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Strategies for large-scale implementation of self-healing concrete using cementitious macro-capsules: an experimental study and economic assessment.

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To Turin,

that has taught me resilience.

Abstract

Self-healing technologies are increasingly being targeted by academic and industrial researchers for concrete applications, because of their potential to actively repair the material when cracked, without the need for external intervention. In this sense they could represent a decisive step toward addressing some of today's greatest challenges: rethinking the entire life cycle of concrete materials starting from their durability, and achieving sustainability, quality, and cost-effectiveness.

However, despite the promising results achieved in research, several obstacles remain for the on-site implementation of self-healing technologies, including cost uncertainties, site feasibility, and the transition to large-scale production.

To explore possible pathways, this work identifies and compares three potential strategies for the use of cementitious macro-capsules, namely incorporating them into the concrete mix through: a) controlled placement, b) semi-controlled placement, c) random placement. Both technical performances and economic implications were evaluated, by means of an ad-hoc experimental study and the relative cost analysis, respectively.

Specifically, tests were carried out to characterize fresh and hardened properties of the mixes, capsule survivability during mixing and casting, and self-healing effectiveness (in terms of recovery of water tightness), in order to assess how different capsule's incorporation methods influence their behavior and the overall technical performance of the material. An economic evaluation was also conducted to estimate the potential impact of this technology on the overall cost of the final product, identifying the threshold for it to be potentially competitive on the market.

Experimental results showed that the capsules, as designed, successfully resisted the mixing and/or casting operations while still being able to break when required, without significantly affecting workability and inherent mechanical properties. Controlled placement of capsules ensured the best self-healing efficiency with an optimized use of material, while semi-controlled or random incorporation within the mix also provided significant benefits compared to not adopting the technology at all.

From the economic perspective, a maximum unit cost for the capsules was estimated, and two scenarios of cost impact were proposed, showing how variations in unit price can determine which strategy is the most economically advantageous.

Summary

Introduction

When it comes to traditional construction materials, concrete immediately comes to mind. Its simple production process, the availability and ease of sourcing raw materials, relatively low costs, and, most importantly, its mechanical and physical properties have made it an indispensable material.

Concrete is characterized by high load-bearing capacity, remarkable compressive and fire resistance, combined with good workability and plasticity, which provide considerable design flexibility. These qualities have made it, over the centuries, an ideal solution for building houses, infrastructure, and other structures of various sizes, designed to last and withstand harsh environmental conditions.

Despite being considered a "traditional" material, concrete has always adapted to engineering challenges, evolving whenever new design and structural needs arose.[1]

For example, reinforced concrete, with carefully placed steel rebars inside the cement matrix, allowed the construction of complex buildings and infrastructure capable of handling not only compression but also tension and shear[2]. Later, prestressed concrete, using pre-tensioned steel bars, made it possible to build lighter structures with slimmer sections and longer spans.[3]

Many other innovations have also improved concrete itself, from chemical mixtures to construction techniques. Examples include high-performance

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[1] (Macdonald, 2008)

[2] (Slaton, 2003)

[3] (Gerwick, 1997)

mixes[4] with fibers or additives to increase durability, self-compacting concretes[5], and even experimental solutions like transparent concrete, used in the Italian pavilion at the Shanghai Expo, [6] which shows that research also explores aesthetic and functional aspects.

These developments show that, despite the fact that concrete has a long construction tradition, it is a dynamic material that continues to evolve and is able to respond to modern construction and engineering challenges. And it is exactly new challenges that we are called to address today.

First, we are witnessing the progressive degradation of much of the building stock constructed during the post-war economic boom, often built with modest quality to meet the high demand for housing and infrastructure. Already in 2018, the 26th Cresme[7] report raised alarms about the maintenance of these buildings, and over time the situation has not significantly changed. About 11% of buildings built between 1960 and 1980 are in poor or mediocre condition, meaning that 182,000 buildings require major maintenance or replacement, and to that we need to add 76,000 more built before 1960. [8]

This aligns with what the Italian Technical Standards for Construction (D.M. 17/01/2018) says, which indicate a nominal service life of 50 years for concrete structures in ordinary environments, where “nominal service life” refers to the period during which structures and/or materials maintain their initial performance, preserving both safety and functional efficiency under

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[4] (Nawy, 2001)

[5] (Siddique, 2019)

[6] (Favole, 2018)

[7] Centro Ricerche Economiche Sociologiche e di Mercato nell’Edilizia.

[8] fonte: *XXVI° Rapporto congiunturale del Cresme*

the expected loads and environmental conditions. Thus, material quality itself often determines long-term durability.

At the same time, we live in the era of climate change, which accelerates the degradation of existing structures. Extreme weather, temperature changes, and increasing humidity put the durability of materials to the test, making the adoption of more resilient construction solutions necessary.

Also, atmospheric CO_2 is a major cause of carbonation of reinforcement in concrete structures such as bridges, buildings, and wharves, and its increase of concentration due to climate change higher this risk.[9]

Meanwhile, the planet requires responsible choices, encouraging the controlled use of resources available and a growing focus on sustainability. This makes it necessary to develop and use low-impact materials that combine mechanical performance and durability with energy efficiency and reduced emissions. This involves not only reducing the extraction of new raw materials but also rethinking the entire life cycle of materials, limiting water consumption during production, reducing transport emissions, and identifying strategies for reuse, recycling, or eventual disposal.

The challenge is therefore not only to build and maintain high-performance structures but to do so within the planet's limits, promoting a responsible approach through careful design and material selection. In this context, *durability* becomes an essential tool for sustainability, quality, and cost-effectiveness.

However, in order not to undermine all the efforts made, it becomes crucial to address the weakest link in the chain: human error, which, according to

[9] (Stewart, Wang, & & Nguyen, 2011)

statistics, accounts for approximately 22% of degradation causes[10] and has the potential to compromise even the most rigorous design choices.

Self-healing concrete could represent a highly promising solution to address these challenges. For this reason, the following chapters will analyze the potential, deficiency, and challenges of this technology, with the aim of bridging the gap that still confines such a promising strategy to laboratory research, slowing down its widespread application in the real world.

[10] (Catalano, 2022)

1. Self-healing, a tool for resilience and durability

1.1 Self-healing concrete: reasons, challenges, and perspectives

For years, research has identified numerous possible approaches to address the topics previously discussed. There has been a growing interest in solutions capable of providing self-healing properties to cementitious materials, moving from a passive repair approach, which requires external manual maintenance interventions and only addresses surface damage, to integrated active methods implemented during the production of the element itself. These active methods are capable of acting from within at the moment the problem arises, not only addressing surface damage but also restoring the original properties or at least slowing down the progressive degradation process.

Concrete in fact, despite remaining one of the most widely used construction materials, is particularly vulnerable to cracking. Cracks can originate from various causes, and when they exceed certain widths, become preferential paths for the penetration of aggressive external agents, promoting the corrosion of reinforcement and accelerating the degradation of the structural element itself.

