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Cracking Resistance and Leaching Safety of Eco-Concrete Foundation Mats in Urban Transportation, Adjacent Buildings

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Abstract

As increasingly sustainable materials are being used in construction, there is a need to ensure that innovative solutions can be developed to meet sustainability concerns, while ensuring structural integrity. With an increasing demand for sustainable construction materials, there is an urgent need for solutions that can achieve sustainability objectives and also provide structural durability. The foundation mats of buildings near urban transportation facilities were subjected to a complex service condition in the form of vibrations, repeated loading, ground movement and even environmental exposure. The vibration of the ground caused by traffic, repeated loading, ground movements and possible environmental exposure were given as a complex service condition to the foundation mats of buildings in the vicinity of urban transportation infrastructure. These conditions resulted in cracking of the concrete and may have affected the performance of the structure, as well as contaminant leaching into the surrounding soil and groundwater. The aim of this research was to explore cracks resistance and leaching safety of eco-concrete foundation mats in buildings located in the vicinity of urban transport infrastructure. It examined the relationship of the concrete composition, mechanical properties, cracking and possible release of harmful substances to the environment. The influence of different Sustainable ingredients on crack control, durability and environmental sustainability was also considered in this research as supplementary cementitious materials and recycled aggregates. Structural and environmental performance was evaluated under representative service conditions through mechanical testing, crack width evaluation and leaching evaluation. It suggested a framework to assess the eco, concrete foundation system based on the load, bearing

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capacity, crack resistance, and safety for the environment. The findings would be used to help inform sustainable urban building opportunities, enhance resilience of nearby buildings at transportation sites, and reduce impacts to nearby soil and groundwater.
Keywords: Eco, concrete, foundation mats, cracking resistance, leaching safety, sustainable construction, urban transportation and groundwater protection.

1. Introduction

The foundation mat (or raft) is, by default, the solution to the substructure problem for medium- and high-rise construction in dense urban cores. It is simply attractive: a single thick plate spreads column and core loads across a wide area, adapts to the changing ground stiffness, is a consistent hydraulic barrier below the water table and avoids the complicated pile and cap geometries that are difficult to waterproof (Abdelrahman, 2023). In transportation, adjacent sites (within a few tens of metres of a metro alignment and a light rail corridor, a road tunnel or a multi-lane arterial road), the mat also acts as a vibration transmission element, a settlement-tolerant bridging structure and the dominant chemical contact between the building and a groundwater regime profoundly altered by a hundred years of urban activity.

At the same time, the concrete being fed into these components is evolving at a different pace than ever since the typical use of ready-mix production. The annual production of cement and concrete contributes to 7–8 per cent of global anthropogenic CO2 emissions, and the most economical mitigation measure is to substitute clinker (Shah et al., 2022). There are many existing, proven, practical options to reduce the amount of emissions associated with concrete that can lower emissions by over 20% without requiring new technology (Tan et al., 2022). The incentive is even greater for mass foundation elements: high-volume supplementary cementitious material (SCM) replacement decreases embodied carbon and early-age cracking, which is the major risk for the thick sections (Akintayo et al., 2025). Eco-concrete refers to a family of cement mixes that have a typically low clinker factor (less than 0.5), a lower cradle-to-gate global warming potential (GWPs) of at least thirty per cent compared to an equivalent ordinary Portland cement (OPC) reference mix (based on a reference with 420 kg of OPC per tonne of cement), and can demonstrate structural and durability equivalency.

Current codes are not well suited to this convergence, which is a design tension. The provisions on crack control in EN 1992,1,1 (Muttoni & Simões, 2023), ACI 224R,01 (Yousef & Spyridis, 2023) and ACI 350,20 (Han & Huang, 2024) were developed mostly for OPC-based concrete mixes where the hydration kinetic, tensile strain capacity, and creep of concrete are well understood. Low, clinker systems have lower strength development, finer pore structure, higher autogenous shrinkage at low W/b ratio, sensitivity to curing time, and significantly different relaxation properties (Zhou et al., 2026). On the other hand, environmental release assessment methods, like the United States Environmental Protection Agency's Leaching Environmental Assessment Framework (Regadío et al., 2022) and the Dutch diffusion tank test (Tokgoz et al., 2023), are conducted on undisturbed, saturated, uncarbonated samples with very different transport properties than a cracked, partially carbonated mat with a century of history of fluctuating hydraulic gradients.

This article is intended to fill that void. It poses and explains a logical sequence of understanding how eco-concrete foundation mats crack during transportation and in surrounding surroundings; how this cracking affects the leaching of alkalis and trace elements in the material; and how a design can be specified and demonstrated with a measurable level of confidence that it will meet requirements for cracking resistance and leaching safety in the surrounding environment. The treatment is a deliberate integrative rather than disciplinary one: the central aim of this treatment is that this is a transport-controlled rather than chemistry-controlled problem of leaching safety, and that transport is dependent on cracking (Elbauomy et al., 2026).

2. Adjacent-Exposure-Environment

2.1 Mechanical and Dynamic Actions

Rail vibration can be generated by wheel-rail interaction, sleeper passing frequencies and dynamic axle loads and travel through the soil skeleton as body and surface waves, before entering the foundation. The vibration level

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measured and modelled inside the building adjacent to surface and underground railways are usually in the range of 0.1 to 5 mm/s peak particle velocity and have a dominant frequency band of 20 to 80 Hz for underground railway type and 60 to 180 Hz for surface railway type (Wang et al., 2026). Structural damage screening curves are derived from the regulations and recommendations in DIN 4150,3 (Baca, 2025) and human annoyance screening curves from the FTA manual (Balážiková et al., 2023).

A shear wave velocity of 200 m/s is typical for soft urban soils and a peak particle velocity of 2 mm/s is equivalent to a dynamic strain amplitude of approximately 10 microstrain. This is considerably less than the tensile strain capacity of mature concrete, and is why service level vibration almost always does not cause visible damage to the structure. There are, however, two caveats that have a material impact on foundation mats. Twenty train passages per hour and an 18-hour operating day result in 2 x 10^8 load cycles over a century, causing high cycle fatigue and progressive microcracking, particularly at pre-existing flaws and paste-aggregate interfaces. Second, and more importantly, vibration will reach the cast between 24 to 72 hours after casting, when tensile strength and bond are lowest and development is slowest. The vulnerability of young concrete is explicitly mentioned in the specification DIN 4150,3 (Pugliese, 2022), and construction next to live rail tracks often involves possession windows or isolating the track or using concrete mixtures with accelerated early strength, which contradicts high SCM replacement.

