

RELEVANCE of STAR 221-SHC

Concrete is the most widely used construction material worldwide and is inherently quasi-brittle, prone to cracking under tensile stress and environmental exposure. Damage in concrete typically initiates at the microstructural level and can evolve into macro-cracks that compromise durability, impermeability, and load-bearing capacity. The ability of cementitious materials to autonomously recover from such damage—termed self-healing—offers an alternative paradigm to traditional damage prevention. With the aim of collecting fundamental and applied knowledge of self-healing in concrete, presenting mechanisms, experimental findings, and applications across various material classes the RILEM Technical Committee 221-SHC Self-Healing Phenomena in Cement-Based Materials was formed in 2005 and STAR 221-SHC was published in 2013.

STAR in a nutshell 221-SHC **“Self-Healing Phenomena in Cement-Based Materials”**

Overview

The STAR introduces a shift from damage prevention toward damage management in material design. Instead of eliminating cracking, the concept accepts that damage occurs but can be counteracted by autonomous or externally triggered healing processes. Two main classes are identified:

- Autogenic (intrinsic) self-healing, relying on ongoing hydration or carbonation of unreacted cementitious phases.
- Autonomic (engineered) self-healing, achieved by embedding capsules, vascular systems, or responsive agents that actively restore mechanical and transport properties.

While autogenic healing utilizes inherent material reactivity, autonomic systems embed healing agents or capsules to trigger active repair upon damage. Examples include hollow glass tubes filled with adhesives, bacterial spores generating calcium carbonate, and microencapsulated polymers releasing sealants. The RILEM framework situates these strategies as complementary—autogenic processes address small, frequent damage; autonomic systems aim at larger or repeated cracking events.

The report discusses definitions harmonized with the RILEM TC 211-SHC framework and the Japan Concrete Institute (JCI) terminology, emphasizing recovery of performance rather than mere crack closure. The goal is to enhance service life, reduce maintenance costs, and minimize environmental impact associated with cement production and structural repair.

Mechanisms of Self-Healing in Cementitious Systems

Autogenic self-healing results primarily from continued hydration and pozzolanic reactions. Unhydrated cement particles, exposed upon cracking, react with ingressing water to form calcium silicate hydrate (C-S-H) and calcium hydroxide (CH). These reaction products precipitate within cracks, reducing permeability and partially restoring stiffness. In systems containing supplementary cementitious materials (fly ash, slag, or silica fume), slow pozzolanic reactions further enhance long-term healing.

Carbonation is another key mechanism, whereby calcium hydroxide reacts with atmospheric CO₂ to form calcium carbonate (CaCO₃), physically sealing cracks. The efficiency of both hydration and carbonation depends strongly on moisture availability, temperature, and, critically, crack width—self-healing is most effective for cracks smaller than 150 µm and nearly complete below 50 µm.

The report also addresses the influence of polymer modification, where co-matrices of polymer and hydrated cement provide longer-term protection of unhydrated particles, prolonging autogenic healing potential.

Recovery Against Mechanical Actions

Self-healing is not only about self-closing of cracks but the actual regaining of tensile or flexural strength. Research on Engineered Cementitious Composites (ECC) and Strain-Hardening Cement-Based Composites (SHCC) is central.

ECC, containing 2 vol.% of short fibre (typically PVA or PE), exhibits multiple microcracking with crack widths below 100 μm , ensuring robust self-healing. Fibers serve dual roles: they mechanically bridge cracks and chemically attract calcium ions, promoting local precipitation of healing products.

Experimental studies demonstrated that:

- Tight microcracks ($< 50 \mu\text{m}$) can completely heal under wet/dry cycling.
- Mechanical testing after healing shows partial to full recovery of tensile strength (recovery ratio $c > 100 \%$ in hybrid fibre systems).
- Raman and SEM analyses confirm the primary healing products as calcium carbonate and, in smaller cracks, C-S-H.

Tests on UHPC and UHP-SHCC revealed similar trends: continued hydration of unreacted cement under water curing produces notable stiffness recovery. Healing is accelerated by fine crack control and the presence of pozzolans or expansive agents.

Resonant frequency methods, uniaxial tension tests, and permeability measurements serve as practical indicators of recovery against mechanical actions.