Cracking is, however, intrinsic and expected in the functioning of reinforced concrete, where the activation of tensile reinforcement, most commonly due to bending stress across the section, induces deformations in the rebars, which in turn produce microcracks in the surrounding cementitious matrix. The 2018 Technical Standards for Construction (NTC 2018) indicate a maximum crack width limit of 0.4 mm[11], within which the crack does not compromise

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[11] *Norme Tecniche per le Costruzioni 2018*, §4.1.2.2.4, punto c

the structure's durability. Beyond this value, however, timely intervention is necessary to prevent long-term consequences.

According to Zhang et al. (2020), the first studies on self-healing date back to the 19th century, conducted by the French Academy of Sciences, which documented a phenomenon of autogenous microcrack repair already utilized during Ancient Roman times. This phenomenon relies on the components of the cementitious matrix itself and can be scientifically explained by the subsequent hydration of cement particles left unhydrated during the casting of the element, as well as by the dissolution and subsequent carbonation of calcium hydroxide dissolved in external water that penetrates through the crack.

Over the years, research has explored numerous autogenous mechanisms, which depends on the matrix components themselves, as well as autonomous mechanisms, which are based on the integration of healing agents such as bacteria or chemical agents into the material matrix through capsules or vascular systems (see Chapter 2.3.2).

The value of this research is further confirmed by the strong interest shown by the European Union, which over the last ten years, through interdisciplinary cooperation programs such as COST (European Cooperation in Science and Technology), has supported and strengthened collaboration among researchers, engineers, and scholars, resulting in the development of numerous research projects[12] on these topics.

[12] For further information: https://www.sarcos.eng.cam.ac.uk/About

Indeed, the key to moving a technology from experimental stages to practical application often lies in the ability to consider multiple needs and perspectives.

This is only possible through consultation with all relevant stakeholders: from academic experts to large multinational companies, from small and medium-sized enterprises to international research institutions and certification bodies, without forgetting those responsible for translating the technology into constructible solutions.

On the other hand, if it's true that scientific research has already produced numerous studies demonstrating the effectiveness of self-healing in its various forms, still remains a significant gap between experimental results and their actual application on a real scale.

As highlighted by Bandeira Barros et al. (2023), this gap can be attributed to multiple factors:

- first, the lack of standardized procedures in regulations makes it difficult to compare results across studies and to ensure their reproducibility over time;
- secondly, there is a scarcity of long-term data, which is essential to demonstrate both the performance and economic benefits of the technology;
- a further obstacle is the higher initial costs of implementation, which, although they may be compensated by reduced maintenance on the long term[13], often create a divergence of interests between builders and users;

[13] (Panza Uguzzoni, et al., 2023)

- cultural resistance to innovation also plays a role, due to the inertia in using established technologies compared to new ones, the lack of specific training for both designers (who must integrate these materials into the design process) and workers (responsible for construction), as well as the limited dissemination and promotion of the technology itself;
- finally, it should be noted that most studies in this field are conducted by materials or structural experts, who lack adequate knowledge of construction processes and specific issues such as safety, additional risks, operational feasibility, construction tolerances, the need for dedicated machinery or equipment, and the challenges introduced by scaling the process from laboratory studies to industrial production.

Nevertheless, it should be emphasized that despite these obstacles, there are currently examples in Europe of start-ups[14] that, while maintaining a close connection with academic research, have successfully applied self-healing technologies to real projects such as road pavements, water infrastructure, and industrial plants. These examples demonstrate the feasibility and potential of these technologies outside the experimental context.

[14] Basilisk, Delft (Netherland): https://basiliskconcrete.com/en/projects/
Mimicrete,Cambridge (UK): https://www.mimicrete.com/

1.2 Main goals and methodological approaches

This thesis is based on the data and knowledge accumulated over years of experimentation conducted in the laboratories of the Polytechnic of Turin, where research on this topic has long been carried out through multiple research projects.[15]

In particular, the focus is on the strategy that involves the insertion of tubular cementitious macro-capsules within the matrix of the element. When these cementitious shells break along with the matrix at the moment cracks form, they release the healing agent contained inside, repairing or at least sealing the crack, thereby preventing future degradation of the reinforcement (see Chapter 2.1).

The interest in this solution, compared to other possible approaches, arises from several advantages, including: high versatility due to the possibility of using a wide range of repairing or sealing agents; the ability to address a broad range of cracks, not only the smallest ones, thanks to the large amount of healing agent contained; flexibility in adopting either a localized or distributed healing approach, depending on the placement of the capsules; and, finally, full compatibility with the cementitious matrix in terms of both material and mechanical properties.

The thesis therefore aims to outline a pathway and a methodological approach to bridge the gap between experimental research and real-scale application of this technology, addressing precisely those gaps that still slow down its effective use in the field.

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[15] For further information: https://smartincs.ugent.be/index.php/about-us
https://build-up.ec.europa.eu/en/resources-and-tools/links/smash-project

To this end, the work is mainly structured around three central themes:

- identification of possible strategies suitable for scaling the process related to the use of macro-capsules;
- testing and comparison of performance related to fresh-state properties (workability), capsule survival during the concrete mixing process (survivability), possible changes in mechanical strength due to the introduction of the capsule element (inherent mechanical properties), and self-healing capacity;
- setting up a unit cost analysis in accordance with art. 32 DPR 207/2010, aimed at determining the maximum possible cost that the capsule element could represent within the process, beyond which the procedure would become unfeasible in the market, and identifying all the aspects that must be considered when moving from laboratory production to real construction applications.

2. Fundamentals and theoretical background

In order to provide a complete understanding of the described topic, this chapter presents a brief theoretical and technical overview summarizing the main information regarding concrete, its behavior, standard maintenance procedures and the self-healing mechanisms studied so far in the research field.

2.1 Damage process in concrete

Concrete is a composite material mainly made of fine and coarse aggregates (such as sand, gravel or crushed stones) embedded in a mortar mix, which is in turn produced by the hydration of cement with plain water. In fact, what transform a granular substance first into a fluid paste and then into a monolithic mass reminiscent of stone, is a chemical process that leads to the formation of calcium silicate hydrate (C–S–H), the binding phase that provides concrete with its strength and cohesion.

Apart from the kind of cement used and the particle size distribution of the aggregates, in general what strongly influence the final properties of the material is the mix proportions: for example, a low water-to-cement (w/c) ratio generally leads to higher strength and durability, but at the expense of workability. Also, chemical additives can be introduced to modify concrete's behavior, such as plasticizers to improve workability, accelerators or retarders to control setting time, and pozzolanic materials (like fly ash or silica fume) to enhance durability and reduce permeability[16].

The result is a material that performs very well under compression making it ideal for foundations, columns and load-bearing walls but that stays extremely weak in tension. This limits its use as a standalone material in

[16] (Lucco Borlera & Brisi)

structural applications, leading to the incorporation of steel reinforcement that provide tensile capacity, giving rise to reinforced concrete (RC).