In addition to this quasistatic mechanical action, tunnelling and deep excavation generate a second quasistatic mechanical action. When the volume loss occurs at the tunnel face, a transverse settlement trough is formed, whose shape can be well described by the inverted Gaussian distribution (Xue et al., 2024). A mat placed across the shoulder of such a trough carries imposed curvature and not imposed load and the imposed hogging/sagging moments can be larger than the moments imposed by the superstructure. The thick and stiff mat creates large moments for moderate flexures; the displacement control loading removes these moments once cracking has occurred; the crack pattern is often through-thickness and not at the location that designers would have anticipated.

2.2 Chemical and Hydrological Actions

Urban groundwater near transport corridors is chemically distinctive. Due to decades of de-icing salt use, the shallow zone underneath arterial roadways contain hundreds to thousands of mg/L chloride ions. Gypsum in made ground, demolition debris, air deposition, and, in some places, oxidation of sulfidic subsoils are the main reasons for elevated sulfate concentrations. Nitrate and hydrocarbons are typical contaminants in the vadose zone under paved surfaces, where dissolved carbon dioxide is harmful. Such water has a pH of 6–8, four to seven units lower than hydrated cement's pore solution (Wang et al., 2023).

Hydrological conditions are unstable (Pal & Singha, 2023). Groundwater level fluctuations from tunnel drainage, dewatering during the construction of adjacent facilities, leaking water mains and sewer exfiltration can cause the upper part of a mat to alternate between saturated and partially saturated conditions. This is important because leaching under cyclic wetting is different from leaching under permanent immersion; drying causes an accumulation of pore solution near the surface, contributes to carbonation, and causes the salt to crystallise, and the rewetting mobilises the salts accumulated in the pore solution in a first-flush event.

2.3 DC traction electro-chemical

One unique and often overlooked aspect of tram/metro adjacency is stray current. There will always be some leakage of current from the running rails into the soil where the resistance of rail to earth is not zero. EN 50162 (Qin et al., 2020) sets out the requirements for protection, and the corrosion literature shows that, even in the absence of chlorides, stray currents can depassivate and dissolve reinforcement at a current density much lower than that required for protection (Tang, 2020). The next two effects can come into play for a foundation mat. The byproducts of corrosion generate expanding pressure that leads to more cracking in the absence of mechanical force. The applied electric field induces the migration of ions, including hydroxide, sodium, potassium, calcium, and trace oxyanionic metals, from the concrete at velocities potentially many magnitudes greater than those of diffusive transport. It is hence not merely a corrosion asset, but also a leaching-control asset, and this connection serves as a compelling rationale for employing SCM-rich binders in traction and adjacent foundations.

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3. Eco Concrete Binders for Foundation Mats, Taxonomy and Hydration Chemistry

The current options for eco-concrete that can be used for large volume mat pourings can be classified into five families, each with characteristic cracking and leaching implications. The first, and most developed, family of family cements is slag rich Portland composite cements, in which the ground granulated blast furnace slag (GGBS) content is usually 50 to 75 per cent. The calcium hydroxide is used up in the slag reaction, and the pore structure is refined, which further reduces the chloride diffusivity and permeability by one order of magnitude or two orders of magnitude compared with OPC (Akturk & Kizilkanat, 2020). The reduction in heat release rate is significant, and this is critical for thick mats. The compromises are that the initial strengths are slower to gain, more sensitive to curing temperature and time, and more autogenous shrinkage due to the increased capillary tension of the pore structure created by the process of refining. In terms of chemistry, the sulfide and ferrous iron in the slag convert the hexavalent chromium to the much less soluble trivalent form and also offer extra binding potential for many divalent metals (Tumolo et al., 2020). Hence, the second family is fly ash and ternary fly ash–slag mixes. Class F fly ash improves workability at lower water contents, slows heat evolution, and regulates ASR. It is especially good for mats where 56 or 90-day strength acceptance is required by contract because the pozzolanic reaction happens slowly. Environmental problems include the mobility of oxyanionic forms of arsenic, selenium, molybdenum and boron in high-pH cementitious matrices and the desorption of ammonia from ash produced at plants using selective catalytic reduction (SCR) to limit NOx emissions (Li et al., 2022).

The third family is limestone calcined clay cement (LC3) and different mixtures of calcined clay. Metakaolin can bind portlandite and reduce porosity effectively, with chloride resistance similar to slag blends, and can generate carboaluminate phases under suitable conditions (Homayoonmehr et al., 2022). LC3 is crucial for the decarbonization of the earth as calcined clay is quite plentiful around the globe where there is no slag or fly ash. High water requirements, significant stiffness development, and reduction of calcium hydroxide buffer which is ambiguous in terms of long-term pH stability under leaching (Huang et al., 2025). However, the fourth family are recycled aggregate eco-concretes, where a portion of the natural coarse aggregate is substituted with crushed concrete from construction and demolition waste (Jia et al., 2025). Old mortar with adhered mortar decreases the porosity of the mortar and its water absorption, unless the water absorption is compensated for by refinement of the binder. The recycled aggregate brings with it an inventory of contaminants, such as sulfate from gypsum plaster, chromium and vanadium from some slags, and high concentrations of dissolved organic carbon, which must be characterized and not assumed (Hasni, A., 2025).

The fifth family includes alkali-activated materials and geopolymers, and CO_2 -mineralized concretes. While alkali-activated slag can be made with very low permeability and excellent sulfate resistance, the pore solution is not calcium rich, but rather sodium, compromising the pH of any leachate as well as the ionic strength, which will increase the potential for efflorescence (Xiang et al., 2026). Eligible emissions reductions are modest and may include a potential strength gain upfront as fresh concrete is mineralised with CO_2 to be stored as nanoscale calcium carbonate; however, the decreased alkalinity must be independently evaluated for their potential impact on trace element solubility (Louvel et al., 2022).

