The same modelling approach, applied more widely, showed that temperature rise inhibition, shrinkage compensation and shrinkage reduction technologies can keep a cracking risk index below a threshold, as demonstrated in two applications (Liu et al., 2021). In bridge piers, replacing normal-strength with high-strength concrete reduced the cross-section by 35% but raised the thermal cracking risk to a level that required insulation during construction (Do et al., 2020). A review of mass concrete cracking classified preventive measures into material optimisation and process improvement, and highlighted monitoring of temperature, stress and crack width as the basis for

feedback control (Zhang et al., 2025). Thick precast elements and cast-in-place stitches at Trojena are therefore both candidates for thermal control plans.

4.7 Cross-cutting patterns

Three patterns cut across the six themes. First, the timing of exposure matters as much as its severity: the decisive damage in several studies occurred in the first hours or days, whether through air loss during mixing and vibration, freezing before a safe strength, or temperature gradients during hydration (Li & Yang, 2021; Zhang et al., 2023; Do et al., 2020). Controls that act on the fresh and young concrete therefore offer the greatest leverage. Second, standard laboratory checks can mislead under cold or variable conditions. Standard cylinders underestimated in-place strength by a wide margin in cold weather, and conventional maturity calculations ignored ambient humidity (Tekle et al., 2022; Utepov et al., 2021), which suggests that acceptance should rest on methods calibrated to the conditions of the element itself. Third, the weakest links are interfaces. In the factory they are the hand-offs between designer and manufacturer; on site they are the grouted joints and stitches that join precast parts (Wuni & Shen, 2023; Chang et al., 2023). These patterns inform the placement of controls in the framework that follows.

5 A hazard-based control framework for Trojena

5.1 Structure of the framework

The framework links four site hazards to four delivery gates, as shown in Figure 1. The hazards are reduced pressure affecting air entrainment, early-age frost, freeze–thaw with possible salt, and thermal and drying cracking. The gates are factory release, transport and storage, erection and connection, and service. Each control in Table 2 is assigned to the earliest gate at which it can act and to an owner, and each carries an evidence grade. The framework is a literature-derived proposal; it is not a specification and requires calibration through trial mixes and early production at the site.

Two design choices shape the framework. The first is that controls are placed as early as possible in the delivery sequence, because a property such as air-void spacing or early strength that is wrong at the factory cannot be corrected by inspection on the mountain. The second is that every control generates a record tied to the identifier of the element concerned, so that a defect found in service can be traced to its mix, batch, curing history and connection details. This traceability serves two purposes: it supports corrective action on the current phase, and it creates the evidence base that later phases will need. For accommodation modules, the same identifier can carry dimensional, connection and finishing records from factory to occupancy, which addresses the information gaps between designer and manufacturer highlighted in risk studies (Wuni & Shen, 2023).