The combination of the both of them is made possible by the fact that steel adheres well to concrete and both materials share a very similar coefficient of thermal expansion (approximately 12×10^{-6} °C^{-1}), which prevents loss of adhesion under temperature variations. In addition, the alkaline environment created by concrete (pH ≈ 11) ensures that the steel remains in a stable condition, protected from corrosion.

Proper workmanship during the casting process is essential to ensure the performance of the material: respecting the setting, hardening, and formwork removal times, vibrating the mix properly and providing the right thickness of concrete cover help create a compact matrix. This makes the material less likely to crack and less porous, which slows down the penetration of harmful substances and improves the long-term durability of the structure.

Despite its inherent strengths and being executed according to best practice, reinforced concrete is vulnerable to a variety of degradation mechanisms, which are important to understand in order to adopt appropriate repairing actions. First of all, it's important to point out that the damage may interest either the reinforcement or the matrix itself and that, most of the times, one influences the other.

Rebars corrosion is probably the most common problem in concrete. When steel corrodes, the material expands, the concrete matrix cracks, steel's effective cross-section is reduced and flakes are released. This happens because the passivation layer, a thin film that protect the rebar from corrosion (consequence of calcium hydroxide produced by cement hydration), get consumed when in contact with CO_2 coming from the extern. In fact, as CO_2 penetrates the concrete, the pH value shifts from around 12–13 to values below 9, compromising the steel's passive protection. This process is called *carbonation* and is influenced by environmental conditions such as atmospheric CO_2 concentration, humidity, or aggressive chloride-rich environment, in addiction with the permeability of the concrete matrix or the poor thickness of the cover.

The concrete matrix, on the other hand, can be damaged for several reasons:

- *Loading*: if excessive or repeated loads beyond the design capacity are applied, structural cracks that usually appear as wide and deep, starting in correspondence of tension zones and propagating through the entire section, may develop. These significantly compromise the element's integrity and its structural strength, however, even under normal service conditions, small cracks are allowed to appear in order to ensure the proper functioning of the reinforcement bars. To avoid them being the starting point of degradation, their maximum width is limited, generally to 0.2 or 0.4 mm depending on the exposure environment.

- *Imposed deformation by accidental factors:* earthquakes, fire exposure, or differential settlements can induce sudden deformations to the structure generating cracks that differs by dimension and shape according to the intensity and direction of the phenomena. They can start as very small and develop rapidly leading even to the failure of the structure itself.

- *Design or building errors:* design mistakes such as wrong concrete cover dimension or bad placement of rebars, together with poor construction practices, often lead to localized weaknesses that can generate problems or worsen other from a different nature. Cracks of this kind are often evident already from an early-age stage, right after curing, reflecting a permanent structural deficiency.

- *Early-age settlement:* within the first hours after casting, if not well compacted and especially in the case of poor mix design, concrete might manifest settlement over the reinforcement. Due to the excess of water, as soon as the concrete is casted and starts to consolidate, water bleeding starts rising up to the surface while solid particles move downward but are restrained by reinforcement or formwork generating cracks. These are shallow, usually vertical and aligned with the reinforcing bars.

- *Plastic shrinkage cracks:* these also appear within the first 24 hours due to an unproperly cure procedure where there is an excessive water evaporation before concrete is hardened. In fact, for proper cement hydration W/C ratio should be around 25% but to improve workability is often increased to 40-45%.[17] The water surplus forces cement particles in suspension and if the rate of evaporation is higher than the bleeding rate, there is a net loss of water that generate a volume loss, a contraction of the mass with the consequent creation of cracks. These are usually shallow, horizontal, forming a parallel pattern

- *Crazing cracks:* if the moisture loss occurs at late age due to a wrong timing in surface finishing with a trowel, while bleeding water is still present, a network of shallow random cracks may develop. Although these are not structurally significant, they can represent an aesthetic issue and a potential pathway for aggressive external agents.

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[17] (Lucco Borlera & Brisi)

- *Thermal cracks:* typical of massive structures such as foundations, dams, or thick walls due to excessive hydration heat or external temperature variations that induce strong gradients making the material expand and then contract as soon as it cools down. However, since in this stage the material is already hardened, tensile stress appears and cracks develop. These can be both vertical or horizontal reflecting the temperature distribution.

Cracks therefore represent an aesthetic, mechanical, functional, and durability issue for the structure. Thus, is important to address cracking in the concrete matrix even when it does not represent a direct structural problem, becoming at least essential in order to preserve the reinforcement.

2.2 Implications of standard maintenance practices

Understanding how maintenance is perceived in the construction sector today, is essential to appreciate the potential of innovative solutions that could extend service life while significantly reducing intervention's costs and their associated risks.

Many national and international standards address this topic, often taking inspiration from industrial practices, and define terminology, procedures, contracts, and operational tools.[18]

In particular, the New Italian Public Procurement Code (D. Lgs. 36/2023), aiming to *promote the quality of the built asset by enhancing circular economy models and environmental requirements in the choice of materials*

[18] including but not limited to: ISO 15686, EN 15221, UNI EN 16646/2015, UNI EN 15331/2011, D.P.R. 380/2001 - *Testo unico delle disposizioni legislative e regolamentari in materia edilizia*)

and components, requires the drafting of the Maintenance Plan of the Work (PMO) from the earliest stages of the project. This document should define, plan, and schedule maintenance activities for the entire building and its components, in order to preserve over time its quality, functionality, efficiency, and economic value.

In particular, due to the complexity of the structures, in order to understand how to act on each of them, there's the need to refer to specific standards: for concrete structures, UNI EN 1504, parts 1 to 10 is considered.

This identifies products, procedures, surface protection and structural repair systems, as well as monitoring and quality control, providing guidelines for the use of solutions that comply with European standards for the durability and safety of structures.

Standard techniques for repairing cracks in cement-based materials involve surface coating, filling, plugging, structural reinforcement and concrete replacement even though each of these methods presents limitations, as well as difficulties related to crack detection and accessibility.

In general, the main maintenance strategies can be classified as:

- *corrective*, when carried out following the detection of a failure, with more or less flexible timing;
- *meliorative*, when performed with the aim of improving the value or performance of the asset;
- *preventiv*e, when conducted according to predetermined schedules with the goal of reducing the probability of failure or degradation;
- *predictive*, when based on data diagnostics that estimate when a failure is likely to occur, allowing timely intervention.

However, in the construction industry, maintenance is generally referred to as either *ordinary* or *extraordinary*, mainly distinguishing the relevance of the intervention rather than the purpose for which it is carried out.

Despite the efforts to encourage the use of preventive or predictive maintenance, common practice remains largely anchored to a corrective approach. Repairs using conventional techniques, over time, tend to deteriorate and fail needing extra interventions that in the end could cost more than the initial investment, needs a significant use of additional resources, could cause potential interruptions or reductions in the operation of the building or the services it provides, with consequent economic losses and inconveniences, and add a good amount of risks associated with setting up a new intervention site.