The general thermodynamic theme across all five families is the immobilization of most cationic metals is strongly dependent on the availability of bindings phases like calcium silicate hydrate, ettringite and hydrotalcite, such as layered double hydroxides, and on the high pH, rich pore solution. A reduction in pH, carbonation, prolonged leaching and CO_2 mineralization causes the speciation to change; in general, the solubility of lead, cadmium and zinc decreases, whilst the solubility of chromium, selenium, molybdenum and vanadium increases (Baniket al., 2025).

4. Mechanics of Cracking in Thick Eco, Concrete Mats

4.1 Early Age Thermal Cracking

For mats over around one meter thick the most important cracking mechanism is early age thermal constraint. Hydration raises the core temperature and the section expands because the concrete is still relatively “stress free” in compression. This is followed by cooling to ambient temperature which induces tensile strain, which is restrained by subgrade, by piles, by previously cast adjacent bays as well as by the internal thermal gradient (Wang et al., 2023).

It is all too evident of magnitude computation using a simple order. The coefficient of thermal expansion is 10 × 10-6

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per degree Celsius (Kostanovskiy et al., 2022). A peak, to, ambient temperature change of 30 °C. An external restraint factor of 0.5 (Li et al., 2023). The tensile strain is fairly small, around 150 microstrain. The tensile strain capacity of the mature concrete is around 80-150 microstrain, and even less at early age. In other words, cracking is not a random occurrence, but a virtually certain byproduct of this behavior unless steps are taken to prevent it. The cracking index is conventionally defined as the ratio of the tensile strength to the developed tensile stress and should not be less than 1.3 to 1.5 to have reasonable assurance; calculation of the cracking index requires reliable inputs for heat generation, development of elastic modulus, creep, and autogenous volume change (Hamedi et al., 2024). However, high SCM replacement can help by decreasing and delaying heat release, but it will delay strength development. This is because the net effect is dependent on the ratio of strength gain rate to heat release rate, rather than either of these factors individually, and is why slag-rich mats can crack even though they have lower peak temperatures. The authors of Giuliani et al. (2023) stress that tensile creep relaxation can convert as much as 30 to 50 per cent of the theoretical elastic stress, and is therefore similarly highly binder- and temperature-dependent, meaning that using OPC-calibrated relaxation models for slag or calcined clay systems is a systematic error.

Internal thermal gradients generate a second, self-equilibrating stress field. For low-conductivity, heat-eco concretes a more important scenario could be a slowly developing gradient that lasts sufficiently long to allow surface stresses to build up with the drying shrinkage. Limiting the gradient insulation can be as significant as reducing the peak cooling.

Avoidance of autogenous and drying shrinkage under restraint. Even if no loss of moisture is experienced, chemical shrinkage can cause autogenous deformation and self-desiccation at water-to-binder ratios less than approximately 0.42 m3/m3. These systems, known as slag systems and calcined clay systems, can create autogenous shrinkage of 100–200 microstrain after just one week (Ghanem et al., 2024). Under such conditions, the deformation happens in the interior, and it is constrained by the cooler, stiffer outer shell, resulting in an increase of the transport coefficients of the material, while the outer surface is not visibly cracked.

Drying shrinkage, on the other hand, is a very slow surface phenomenon in thick elements and after a few years the effective drying depth can be only a hundred or two hundred mm. In the case of mats, its practical use is therefore limited to the cover zone, where reinforcement protection is the most important, and up to the time of application of a waterproofing.

Sucharda et al. (2022) showed experimentally that reinforcement can help to control shrinkage in the concrete, thus creating additional tensile stress at the points of reinforcement and also creating desirable compressive pre-stress in the concrete in the area between the points of reinforcement.

4.2 Avoidance of autogenous and drying shrinkage under restraint

The largest and most common concrete members that are cast in the field are foundation mats and fracture mechanics suggests that the nominal tensile strength for a structure decreases as size increases (Zhang et al., 2022). The relevant framework is the fictitious crack model of (Ahmad, 2024): initiation of cracks in the solid is controlled by tensile strength, while propagation of cracks is controlled by fracture energy and characteristic length of fracture process zone. Reduced fracture energy is often observed for eco-concretes with recycled aggregate or high content of SCM, due to the change of the ITZZ and the difference in the stiffness of the aggregates as a result of use of recycled aggregate or high content of SCM, even if the mixture fulfils the splitting tensile strength criterion.Eco-concretes with recycled aggregate or high content of SCM may have reduced fracture energy, because the above criterion is fulfilled, but the ITZZ and the difference in aggregate stiffness changes, resulting in a reduction in the ductile, more localized cracking at full scale of the material. Thus, it is better to specify fracture energy (or at least fracture energy of a notched beam post peak) than just strength for critical mats.

4.3 Fracture, Mechanical Size Effects

The imposed deformation due to tunnelling, induced settlement, seasonal ground movement, rebound from groundwater dewatering after excavation, and differential consolidation are associated with the sustained flexural loading over the service life (Zeng et al., 2023). These actions are displacement-controlled; therefore, nonlinear analysis using tension softening, rather than elastic stress comparison, is a better way of assessing their effects on a stiff mat. On top of this is the extremely high-cycle vibration field, which serves primarily to propagate and link microcracks created

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by the other fields and not to initiate them. Lastly, the presence of chloride in the concrete leads to cracking, which in turn results in the ingress of chloride, the depassivation of steel, which further leads to cracking, and the accelerated ingress of chloride again, in a vicious circle, as described by Liu et al. (2023) for DC traction environment with the presence of stray current.

4.4 Long-Term and Coupled Actions

The imposed deformation due to tunnelling, induced settlement, seasonal ground movement, rebound from groundwater dewatering after excavation, and differential consolidation are associated with the sustained flexural loading over the service life (Zeng et al., 2023). These actions are displacement-controlled; therefore, nonlinear analysis using tension softening, rather than elastic stress comparison, is a better way of assessing their effects on a stiff mat. On top of this is the extremely high-cycle vibration field, which serves primarily to propagate and link microcracks created by the other fields and not to initiate them. Lastly, the presence of chloride in the concrete leads to cracking, which in turn results in the ingress of chloride, the depassivation of steel, which further leads to cracking, and the accelerated ingress of chloride again, in a vicious circle, as described by Liu et al. (2023) for DC traction environment with the presence of stray current.