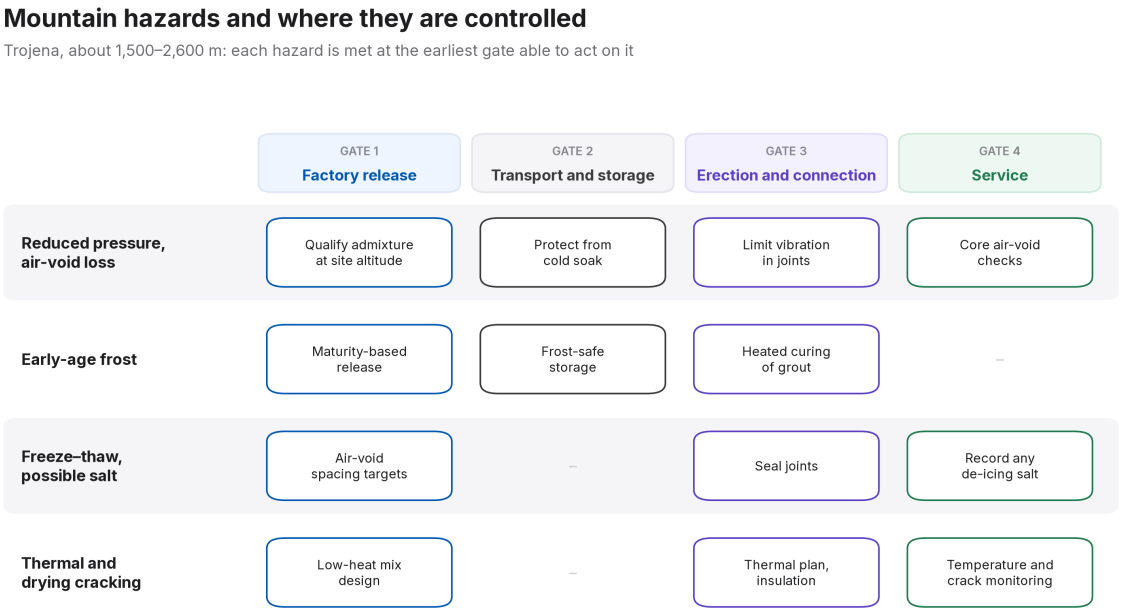

Figure 1. Site hazards at Trojena mapped to control gates from factory to service

5.2 Gate 1: factory release

Factory controls concentrate on the properties that will be hard to correct later. Air content and air-void parameters should be specified as targets for hardened concrete, with fresh air content limits calibrated on site through trials at the factory altitude and with materials at winter storage temperatures, reflecting the evidence that cold raw materials and vibration time can reduce entrained air (Chen et al., 2020; Li & Yang, 2021). Admixture selection should be qualified at site pressure rather than at the supplier's laboratory. Element release should be governed by maturity-based strength estimates calibrated for the mix, with a minimum release strength well above the frost-safe threshold (Tekle et al., 2022; Utepov et al., 2021; Cui et al., 2022). Acceptance sampling should follow switching rules driven by observed defectiveness (Skrzypczak, 2023), and quality data should be held in a structured information system linked to each element identifier (Shin & Choi, 2022; Tripathi et al., 2025).

5.3 Gate 2: transport and storage

Transport on mountain roads exposes elements to impact, vibration and cold. Controls include protection of young elements from freezing during storage, inspection for transport damage at arrival, and dimensional checks before lifting, given that dimensional conflicts are among the most critical modular risks (Wuni & Shen, 2023). Low-cost visual tracking with fiducial markers allows each module to be identified and its position checked against the design model on arrival and after placement (Liu et al., 2024). Where near-site or mobile factories are used, this gate shortens, but its checks should not be removed.

5.4 Gate 3: erection and connection

Connections are the most vulnerable point in a cold mountain setting because they are made in small volumes on site. Joint and grout materials should be selected for early strength and low permeability, following the evidence for high-performance joint concretes and closest-packed grouts (Zhang et al.,

2022; Jiang et al., 2023), and placed only when the joint and adjoining elements are above a stated minimum temperature. Heated enclosures or insulated formwork should keep grout above freezing until it reaches the frost-safe strength, verified by embedded temperature sensors and maturity calculation (Cui et al., 2022; Tekle et al., 2022). Cast-in-place stitches and thick sections should carry a thermal control plan using cracking risk models, insulation and, where justified, shrinkage-compensating admixtures (Hu et al., 2024; Liu et al., 2021; Do et al., 2020). For precast pavements, dowelled joints, levelling layers and sealing should be inspected as hold points (Fang et al., 2022).