This demonstrates how integrating maintenance strategies directly into the construction phase can be extremely advantageous, effectively eliminating all these issues.

2.3 Self-healing mechanism and technologies

As aforementioned, conventional methods of crack repair are applied to visible cracks, and often their physical repair does not imply that the impact induced on the structure, like the triggered rebars' corrosion, has been solved.

Self-healing technologies instead, acting directly from the inside, address the crack as soon as it appears, healing it instantly and continuously, without the involvement of external manual intervention, preventing the entry of destructive chlorides or moisture that could lead to more serious problematic.

Moreover, regardless of the specific typology used, the self-healing component is integrated directly during the manufacturing of the element, being present from the very beginning of the construction process and able to act as soon as micro-cracks form, for whatever reason they occur and even before they are visible to the naked eye.

The available current literature distinguishes two main healing mechanisms, an *autogenous* one and an *autonomous* one.

2.3.1 Autogenous self-healing mechanism

The autogenous mechanism relies on the use of inner concrete constituent to heal the crack basing its functioning on three main processes[19]:

- the *physical* one, refers to concrete swelling, a partially reversible phenomenon caused by the cement and aggregate water absorption. In fact, this occurs as a result of the propagation of a crack and the consequent penetration of water which, absorbed, helps the two surfaces to gradually expand and create a bridge bond.

  However, this phenomenon is strictly related to this humid environment and the crack may reopen as soon as it dry. Moreover, it is often difficult to distinguish the impact of concrete swelling without considering supplementary occurrences such as autogenous shrinkage and excessive calcite precipitation, or hydration.

- the *chemical* one, includes the continuing hydration of un-hydrated cement particles and the carbonation of calcium hydroxide.

[19] (Abdulahi, et al., 2023)

The first means that depending on how many un-hydrated cement grains remain at the end of the curing, the material retains a sort of "reserve" that, when in contact with water coming from the extern, allows further hydration producing calcium silicate hydrate gel (CSH) as well as other hydration products such as calcium hydroxide, calcium sulphoaluminate, and aluminates that acts filling crack.

Clearly, the lower the W/C ratio is in a concrete mix, the higher the number of un-hydrated particles will be, but in any case, this is a process that depends a lot on the age of the concrete at the time of cracking: if young, it is more likely that still a lot of particles are available, while at later ages there might not be many left.

Instead, several studies reports that carbonation of calcium hydroxide is to be considered the primary mechanism in autogenous healing.

As reported by Abdulahi M. et al. (2023) when water penetrates through the crack, soluble composites released from the concrete matrix reacts according to the following proportions and form calcium carbonate precipitate ($CaCO_3$) that deposits in the crack and helps closing it.

$$H_2O + CO_2 \leftrightarrow H_2CO_3 \leftrightarrow H^+ + HCO_3^- \leftrightarrow 2H^+ + CO_3^{2-} \quad (1)$$

$$Ca^{2+} + CO_3^{2-} \leftrightarrow CaCO_3 \qquad (pH_{water} > 8) \quad (2)$$

$$Ca^{2+} + HCO_3^- \leftrightarrow CaCO_3 + H^+ \qquad (pH_{water} > 8) \quad (3)$$

- the *mechanical* one, that consists in the accumulation of loose concrete particles and small debris transported by the flowing water. These both constitute a physical barrier against the further entrance of external aggressive agents and a skeleton for $CaCO_3$ crystals to deposit.

The schemes reported in Fig. 1 shows how all these mechanisms operate together to promote autogenous healing.

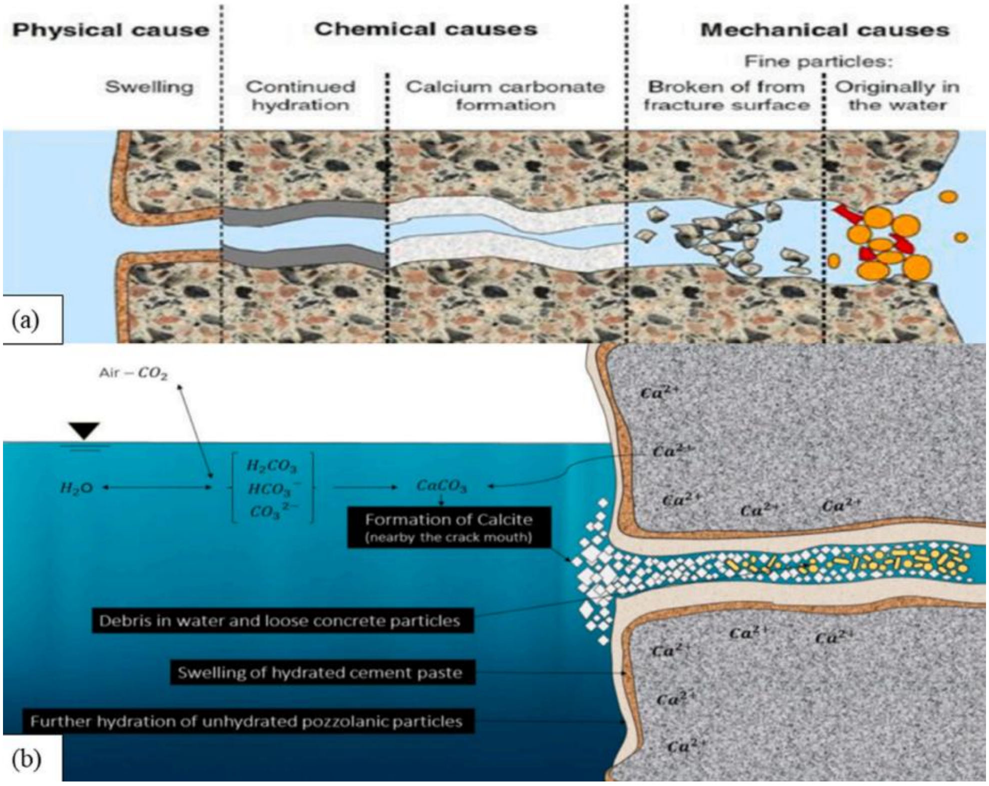

Figure 1 - Causes of autogenous self-healing (Tumwiine, et al., 2025)

Despite that, the actual contribution of these mechanisms is still under debate as they appear to depend on several factors such as W/C ratio, cement particle size and chemical composition, additives included, water availability, concrete age and, of course, crack width.

In fact, according to literature[20], some studies report that only cracks up to 0.1 - 0.2 mm can be healed through the autogenous mechanism, while others indicate that this technique can be effective also for 0.3 mm cracks. Such variability in results can likely be justified by the influence of the previously mentioned factors.

The efficiency of autogenous healing can however be enhanced by incorporating mineral admixtures, fibers, superabsorbent polymers and curing agents with the purpose of providing extra water, restricting the cracks, modify the duration of the hydration process or improve the crystallization.