5. Cracking Resistance Strategies

5.1 Mixture Measures

Pennelli et al. (2022) identified thermal optimization as the first lever to be pulled. This involves lowering the overall heat release by decreasing the Portland clinker concentration and the overall binder content, increasing the aggregate size to its maximum, and optimizing the grading to limit the volume of paste. In most cases, slag or fly ash can be used in place of clinker to lower the adiabatic temperature rise by 30–45 percent. Another benefit is that the binder can be reduced even more because the material can absorb strength at 56 or 90 days instead of 28 days (Mohamed et al., 2023). Instead of raising the clinker factor, tailored accelerators or a tiny ternary OPC percentage should be used if early strength is still required for construction sequencing near active track.

The second tool is internal curing, which reduces shrinkage. According to Tutkun et al. (2023), when water starts to leak out of the pore structure, materials like superabsorbent polymers or pre-saturated lightweight fine aggregate release water from their internal water reservoir. This helps to minimize autogenous deformation and the microcracking that comes with it. For low permeability SCM concretes, external curing water can only penetrate a few millimetres to cure the interior of the concrete, which is the reason why internal curing is effective for these concretes. Shrinkage-reducing admixtures (SRAs) reduce surface tension of the pore solution, which is a complementary pore-solution capillary stress reduction, and can be used with internal curing.

The third lever is fibre reinforcement. The combination of short polypropylene fibres (0.5-1.5 kg/m³) and polyvinyl alcohol fibres, which provides a post-crack residual tensile capacity at higher dosage levels, can help control crack width and crack pattern in finer, less permeable patterns (Vairagade & Dhale, 2023). Fibres do not inhibit the initiation of cracks, they only make a small number of wide cracks many more narrow cracks, and as Section 7 explains, this is the most useful transformation that can be achieved in the leaching control for use.

5.2 Structure and Detail

Mat reinforcement should be based on minimal reinforcement to prevent restraint cracking, not merely flexural demand, since load moments are generally less than restraint moments in thick plates (Tong et al., 2023). EN 1992,1,1 and fib Model Code 2010 provide crack- and width-based formulae where the reinforcing ratio is proportionate to the steel's effective tensile strength and inversely related to its permitted tensile stress. Smaller bars have closer spacing, finer crack spacing, and narrower cracks, even when the total strain is the same on both faces and in both directions. ACI 350,20 specifies conservative crack width restrictions of 0.20 mm and lower steel stress limits, which is an acceptable baseline for mats when leaching is limited, Amanat (2025), in terms of environmental containment.

Cover restraint reduction too. Sliding layers under the mat (layered polyethylene membrane under sand blinding) reduce base friction and external restraint. Early thermal contraction can be reduced by casting sequence design, closing

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strips, staggered bays, and delayed infill pours. For mats with significant leaching, post-tensioning (unusual) can prevent cracks (You et al., 2023).

5.3 Construction, Process

Thermal control usually destroys design intent. Pre-cooling aggregates and mixing water, night-time placement in hot areas, surface protection, and insulated formwork to lessen gradients, not just peaks, are practical options (Osei-Owusu et al., 2026). Stopping cooling too quickly can cause cracking. Congratulations, curing requires discipline. Some SCM-rich binders react for months, so if they dry too soon, the cover zone does not hydrate and loses its transport capabilities. Thus, in-situ measurements should prove the refinements of extended moist curing, curing membranes, and wind and sun protection. Surface air permeability and sorptivity testing in a two-chamber vacuum cell (Kubissa et al., 2022) and core resistivity and chloride migration testing from companion studies (Kribes et al., 2023) are feasible bulk indicators.

6. Leaching Safety

6.1 Mechanisms, Substances and Assessment

Leaching from a cementitious material is the removal from the pore solution and the solid assemblage into water that comes in contact with the material. The major released species are hydroxide, calcium, sodium, potassium, and sulfate, and these species collectively control the pH and ionic strength of the leachate. The pH of unmodified Portland cement pore solution ranges from 13 to 13.5 and the leachate (buffered) from a mature mat is often > pH 11 (Zhang et al., 2023). This alkalinity itself is potentially an environmental hazard: measurable geochemical changes have been documented in urban waterways receiving concrete drainage, such as elevated pH, increases in calcium and bicarbonate, and changes in the speciation of the metals which harm aquatic biota (Udoh, 2024).

Regulatory elements of concern: chromium, vanadium, molybdenum, selenium, arsenic, antimony, lead, cadmium, nickel, copper, zinc, and barium in addition to chloride, sulfate and fluoride. The release of contaminants is influenced by two factors, their chemical speciation and their pH and redox potential and the rate at which contacting water can reach and extract them (Gidudu & Chirwa, 2022). Cationic metals like lead, cadmium, nickel and zinc, have amphoteric solubility minima in the alkaline region and are therefore well retained in sound, high pH concrete. The elements forming oxyanions, for example chromium as chromate, selenium as selenate, molybdenum as molybdate, vanadium as vanadate and antimony as antimonate, are poorly bound at high pH and their release is often restricted by availability, not solubility. This is critical: pH reduction, like carbonation or CO_2 mineralisation, tends to decrease the release of cationic metals and increase the release of oxyanions and is not necessarily always advantageous (Hamedi et al., 2025).

These things can be predicted according to the binder families of Section 3. Slag can supply the reducing capacity to lower Cr(VI) to Cr(III) and at the same time, precipitate the Cr(III) as a hydroxide or incorporate it in the C–A–S–H and hydrotalcite phases, and can provide extra sorption sites for divalent metals (Liu et al., 2022) The formation of alumina increases with calcined clay, and therefore the layered double hydroxide formation in the system, which may also bind chloride and some oxyanions. On the other hand, the fly ash and recycled aggregate can also increase the inventory of certain trace elements, even when binding is effective, meaning that increased binding can be accompanied by reduced permeability (Gao et al., 2022).

6.2. Carbonation as the Master Variable

The carbonation of the atmosphere or dissolution of carbon dioxide with hydrated cement phases (portlandite and C–S–H) creates calcium carbonate and silica gel and lowers the pH in the pore solution to 8 to 9. High CO_2 levels and elevated air velocities in the transportation corridors accelerate the process on exposed surfaces, while high levels of dissolved CO_2 in groundwater do the same at the ground–mat interface in tunnels (Ji et al., 2024).