Other Materials, Applications, and Future Developments

Self-healing concepts can go beyond cementitious systems, illustrating cross-disciplinary innovation inspired by polymer and composite research. Some examples are given through:

- **Self-Healing in Polymers** - microcapsule-based epoxy systems demonstrated the feasibility of autonomous healing. Later developments include latent catalysts activated by local stress or temperature, and reversible supramolecular polymers that can re-form hydrogen bonds for multiple healing cycles. These approaches influenced similar encapsulation strategies in concrete.
- **Fiber-Reinforced Composites** - self-healing fibre composites integrate supramolecular matrices, shape-memory alloys, or liquid-filled hollow fibres. Upon damage, localized heating or rupture of micro-capillaries releases repair agents, restoring stiffness. These concepts parallel vascular and capsule-based systems explored for concrete.
- **Self-Healing Asphalt** - two main technologies are highlighted:
 1. Encapsulated rejuvenators, releasing oil into microcracks to restore binder ductility.
 2. Induction heating, where steel fibres embedded in asphalt are magnetically heated, melting the bitumen to close cracks.

Both approaches have advanced to field trials on Dutch highways, demonstrating direct applicability of self-healing design.

- **Metals and Ceramics** - in metallic and ceramic systems, healing can occur through high-temperature oxidation forming protective oxides (e.g., Al_2O_3 , TiO_2 in Ti_2AlC composites) or through electrochemical processes at ambient temperature. These phenomena suggest pathways for future development of high-temperature or corrosion-resistant self-healing construction materials.

Challenges and Experimental Considerations

The STAR identifies several experimental challenges common to self-healing research:

- Quantification: differentiating between mechanical recovery, permeability reduction, and aesthetic crack closure.
- Environmental dependence: moisture, pH, temperature, and CO_2 levels control reaction kinetics.
- Testing artefacts: permeability and resonant frequency tests may themselves trigger healing or yield non-representative data.
- Microstructural characterization: distinguishing calcite, C-S-H, and mixed phases requires complementary use of Raman, SEM-EDS, XRD, and FTIR.

Understanding these limitations is crucial for translating laboratory findings into durable design specifications.

Outlook and Future Work

The RILEM report emphasizes that self-healing concrete is no longer a scientific curiosity but an emerging engineering approach. Research efforts now focus on:

- Long-term performance under cyclic loading and environmental exposure.
- Integration of healing functions with sustainability goals (CO_2 reduction, waste reuse).
- Development of standardized testing protocols within RILEM and JCI.
- Scaling from lab specimens to full-scale structures, including bridges, tunnels, and offshore platforms.

Cross-fertilization with polymer, asphalt, and ceramic systems continues to provide new healing strategies. The ultimate vision is a new generation of cementitious materials capable of lifelong maintenance through intrinsic and adaptive recovery mechanisms.

Concluding Remarks

STAR 221-SHC – Self-Healing Phenomena in Cement-Based Materials presents a comprehensive overview of the scientific basis, experimental evidence, and future potential of self-healing technologies. It establishes that microstructural control—especially crack width limitation—combined with intrinsic hydration and carbonation reactions, can yield substantial recovery of both durability and strength. The integration of self-healing mechanisms into modern concrete design marks a paradigm shift from preventive maintenance to autonomous durability, aligning with global sustainability and resilience objectives.

RELATED DOCUMENTS¹:

1. Mignon, A., Vermeulen, J., Snoeck, D. *et al.* [Mechanical and self-healing properties of cementitious materials with pH-responsive semi-synthetic superabsorbent polymers](#). *Mater Struct* **50**, 238 (2017).
2. De Belie, N. [M&S Highlight: Hearn \(1998\), Self-sealing, autogenous healing and continued hydration – What is the difference?](#). *Mater Struct* **55**, 30 (2022).
3. Anglani, G., Van Mullem, T., Tulliani, JM. *et al.* [Durability of self-healing cementitious systems with encapsulated polyurethane evaluated with a new pre-standard test method](#). *Mater Struct* **55**, 143 (2022).
4. Al-Obaidi, S., He, S., Schlangen, E. *et al.* [Effect of matrix self-healing on the bond-slip behavior of micro steel fibers in ultra-high-performance concrete](#). *Mater Struct* **56**, 161 (2023).

¹ Upcoming proceedings of the [10th International Conference on Self-Healing Materials](#) (ICSHM2026), RILEM co-sponsored event.