2.3.2 Autonomous self-healing mechanism

The autonomous mechanism is based on the incorporation of a *healing agent*, either chemical or biological, into the concrete during its production. This can be directly added into the matrix, or protected and spread as needed by a *vascular* or *capsular system*. These two mechanisms differ for how the healing agent is stored and distributed, but both relies on the local break of the system, when the crack occurs, to release the healing agent.

2.3.2.1 Bacteria based systems

Belonging to this category are *bacteria-based systems*, which incorporate specific species of bacteria capable of producing calcium carbonate through their metabolism that than deposits and heals the crack. The spores can either be directly poured into the concrete mix or be encapsulated for additional protection and may be combined with silica gel or polyurethane foam to shield them from the alkaline environment.

[20] (Ghazy, Emara, & Abdellah, 2023)

In fact, according to the studies conducted, the main challenge with this solution regards creating a suitable environment for the bacterial activity: in fresh concrete, the pH is high, and slows down bacteria's growth. However, once the pH level slightly decreases when water penetrates through the crack, their metabolism to start producing $CaCO_3$.

This appears to be one of the most durable self-healing techniques, keeping its effectiveness for indefinitely long time and being able to heal larger cracks, up to 0.97 mm[21], but presents complexities coming from having to deal with the biochemical world.

2.3.2.2 Capsule-based systems

Another high versatility solution, capable of healing both small and large cracks and that can provide either a diffuse or localized healing action, is the use of *polymers* as healing agent in encapsulated or vascular systems. Although different types of polymers may vary in their specific properties, they all work similarly. In fact, once released and in contact with air or moisture, depending on the agent, the polymerization process starts: the material flows towards the cracked area and solidifies, healing or at least sealing the opening.

In order to select the appropriate healing agent for a given application, several parameters must be considered, as they can affect the agent's behavior and potentially compromise the effectiveness of the entire system:

- *viscosity* should be in between 100-500 mPa*s because if too low, the agent may leak out of the crack or it be completely absorbed by the

[21] (Tumwiine, Chala, Ssenyonjo, Kirigoola, & Al-Fakih, 2025)

surrounding matrix, whereas if too high, it may not be able to flow and fill the crack;

- needed *curing condition* should be carefully evaluated, as the agent often should be able to react under wet circumstance, frequent when the crack appears. This can be an issue for agents whose reaction is instead triggered by exposure to air, CO_2 or heat rather than moisture;
- also *curing time* should be sufficiently long to allow the agent to flow and fill the crack, but at the same time not too long, otherwise the crack could evolve;
- an *expansive action* of the agent, combined with an *elastic behavior* once hardened, is considered desirable to properly fill the crack, however, it must be ensured that the strain caused by the expansion does not exceed the tensile strain capacity of the material, in order to avoid generating new microcracks.
- the *strength* of the healing agent and the *bond strength* with the surrounding concrete matrix should be similar or higher than the concrete's one otherwise the repairs are weaker and more vulnerable to furtherly crack once the healing agent is already exhausted.

An unexhaustive list of the main healing agent used and their characteristics is reported in the following tables:

Agent	Number of components		Viscosity (mPa·s)	Curing method	Curing time	Expansion	
	1	≥ 2				Yes	No
Epoxy	✓	-	-	Moist., air, heat	60 °C, <100 min	-	✓
Epoxy	-	✓	80 ÷ 500	Contact component	(30 ÷ 60) min	-	✓
MMA	✓	-	-	Heat	-	-	✓
MMA	-	✓	1 ÷ 34	Contact component	(30 ÷ 60) min	-	✓
PU	✓	-	7200	Moisture	(40 ÷ 180) min	✓	-
PU	-	✓	600	Contact component	(50 ÷ 300) sec	✓	-
Silicone	✓	-	-	Air	-	-	✓
Polyacrylate	-	✓	7	Contact component	40 sec	-	✓

Figure 2 - Healing agents characteristics, table 1
(Antonaci, P. - Self-healing cementitious material a/y 2024-25)

Agent	Number of components		Viscosity (mPa·s)	Curing method	Curing time	Expansion	
	1	≥ 2				Yes	No
Cyanoacrylate	✓	-	<10	Moisture	Seconds	-	✓
PU + bacteria	-	✓	600	Contact component	-	✓	-
Bacteria	✓	-	-	Water and O_2	100 days	-	✓
Bacteria	-	✓	-	Water	-	-	✓
$Ca(OH)_2$ sol.	✓	-	-	CO_2 in air	-	-	✓
Na_2SiO_3 sol.	✓	-	-	$Ca(OH)_2$ in matrix	-	-	✓
Na_2FPO_3 sol.	✓	-	-	Matrix	28 days	-	✓
$Ca(NO_2)_2$ sol.	✓	-	-	Matrix	-	-	✓

Figure 2 - Healing agents characteristics, table 2
(Antonaci, P. - Self-healing cementitious material a/y 2024-25)

Concerning the agent's storage and diffusion mechanisms instead, as previously mentioned, two are the main strategies used: capsules and vascular systems.

In capsule-based systems, one or more healing agents are stored inside a shell that, according to the size and the manufacturing technique, can be categorized as micro or macro capsule. This appears to be an extremely promising strategy because, of course, the bigger is the vessel, the more is the healing agent contained, the wider can be the crack successfully healed.

The shell however needs to satisfy many parameters in order to be able to fully work and being compatible both with the matrix and the agent contained:

- *survivability*, they have to resist the impacts received during the mixing and casting operations;

- *workability*, they don't need to be an obstacle and modify too much the mix consistence;

- *hardened concrete mechanical properties*, being a "defect" introduced into the matrix, their dimension and shape should be evaluated in order to not constitute a significant reduction of strength. Model tools can be used to eventually estimate strength loss and redefine the concrete cross section to achieve the required characteristics;

- *matrix compatibility,* the capsule has to stay stable in a high alkaline environment in order to protect the healing agent inside;

- *healing agent compatibility,* also the healing agent itself should not damage the stability of the capsule-based system;

- *responsiveness to cracking,* a brittle behavior is wanted with the aim of guarantee the healing agent release once the crack occurs, however the material should not be too weak to satisfy also the survivability requirement. Also, a good bond with the surrounding matrix is needed to avoid the propagation of the crack at the interface between the two of them;

- *probability of interception*, with this solution the healing agent is concentrated where the capsules are, so they need to be well positioned and in a proper number in order to be sufficient;

- *release efficiency,* even though is the healing agent viscosity the main responsible for a proper release, also the capsule has to minimize the resistance forces of capillary action with a proper diameter that has to be bigger than the expected crack dimension;

- *maximum healable crack volume,* depending on the maximum healing agent volume contained by the capsule.

Trying to guarantee these characteristics and find the right balance between efficiency and cost, multiple materials were tested thanks to the research. These include cementitious capsule shells, produced using various methods such as extrusion[22], 3D printing[23], or manual fabrication, as well as glass[24], ceramic[21] or polymeric materials[25] with different shapes.