There are three effects of leaching. The first is that the pH change alters the metal speciation as discussed above, usually causing the mobilisation of chromium and other oxyanions. Secondly, the decalcification of C–S–H eliminates the main binding phase that many metals rely on for binding. Third, in OPC concrete, the volumetric change of the portlandite carbonation mechanism creates a barrier to pore access; however, in low-portlandite SCM concrete, in

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which the mechanism of carbonation is C–S–H, the change in the structure of the concrete can be coarser, leading to an increase in porosity. This last aspect is important for the eco-concrete: the carbonation resistance which is usually assumed from a fine pore structure is compensated for by the lower alkaline buffer and low-clinker mats often carbonate quicker than OPC mats with the same permeability. The design for the safety of leaching should thus be based on measured values of carbonation coefficient and not on permeability as a surrogate (Ashraf et al., 2026).

6.3 Assessment Frameworks

The use of single point extraction tests has been replaced by scenario-based approaches to assessing modern leaching. The Leaching Environmental Assessment Framework includes four complementary approaches: a pH-dependence test that provides the solubility envelope over the pH range; a percolation column test for granular materials; a semi-dynamic tank leach test for monolithic materials that generates apparent diffusivities (Kasiński et al., 2025); and a batch equilibrium test at a fixed liquid-to-solid ratio. In Europe, the diffusion tank test of NEN 7375 is used for shaped construction products, and the cumulative emissions from 64 days are compared to the limits in the Dutch Soil Quality which are still one of the strictest and most widely referenced regulations for emissions from construction products (Álvarez-Ayuso et al., 2022).

If it is a foundation mat, the correct situation is a monolithic element that has been fully saturated with slightly acidic to neutral groundwater with a known chloride, sulfate and carbonate content, and a minor but definite hydraulic gradient, and a cracked, partially carbonated surface layer. The following situation does not have a complete specimen in a fresh tank: The suggested assessment protocol is therefore a combination of the standard tank test to get the intrinsic diffusion parameters, pH-dependence testing of sound and artificially carbonated paste or mortar, and geochemical speciation modelling, such as with PHREEQC (Stoikov et al., 2022), to project release under the site-specific groundwater chemistry and over the intended service life. When the mat is in hydraulic continuity with a potable water aquifer or a water main trench then further screening based on requirements for drinking water contact, such as NSF/ANSI/CAN 61 (Tóth et al., 2022) and World Health Organization guidelines, is suitable.

6.4 A Quantitative Reference Point

The diffusion controlled release could be directly measured. The total release per unit area is about $E = 2C_0\sqrt{(Dt/\pi)}$ for a semi-infinite medium when a concentration, C_0 (mg/m³), is available, and the apparent diffusion coefficient, D (m²/s) is known. Taking a conservative D of 1×10^{-13} m²/s appropriate to a dense slag, blended concrete, and t equal to 64 days (5.53×10^6 s), the diffusion length $\sqrt{(Dt/\pi)}$ is about 4.2×10^{-4} m. If the concentration is available as 2000mg/m3 the emission over 64 days is approximately 1.7mg/m2. This is the order of magnitude to which regulatory tank test limits relate and is an example of the reason that good quality, intact, concrete is generally compliant - the diffusion length in 2 months is less than ½ mm. Even without any cracks and advection, this amounts to approximately 10 mm when extrapolated to 100 years, which reflects a very thin skin with respect to the thickness of the mat.7. The Coupled Cracking Leaching Problem

7. Why Cracks Dominate

The above calculation proves the main point of this article. Given that it can take over a hundred years to leach a tenth of a millimetre of fully intact skin, the environmental performance of the element depends mainly on how much of the crack and construction joint interface is left unfilled with the skin.

The crack transmissivity T can be obtained from the parallel-plate cubic law as $T = w^3\rho g/(12\mu)$, where the width of the crack w = 0.2 mm, the density of the fluid ρ, the gravity acceleration g and the viscosity of the fluid μ. Substituting $w = 2 \times 10^{-4}$ m, water density 1000 kg/m³, gravitational acceleration 9.81 m/s² and dynamic viscosity 10^{-3} Pa·s gives $T \approx 6.5 \times 10^{-6}$ m²/s. The hydraulic conductivity of dense eco–concrete matrix can be taken as ~ 1×10–12 m/s. If the hydraulic gradient was 1, then the flow per metre of such a crack would be about 106 times that of the flow per sq metre of intact concrete. In reality, cracks have tortuous paths, are partially-filled, unsaturated and have variable apertures, and are self-healing to further reduce flow (so that the actual ratio is even less, but for a factor of three orders

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of magnitude advection remains dominant). Also, the crack will have new surface area which will be open to diffusive exchange on its sides, making a one dimensional surface problem into a three dimensional network problem. However, Two mitigating mechanisms are highlighted. First, autogenous sealing of cracks narrower than about 0.1 to 0.2 mm occurs significantly within weeks when flowing water is applied with low hydraulic gradients, which is likely due to ongoing hydration and deposition of calcite. Second, crack width control by distributed reinforcement and fibres: transmissivity is proportional to the cube of aperture, so if crack area is comparable it is a lot better to have a design that produces twenty 0.05 mm cracks than five 0.2 mm cracks. This is the reason why the treatment of crack width, and not number of cracks, is used as the governing leaching parameter.

7.1 Basic Diagrams

Figure 1. Schematic cross section of a foundation mat, as installed for a transportation adjacent structure, including exposure actions and leaching paths.