Table 2. Hazard–control matrix for precast elements at Trojena with evidence grades

Hazard	Primary gate	Key controls	Evidence grade	Calibration need
Reduced pressure and air loss	Factory	Qualify admixture at site altitude; air-void targets in hardened concrete; limit vibration time	Mixed	Trials with winter-stored materials
Early-age frost	Factory and erection	Frost-safe minimum strength; maturity-based release; heated or insulated curing	Supportive	Mix-specific maturity curve
Freeze–thaw with possible salt	Factory and service	Air-void spacing limits; fibre where justified; record any de-icing salt use	Mixed	Exposure class once salt use is known
Thermal and drying cracking	Erection	Cracking risk model; insulation; shrinkage-compensating admixture	Supportive	Thermal properties of local mixes
Connection and grout failure	Erection	High-performance joint material; minimum placement temperature; sensors in joints	Limited	Cold-placement trials of grouted joints
Dimensional and transport damage	Transport	Arrival inspection; marker-based position checks; protected storage	Mixed	Tolerance limits for mountain haulage
Factory drift in defect rate	Factory	Switching between normal, tightened and reduced inspection; element-level quality records	Mixed	Baseline defect rate for site factories

5.5 Gate 4: service

Service controls monitor whether durability assumptions hold. Temperature and crack-width monitoring on representative structures, combined with feedback to construction methods, follows the practice recommended for mass concrete (Zhang et al., 2025). Periodic testing of cores from exposed elements for air-void parameters and frost damage would show whether site-calibrated air limits are adequate (Zalegowski, 2025). If de-icing salts are adopted, their type and application rate should be recorded and exposure classes revisited, given the strong interaction between salt, load damage and frost (Zhou et al., 2022; Ren & Lai, 2021). Findings from the first winters should be fed back into the factory and site controls for later phases, an arrangement suited to the phased delivery now indicated for NEOM (Table 1, D5).

Figure 2 shows the resulting sequence of hold points from mix qualification to service feedback. It is a schematic of the framework logic rather than a record of any project procedure.

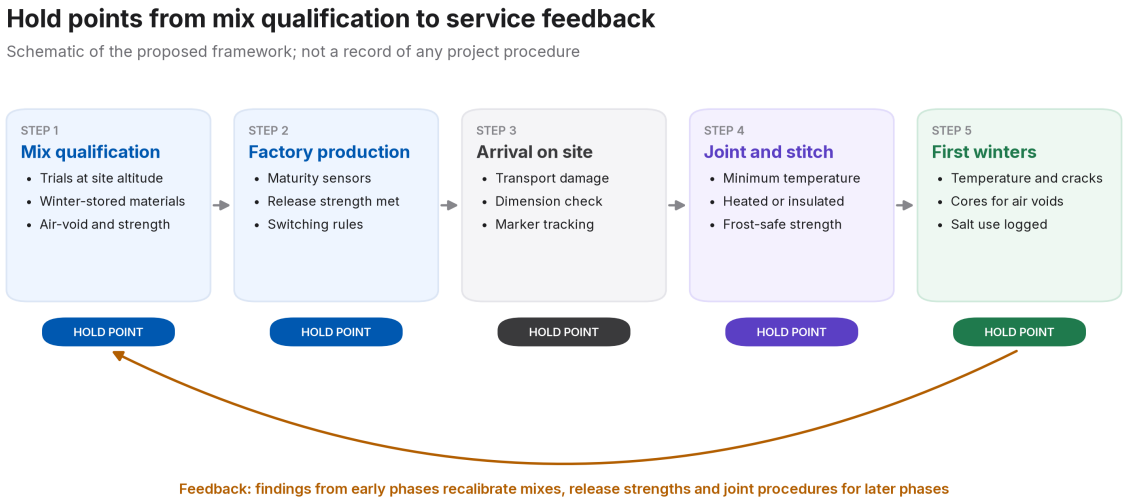

Figure 2. Production-to-service sequence of hold points in the proposed control framework (schematic)

6 Discussion

The review answers the first research question by identifying early-age frost and inadequate curing as the best-evidenced threat. Several studies agree that concrete frozen or cured at low temperature before reaching a modest strength suffers lasting losses in strength and frost resistance (Zhang et al., 2023; Cui et al., 2022), and survey evidence shows that schedule pressure can override cold-weather rules (Narantogtokh et al., 2022). Reduced pressure is a real but less certain threat at Trojena's altitude: the clearest losses were measured at pressures lower than those at the site (Li & Yang, 2021), and a carefully controlled study found little effect with suitable admixtures (Chen et al., 2020). Thermal and drying cracking, and the vulnerability of small-volume connections, complete the set of priority mechanisms.