2.4 Fields of use and potential advantages

To understand in which cases this technology could best express its potential, is important to consider how each actor involved into the construction process (owner, designer, constructor, …) is likely to evaluate it, focusing in particular on the practical or short-term economic advantages that could encourage its adoption.

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22 (Anglani, Mullem, Tulliani, & Tittelboom, 2022)

23 (Riordan, et al., 2023)

24 (Qureshi, Kanellopoulos, & Al-Tabbaa, 2016)

25 (Tettelboom, Belie, Loo, & Jacobs, 2011)

For example, when thinking about for which type of cracks this technology would be most suitable for, it soon becomes clear that in the case of early-age cracks, such as those caused by plastic settlement or shrinkage, the use of self-healing seems less competitive than traditional techniques, which instead involve simple and nearly cost-free procedure like improving casting or curing condition. In fact, in these situations the healing agent would be almost immediately consumed, nullifying its availability for addressing subsequent deterioration.

Instead, when considering the long-term cracks, such as those occurring for long-term *shrinkage or thermal damage*, both already very difficult to repair with traditional techniques, the advantages of implementing self-healing solutions become clear and embody a shared view: contractors benefit by avoiding the extra costs associated with expensive procedures, such as additional reinforcement or cooling methods, owners appreciate the improvement in overall structural performance, and researchers gain a valuable opportunity to demonstrate the effectiveness of this technology.

Preventing damage is, in fact, particularly crucial in large structures, such as underground facilities or containers for hazardous liquids, where such cracks are more likely to occur. The presence of groundwater or leakage of chemicals can be extremely dangerous for both the structure and people nearby, making it essential to find solutions that can effectively mitigate these risks.

Further potentiality must be seen also in other side application.

For example, the addition of self-heling technologies into patching mortars during *repair intervention* can enhance their ability to bond and extend the service life of the restored component. Or moreover *hybrid design solutions*, where self-healing concrete is used as a protective outer shell embedding a traditional concrete core, provides a “regenerative barrier” against environmental ingress and degradation, while the inner concrete would ensure the structural performance, resulting in a combined system that maximizes durability, cost-effectiveness, and resilience

Another interesting application could be in providing *extra safety* in situations not explicitly covered by current regulations, such as minor cracking caused by low or mid-magnitude earthquake that, how reported from the INGV[26] in their annual seismology report, take place relatively often. In fact, especially in the case of structures built with less resistant materials or that are particularly near the epicenter, cracking that usually not compromise the structural stability may appear. These can however reduce the long-term durability of the reinforcement being a preferrable path for the ingress of aggressive agents.

Nowadays, there is no standard that specifically addresses this topic. However, historically in Italy, when such earthquakes occurred, the government promulgated ordinances[27] that provided parameters for the compensation of damages. These measures were generally focused on strategic buildings or on cracks larger than 1 mm leaving the issue of micro-cracks unaddressed, which could still pose a risk to the durability and long-term integrity of buildings.

[26] Istituto Nazionale di Geofisica e Vulcanologia

[27] D.P.C.M. 16 luglio 2020, D.P.C.M. 24 agosto 2016

3. Strategies for scaling capsule-based implementation

Among all the technologies described so far, and as previously anticipated, this thesis focuses on the use of cementitious macro-capsules, which, as demonstrated by previous studies, offer the advantage of being perfectly compatible with the surrounding concrete matrix: they offer good adherence, tend to break along a clean crack, have a high healing agent capacity, and do not cause instability either with the agent contained inside or with the matrix itself.

Thanks to the research projects carried out by the Polytechnic of Turin in the last years and its collaboration in numerous international initiatives, several studies[28] have already focused on the optimization and refinement of the self-healing mechanism itself.

However, the application of any type of macro-capsule is still mostly limited to the paste and mortar level[29], generally for laboratory convenience. Only a few recent studies have addressed the complexities arising from their interaction with concrete, representing an additional obstacle on the path toward the scalability of this solution.

On the other side, the results obtained were very promising: the presence of capsules did not significantly affect the compactness and the mechanical properties of the hardened concrete while being able to successfully cracking

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[28] (Anglani, Mullem, Tulliani, & Tittelboom, 2022), (Anglani, Montanari, Tulliani, Lacidogna, & Antonaci, 2023), (Hermawan H. , et al., 2023)

[29] (Hermawan H. , et al., 2023)

and releasing the healing/sealing[30] agent, restoring the opening and showing a consistent reduction in permeability and sorptivity.

Despite the remarkable qualities demonstrated, compared to other technologies whose scalability has already been proven[31], as in the case of the bacteria's one, employed even in the renovation works of the ARTIS Aquarium[32] in Amsterdam, till today the capsule-based solution remains at the laboratory scale, due to the numerous uncertainties related to the industrial-scale capsule production, site implementation, and associated costs.

3.1 Scalability challenges

With the aim of identifying strategies to be subsequently tested experimentally, in order to facilitate the transition toward large-scale applicability, attention was focused on examining in detail the elements that still represent obstacles.

These have been grouped into three categories:

1. Capsule production-related issues:

- *manufacturing methods*. Techniques such as handmade production, 3D printing or manual extrusion could work in a laboratory environment for experimental purpose, when small quantities are

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[30] Depending on the type of agent used, the process is referred to as *healing* if it repairs the crack and allows the specimen to recover strength, or as *sealing* if it only closes the crack, preventing the ingress of external agents and protecting the reinforcement, but without any recovery of strength.

[31] (Mullem, Gruyaert, Caspeele, & Belie, 2020)

[32] With the aim of building the most sustainable aquarium in the Netherlands, self-healing technologies and other sustainability-oriented solutions were employed.

For further information: https://basiliskconcrete.com/en/portfolio-items/not-a-basement-nor-tunnel-but-an-aquarium-with-self-healing-concrete/

https://www.artis.nl/en/artis-zoo/aquarium/the-refurbished-artis-aquarium needed, but they may not be feasible, efficient or cost-effective on a large scale. For these reasons, industrial processes such as molding, continuous casting, or sheeting need to be explored.

Considering the main procedures required for the shell production (*see Chapter 4.2.1.1*), analogous industries such as pasta, chocolate, or pharmaceutical production can provide a valuable starting point for gathering information. However, accessing this type of data seems extremely hard without already being embedded in the sector.

- *production quantities*. At present, it remains difficult to predict how many in the future would be willing to adopt this technology, which makes it highly challenging to estimate the required production quantities and the corresponding size of the production facilities.
- *production time and yield.* Without a clear understanding of the production methods and the expected quantities, it is obviously impossible to provide a reliable estimate of production time and material yield. While industrial-scale manufacturing would undoubtedly accelerate the availability of the product compared to manual fabrication, thus representing a 'positive' variable in the process, yield remains an uncertainty. On the one hand, automated processes can reduce waste associated with human error, on the other, they inevitably generate processing losses due to machine start-up and adjustment, which are difficult to quantify at this stage.
- *quality control*. Ensuring that all capsules meet the required properties (such as strength/fragility, leak-tightness, external roughness, and other previously mentioned characteristics) is essential for the proper functioning of the technology. While element-by-element inspection is feasible at laboratory scale, in industrial production it is only

possible on small samples, relying primarily on the reliability of the process itself.