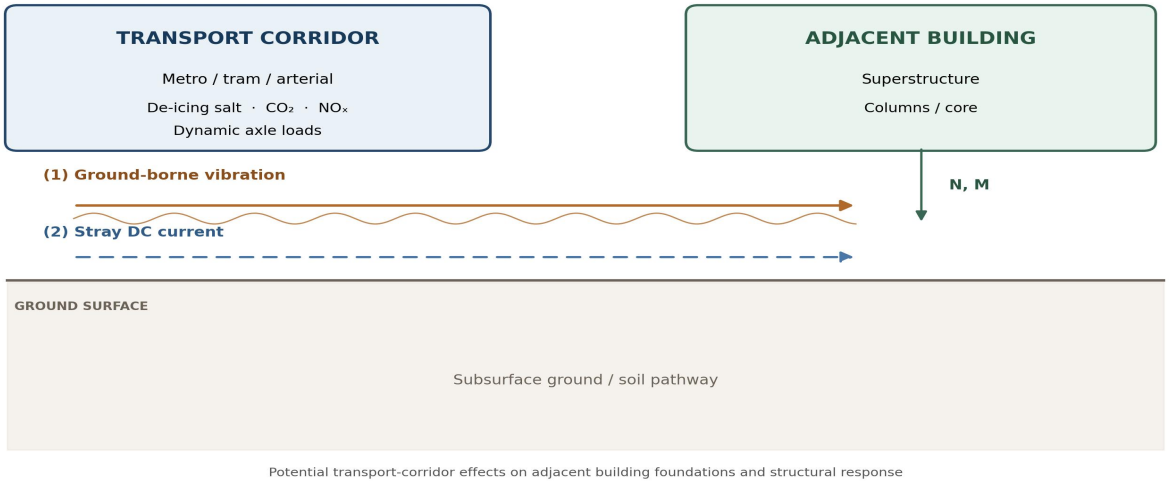


Figure 1. Interaction pathways between a transport corridor and an adjacent building.

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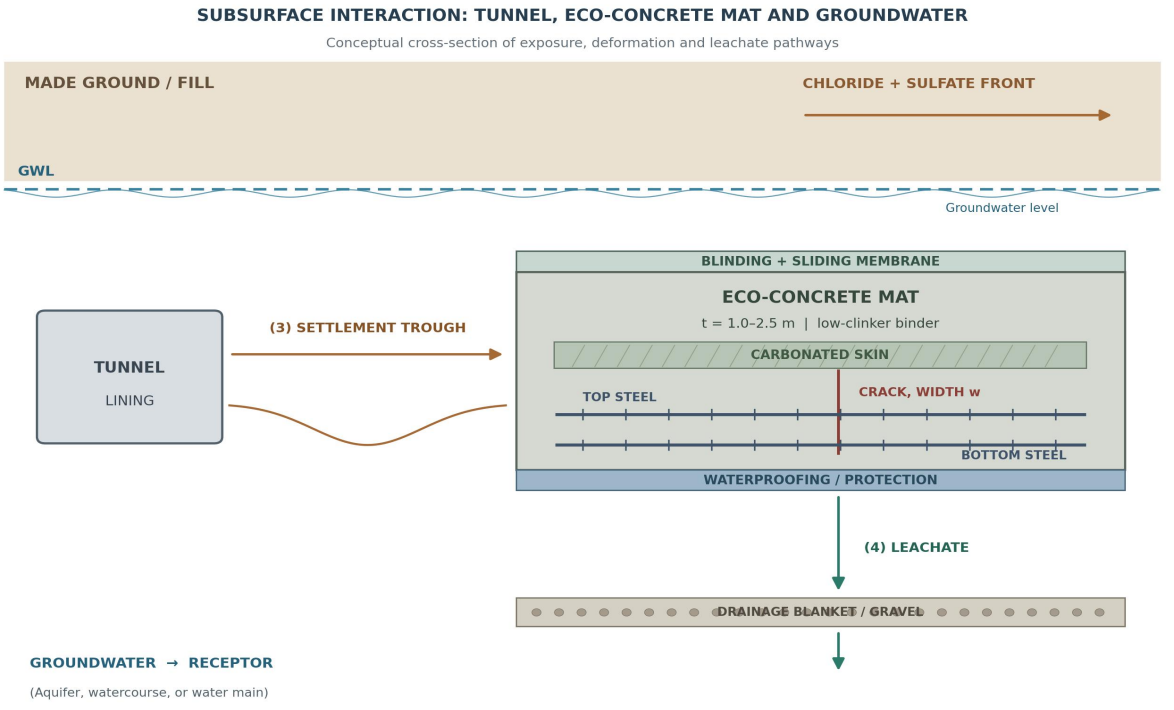


Figure 2. Exposure and interaction pathways

KEY (1) 20–80 Hz cyclic strain, ~10^8 cycles / 100 y
(2) stray current: corrosion + electromigration of ions
(3) imposed curvature → through-thickness cracking
(4) advective flux through cracks is much greater than diffusive flux through matrix.
Eco-binder selection for cracking resistance and leaching safety: coupled process framework.

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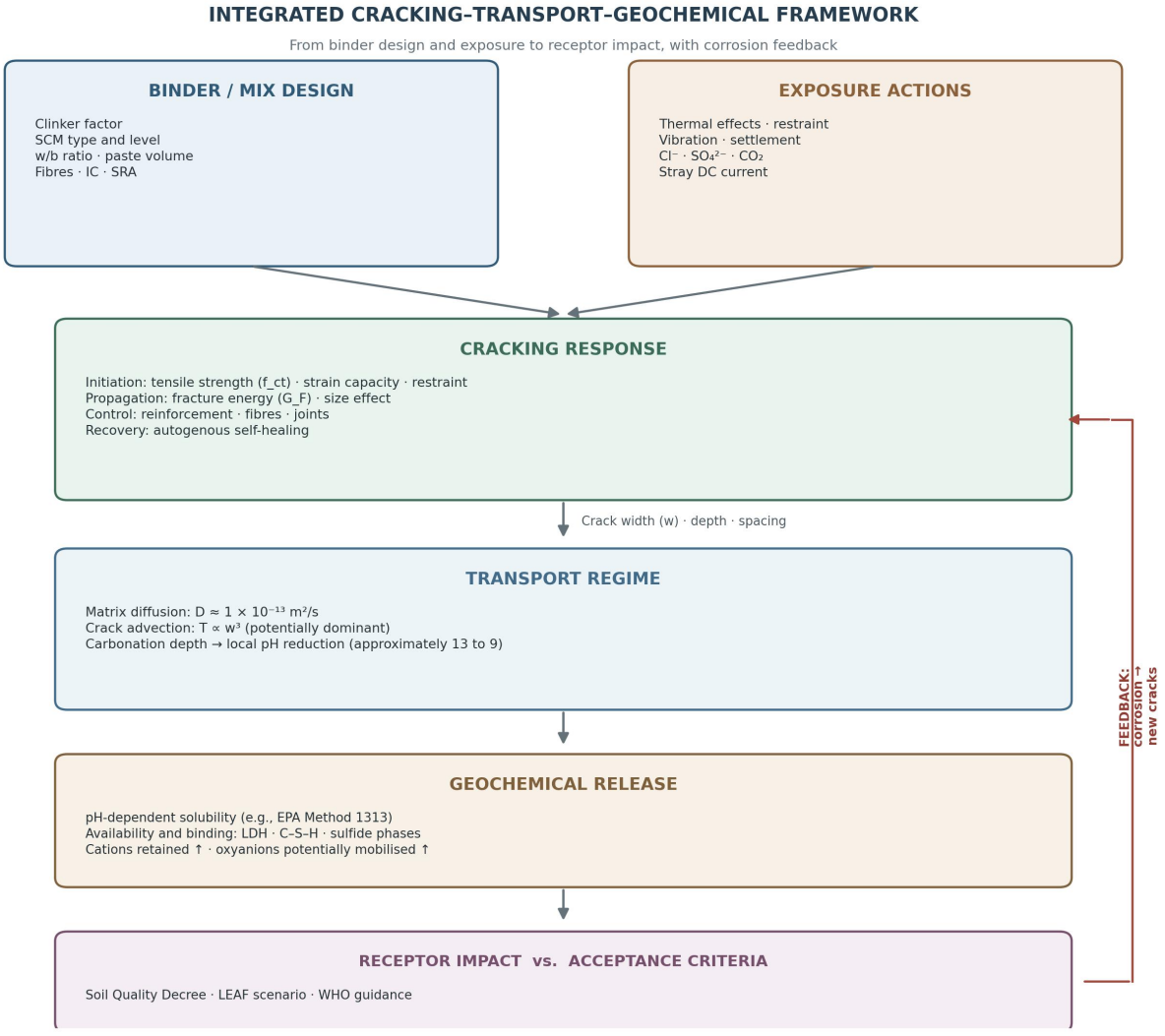