For the second question, the framework shows that most controls can act at the factory, where conditions are best controlled, but that the connection gate carries the highest residual risk because it moves exposed, small-volume work back to the mountain. For the third question, Table 2 indicates that maturity-based strength verification, frost-safe minimum strength and thermal control planning are supported strongly enough for immediate adoption, whereas air content limits, connection curing regimes and salt-related exposure classes require site calibration. Factory quality information systems and statistical switching rules are soundly based in their own domains, but their effect on durability at altitude has not been tested.

These conclusions have practical consequences. Owners should write air-void and maturity requirements into specifications rather than rely on generic cold-weather clauses. Contractors should treat connection grouting as a temperature-controlled operation with its own inspection and test plan. Factories serving the site should qualify admixtures and mixes at site altitude and with materials stored at winter temperatures. The Saudi evidence that erection productivity and design schedule are the dominant precast risks (Al-Gahtani et al., 2024) suggests that these controls must be built into programmes from the start, or they will be the first to be compressed.

The balance of controls differs between accommodation and infrastructure. Accommodation modules and panels are usually thinner, produced in larger numbers and joined by many small connections, so

their main risks lie in dimensional fit, connection quality and early frost on slender sections; statistical switching rules, element-level records and marker-based position checks therefore carry most weight (Skrzypczak, 2023; Liu et al., 2024). Bridge piers, deck panels, retaining structures and pavement slabs are fewer but more massive or more exposed, so thermal control plans, air-void verification and joint durability dominate (Hu et al., 2024; Zhang et al., 2022; Fang et al., 2022). Life-cycle evidence from Saudi buildings, in which operation and maintenance account for about a quarter of the cost over fifty years (Alshamrani, 2022), indicates that durability lapses in either category would weigh on owners long after the construction phase.

Several limitations apply. Much of the altitude evidence comes from the Tibetan Plateau, where pressures are lower and temperatures colder than at Trojena, while much of the precast and modular evidence comes from buildings at low altitude. The connection studies did not consider cold placement. The corpus of thirty studies cannot claim completeness, and the evidence grades are judgements. Site conditions were taken from public documents, which may simplify the climate; detailed meteorological records, including the frequency of freeze–thaw cycles and the use of de-icing salts, were unavailable. The framework has not been tested on a project, and the changing status of the Trojena programme means that the mix of buildings and infrastructure may differ from what was announced.

Future work should begin with trial production at site altitude to measure fresh and hardened air-void parameters under winter conditions, followed by instrumented trials of grouted connections placed in cold weather. Monitoring of a sample of early structures through several winters would test the assumptions behind the service gate. Comparative studies of mobile and fixed factories serving mountain sites would show whether proximity improves quality as well as logistics.

7 Conclusion

Trojena brings together reduced air pressure, recurrent frost, arid exposure and a delivery model that leans on precast and modular elements. This paper has synthesised thirty recent studies to show that the most reliable protection against these conditions lies in controlling early-age strength gain and curing temperature, verifying strength through calibrated maturity methods, qualifying air entrainment at site conditions and treating connections as temperature-controlled operations. These measures have been organised into a four-gate framework that runs from factory release to service monitoring, with each control graded by the strength of its evidence.

The framework is a starting point rather than a finished specification. Its strongest elements can be adopted now, while those resting on mixed or limited evidence call for trial calibration on site. If the programme proceeds in phases, the first winters of construction will offer the data needed to refine the controls, provided those data are captured deliberately and returned to the factories and crews that build the later phases.

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