- *standardization of procedures*. Being a completely innovative product, it is necessary to establish standards that define procedures, technical specifications, and production and quality control plans to ensure proper process replicability. To support this and guarantee quality and safety, at the European level it is necessary to mainly rely on harmonized ISO 9000 standards, which effectively govern the management of processes, raw materials, and workers.
- *storage and transport*. At the experimental level, capsules never leave the laboratory, are handled with care, and generally remain unused for only a short period. In large-scale implementation, however, capsules must retain their properties until the moment of use, without breaking or degrading. This aspect is also addressed by ISO 9000, which requires the establishment of control charts before the material leaves the production facility.

  Furthermore, it is necessary to define the characteristics of the storage facility as well as the storage methods, the number of items per package to optimize storage and transport, and all related information.
- *ties with research*. Being a technology under development with significant potential for further advancement, it would be useful to define how the production side would continue to collaborate with research centers in order to ensure ongoing optimization, quality control, and the successful translation of laboratory findings into large-scale applications.
- *initial investments***.** Given all the considerations outlined above, it becomes extremely difficult to estimate the investments required to start industrial-scale production of the capsules. For this reason, in this

thesis (see *Chapter 5.1*), a bottom-up approach was used to estimate the maximum unit cost of a capsule, taking into account its overall impact on the total cost of the work. Instead of starting from the estimation of all direct and indirect production costs, which are difficult to quantify at this stage, an inverse approach was adopted: a unit cost limit for the capsule was defined so that its contribution to the total production cost would not exceed a predetermined threshold (15–20%).

2. Construction-related issues:

- *technical feasibility and added complexity***.** At the experimental level, the most common approach adopted in previous studies has been to manually place the capsules inside the specimens in predetermined positions, using a rudimentary support system (see *Chapter 3.2.1*) designed to ensure proper concrete cover and to localize the capsule in the position most likely to be intercepted by the crack. This method ensures the release of the self-healing agent and achieves a crack repair/sealing probability close to 99%.[33]

  However, even at the laboratory scale, it proves to be a very elaborate system to implement, prone to placement errors, requiring skilled manual handling, and resulting in a rather delicate outcome. From these premises, it can be state that a direct transposition of such a method to the construction site would be highly complex.

  A more feasible solution could involve the development of a prefabricated anchoring system integrated into the capsule production process itself. One possible design, suggested here, is an S-shaped system (as shown in the figure 5-6-7) that would secure the capsule

[33] (Uguzzoni, Anglani, Antonaci, & Tulliani, 2023)

on one side and attach it to the reinforcement stirrups on the other. This would reduce on-site operations to a simple fixation to the reinforcement, once the steel framework has been arranged, with operators following the quantities and locations specified at the design stage.

An alternative would be to directly integrate the capsules into the concrete mix. However, this introduces a different set of challenges, including ensuring that the capsules survive the mixing and casting process, that they are evenly distributed within the formwork, and that they do not float to the surface. These aspects are examined in greater detail in the experimental section of this thesis (see *Chapter 4.4*).

- *additional risks***.** The introduction of new procedures and materials on construction sites inevitably involve additional risks, ranging from worker safety concerns to longer execution times, as well as the need to reconsider traditional design aspects, such as concrete cover thickness. For this reason, it is essential to carry out a detailed risk assessment, systematically identifying and evaluating all these factors and implementing the necessary preventive and protective measures.
- *training.* Depending on the specific technology employed, it will be necessary to provide training for both design engineers and site operators, in order to ensure compliance with the required performance standards. This will certainly be more demanding depending on how far the process deviates from the standard procedures commonly adopted in traditional practice.
- *additional tools and machinery required.* Procedures such as manual placement or controlled dispersion of the capsules within the mix require the development of dedicated and suitable equipment.

For the first solution, a prefabricated anchoring system has previously been suggested, whereas for the second one, a possible solution could involve a device similar to a seed drill used in agriculture, capable of releasing a predetermined number of capsules at regular intervals to ensure their homogeneous distribution within the concrete element.

However, while such a system may be effective for planar elements such as beams or slabs, in the case of vertical or more complex geometries, it would be necessary to design a device that could be integrated with the concrete pumping system, gradually releasing the capsules during the casting process.

3. Cost estimation-related issues:

- *capsule per-unit cost.* Attempting to estimate the unit cost of a capsule, as previously mentioned, involves numerous layers of complexity. These are not limited to the production process itself, which considers raw material costs, manufacturing methods, and initial plant setup costs, but extend to a broader range of factors. For instance, the scale of the production facility may cause price fluctuations itself, while the distance between the production site and the construction one can affect transportation costs, potentially increasing or decreasing the overall unit cost.

- *processing cost due to required specialized equipment or additional labor.* Depending on the specific technology used, different cost component may have a varying impact on the total processing cost. Manual placement, for example, may incur higher labor costs due to increased time and the need for skilled operators, while automated or semi-automated devices could reduce labor but introduce additional capital and maintenance expenses.

Furthermore, equipment designed to ensure homogeneous distribution, controlled dispensing, or anchoring of the capsules may also require adaptation for different geometries, element sizes, or site conditions, further influencing the overall cost of the process.

- *indirect site costs related to extended construction times.* The addition of a new procedure may lead to longer execution times due to additional handling, placement procedures, and equipment setup. These delays can increase indirect site costs, including labor overhead, equipment rentals, site supervision, and temporary facilities.

  It is well known that even small extensions in the construction schedule can accumulate significant additional expenses, however should be sufficient a good project timeline planning to avoid further costs.

3.2 Implementation strategies

To address these challenges, three strategies for the implementation of cementitious macro-capsules have been developed and subsequently tested to compare their performance in relation to their costs evaluated taking into account all the previously mentioned aspects specific to each strategy.

3.2.1 First strategy: controlled placement

The first strategy follows the manual placement of capsules using supports, a method traditionally employed in previous experiments, but here applied to a concrete element rather than mortar.

This technique has proven to be reliable[34], allowing the capsules to be placed precisely where cracks are expected to form and, for this reason, optimizing the utilization of the material and reducing the number of capsules required.

This strategy was conceived using long capsules (4–5 cm) to ensure that a sufficient amount of healing agent is concentrated where needed, thereby increasing the likelihood that the stored material will be in an adequate amount to fully seal the crack once it forms..

Figure 3 - First strategy, controlled placement

It should be noted, however, that these might constitute an obstacle for the larger particles during the pouring of the mix, so distances from the rebars and concrete covers need to be carefully designed in order to prevent the formation of any void and ensure a matrix with no defects.