Figure 3. Integrated-framework

7.2 An Integrated Acceptance Logic

This section discusses an Integrated Acceptance Logic. Looking at the structure of Figure 2, there is an apparent three-level acceptance logic. The first level is verification of the intrinsic material quality on undamaged specimens: apparent diffusion coefficient for tank testing, pH, dependence envelopes, chloride migration coefficient and carbonation coefficient. In the second tier we use pre-cracked or carbonated samples to investigate the cracked and carbonated conditions, and model the site-specific hydraulic regime, to provide a predicted source term in the form of material parameters. At the third tier, the source term is compared to receptor based criteria, and a source–pathway–receptor model is used that considers dilution, dispersion, and aquifer and vadose zone attenuation. It's the third tier that addresses the question regulators and neighbors are asking and the one least often used in practice.

8. Integrated Design Specification and Quality Assurance

A defensible specification for a transportation, adjacent eco, concrete mat combines structural, durability and environmental clauses, not adds them. Performance-based thinking is supported by approaches to durability index and

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service life modelling, and has been reviewed critically by Richardson (2023), who warn against relying solely on any given durability index.

The cracking control should be specified as a limiting crack width under the controlling restraint scenario, supported by a nonlinear thermal stress analysis with inputs for the binder such as creep and shrinkage of the binder, and should be supplemented by an early-age cracking test (e.g. ASTM C1581 Restrained Ring Method (Shen, 2023), or any equivalent frame test that measures cracking). Ring tests are more useful than shrinkage or strength tests to compare mixtures because they relate to the composite response of the mixture to a specific restraint and drying condition (Shen et al., 2022). The analysis should include a target value for the cracking index and the construction method statement should include how the cracking index is to be achieved through placing temperatures, insulation, cooling and curing.

For the reason that it protects without relying on crack control, hydraulic decoupling is a crucial issue to take into account. An external layer that has a continuous waterproofing membrane that is properly detailed and is protected by reinforcement from puncturing and construction traffic is able to impede the advective channel even in the event that cracks emerge. The usage of a drainage blanket that is equipped with a controlled discharge point transforms diffuse seepage that is not monitored into a single discharge point that can be sampled. Sliding layers minimize restraint and hence cracking in the first place. The leaching consequences are expected to be more important, for example over a shallow potable aquifer, and can be mitigated by introducing a sacrificial reactive layer containing iron oxides, activated alumina or organic-rich material that is able to reduce the oxyanionic species before they enter the receptor. The measures will take the safety case from relying on one material property to a multi-layered one, which is the correct approach for a century long, inaccessible element. Further, Quality assurance should be evidence based. For mats more than ~ 1 metre thick, it is recommended that thermal instrumentation is capable of resolving the core response as well as the near surface response and that there is a real time comparison with the agreed envelope and intervention thresholds (Han et al.,2024). This can be verified by companion cores which were tested for surface air permeability, resistivity and chloride migration, both of which indicate that the in-situ cover zone is not a poorly cured zone. Baseline leachate characterization is done before loading of the superstructure to give a baseline against which future monitoring is interpreted.

9. Monitoring, Digital Twins and Service Life Management

Due to their inaccessibility after construction, foundation mats require long-term verification to be based on embedded instrumentation and inferential modelling. Distributed fibre-optic strain sensing along reinforcement cages allows for continuous monitoring of the entire spatial area of strain measurements, which enables the identification and localization of crack formation during the critical first few weeks and can be re-interrogated years later, to capture crack formation from the location of adjacent tunnelling. In addition to the depassivation front sensors, there are also complementary sensors of active microcracking such as acoustic emission arrays. Flow meters and piezometers measure the hydraulic driving force, and periodically collecting samples of the leachate for pH, conductivity, sulfate, chloride and agreed suite of trace elements completes the environmental loop.

The most useful of these data streams would be when they are used as inputs for a calibrated numerical model, which is a digital twin that couple's hydration, thermal and mechanical simulations with reactive transport. This model is first calibrated during the construction phase on the base of the thermal and strain data obtained during that time and can be adjusted as monitoring progresses in time to predict the growth of cracks and the total release. Also, service-life prediction frameworks would be developed for chloride-induced corrosion (Borah & Sil, 2023) & geochemical speciation codes supply source-term chemistry (Minougou et al., 2024). The bottom line is that maintenance and remediation can be planned by evidence rather than roll on deterioration at an assumed rate, and the environmental compliance case can be extended as regulatory thresholds are lowered. The implications are asymmetrical, which is noteworthy. Poor stability or support in a mat would be fixed via strengthening or underpinning at great cost and might be noticeable. Remediation of an aquifer that has been contaminated under a building that is in use is almost impossible, and environmental underperformance may only be identified after a receptor is impacted. This asymmetry is an argument to apply a higher target reliability to the leaching limit state than is commonly used and justifies the approach that defends the leaching limit state.

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10. Illustrative Comparative Assessment

With a w/b of 0.40, for a mixture with a binder content of 360 kg/m³ an alternative mix is made up using 65 per cent slag as the replacement for the clinker, which is denoted as mixture B. Mixture C is a system of clay-limestone, which is prepared with the calcined base, includes lightweight fines pre-saturated with water and serves as internal cure. Hence, Mixture D is Mixture B containing macro, synthetic fibres, a shrinkage-reducing admixture and with a 28 per cent reduction in the volume of paste, due to optimising the use of the aggregate. Thermally, however, Mixture A will have the highest adiabatic rise, and for the same insulation and the same creep, the lowest peak-to-ambient drop; Mixture A is also likely to have the lowest cracking index when computed using binder, and will likely experience through-cracking without the active cooling. The peak temperature of Mixture B is significantly reduced, but the autogenous shrinkage is high and the early strength is slow, making it difficult to avoid cracking, and the interior microcracking is significant. The internal curing of mixture C is good, because the tendency of self-desiccation is largely suppressed; however, the high early hardness and low alkaline buffer capacity of mixture C need to be verified for its carbonation performance. Thermal advantage of slag, reduction of paste volume, shrinkage mitigation and post-crack width control are all advantages that are expected to be obtained by using mixture D, which will produce the finest, most distributed crack pattern. On the other hand, the ranking is not the same when taking into account leaching grounds. Mixture A has the largest pore solution pH and the largest portlandite reserve, leading to the largest advective source term and the highest permeability and wide cracks. Mixture B is good in diffusion resistance and has good Cr(VI) reduction capacity, but it is thinner alkaline buffer. Mixture C forms good binding of chloride through carboaluminate reaction and LDH formation but has a low amount of portlandite, so the uncertainty is carbonation. Even if chemically similar to Mixture B, Mixture D can reduce the crack aperture to reduce the advective term which is dominant in total, and performs best overall. The lesson to be learned is that the option with the lowest measured diffusion coefficient for the intact specimen is not necessarily the best option in terms of controlling the crack width in the field, a fact that conventional compliance testing would not show.

11. Research gaps and priorities

There are several limitations to confident prediction. First, there is a lack of data on tensile creep and relaxation of calcined clay (CC) and alkali-activated systems (AAS) at the early age of the materials and under realistic temperature conditions, and reliance has to be placed on models that have been calibrated on OPC, and for which the error of the models has never been quantified (Chidiac, 2023). Second, there is little understanding of the interactions between the carbonation process and the remobilisation of trace elements in low-portlandite binders: it is not known if reduced Cr (III) that are stabilized due to the presence of slag sulphide can be re-oxidised during prolonged carbonation by the presence of manganese oxides, which has direct regulatory relevance. Third, as a coupled exposure combination of traction and adjacent foundations to very high cycle vibration and stray current ion transport, there is, to the author's knowledge, no accepted experimental protocol. Fourth, self-healing becomes typically indicated under clean water; moreover, low-gradient laboratory conditions & sulfate-bearing chloride long-term performance & organic-contaminated urban groundwater are not confirmed. Fifth, there is no harmonised standard that allows the assessment of leaching in cracked specimens of monoliths, which is the most significant field condition, and is therefore systematically missing from the compliance testing. The approach to this 5th gap, on defining a reference crack state and a test protocol for that state would do more to advance the safety of leaching than would further refinement of intact specimen diffusion measurement.

Lastly, there is still a lack of integration of life-cycle. The impacts of cradle-to-gate can be reported, and use-phase leaching is only marginally monetized and not included in comparative assessments (Pindek, 2020). A binder which saves 40 kg of CO_2 per m³ but whose replacement occurs earlier may not be the most environmentally friendly option, nor may it be the one which frees up chromium at a receptor. For truly evidence, based eco, concrete specification, it is thus crucial to couple life, cycle assessment with scenario, based leaching and probabilistic service, life models is therefore an essential next step.

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12. Conclusions

The coupled mechanical and geochemical limit state for eco-concrete foundation mats in transportation and adjacent buildings has not been handled by the current prescriptive codes. Here are six conclusions drawn from the analysis. High volume clinker substitution is beneficial for the structure of the thick mats due to the lower heat release but also makes the mixture more sensitive to autogenous shrinkage, curing dependency and carbonation susceptibility. This net benefit should be demonstrated and analyzed in terms of the specific binder and not assumed. For mats greater than one meter thick, early-age thermal restraint is the controlling factor for cracking, and the cracking index should be based on the tensile creep and shrinkage properties of the actual binder. Ground borne vibration at service levels is not expected to cause cracking in established concrete, but can be a serious risk during the early days after casting and can cause very high cycle propagation after that. Through thickness cracking can occur where it is not expected based on flexural detailing; such cracks can be caused by imposed curvature at the point of tunnelling. The leaching from intact and dense Eco-concrete is, naturally, very small, say 10mm in diffusion penetration depth after 1 century of use. Crack mediated advection is the dominant process for cumulative release and its magnitude is proportional to square of the crack aperture. These three measures—crack-width limitation, autogenous self-healing capacity and hydraulic decoupling—must therefore be implemented and proven to be leaching control measures, not refinements of the structure with incidental environmental advantages. Ultimately, compliance demonstration should be shifted from intact, specimen tank testing to scenario testing of cracked and carbonated specimens, involving geochemical speciation modelling and source-pathway-receptor framework, and with embedded monitoring, allowing safety case to be renewed throughout the service life.

The message for the wider application is that decarbonization and durability are not mutually exclusive goals in this instance, but are complementary if the design is implemented as a system. The same slag or calcined clay that reduces the clinker factor also increases the electrical resistivity to stray current, improves the pore structure to resist chloride penetration and also provides unreacted particles to allow self-healing. So, it is not a green versus durable concrete dilemma, but rather it is the analytical and procedural practice that must ensure that the concrete produced for the excavation is the one that is actually cured on site, and cracked under site restraints.

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