To implement this strategy, at the design stage, type of capsule, healing agent contained, capsule dimension, quantities and positions must be defined, while for implementation at least 1–2 additional trained operators, alongside the reinforcement team, will be required to handle the manual placement of the capsules. This methodology involves significantly longer installation times

[34] (Anglani, Mullem, Tulliani, & Tittelboom, 2022)

compared to the following two strategies and carries the risk of errors due to incorrect capsule placement.

Up to now, experimental setups have relied on placement mechanisms based on weaving cotton threads to create an internal framework within the specimen's formwork, onto which the capsules were glued using the same resin that coats them. However, such procedures are unfeasible on construction sites due to the different type of formworks, the high precision required, and the time spending operations involved in marking the positions, building the framework, fixing the capsules, and allowing the resin to cure.

These steps would significantly extend construction times, making the process extremely costly, while also being logistically impractical from the outset and potentially unsafe for workers, who might be required to operate in particularly challenging positions.

A possible solution to facilitate on-site implementation would be the use of prefabricated supports (fig. 5), possibly made of plastic, printed and attached to the capsules directly during their production process.

Figure 4 - Capsule support system

These supports would allow the capsules to be anchored directly to the reinforcement bars according to the design specifications, in the required quantities and orientations, eliminating the need for on-site measurements and reducing the risk of incorrect spacing, as illustrated in the following images.

For example, when aiming to position the capsules within a beam where flexural cracking is expected, a placement scheme such as the following could be adopted:

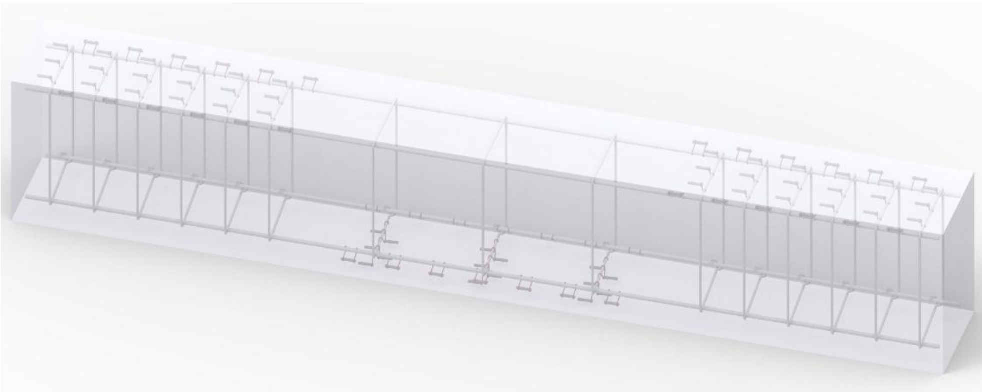


Figure 5 - Example of capsule placement within a beam subjected to flexural stresses

With reference to the capsule dimensions adopted in the experimental phase (see *Chapter 4.2*) and the concrete mix design used, where the maximum aggregate size is 16 mm, the following images illustrate the possible dimensions that the system could assume in order to simultaneously ensure capsule anchorage, correct placement, and adequate spacing from both reinforcement bars and concrete cover.

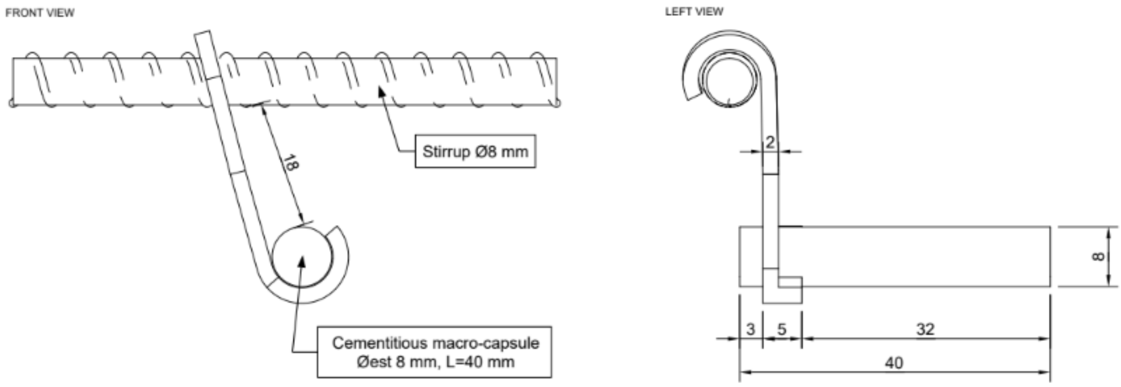


Figure 6 - Support for orthogonal placement of the capsule to the rebar (not in scale)

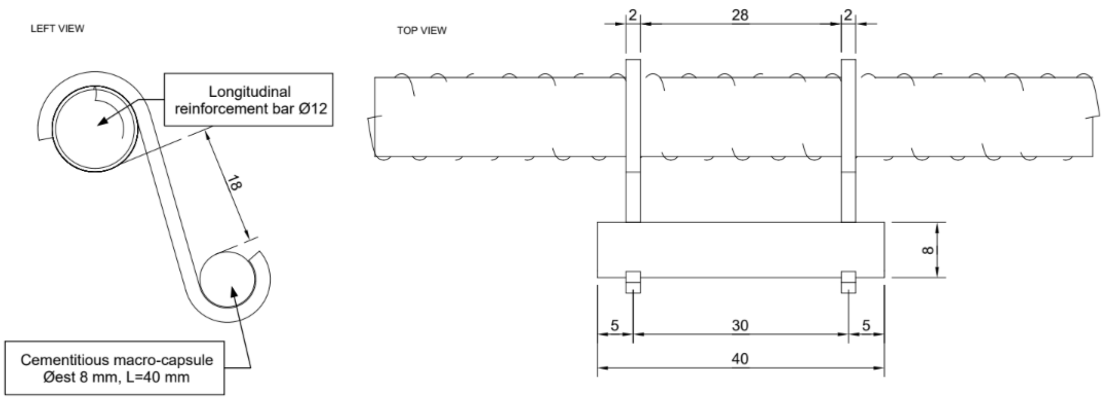


Figure 7 - Support for parallel placement of the capsule to the rebar (not in scale)

3.2.2 Second strategy: semi-controlled placement

The second strategy aims to simplify the introduction of capsules into the process by shifting from manual placement to an automated system, which disperses the capsules either in predetermined positions defined by the design or uniformly throughout the element during concrete casting.

This approach eliminates the complexities associated with controlled placement while ensuring uniform distribution, accurate quantities, and proper capsule integrity at the moment of insertion.

Previous studies[35] have shown that the introduction of macro-capsules can affect the particle packing of the mix, leading to the formation of voids and, consequently, defects in the matrix.

However, it has also been demonstrated that these effects are significantly reduced when the capsule closely approximates the shape and size of the coarse aggregate fraction, allowing it to blend effectively with the aggregates and integrate properly within the concrete matrix.

Figure 8 - Second strategy, semi-controlled placement

While this process has been carried out manually at the experimental level, on a larger scale it could be easily implemented on-site through the use of dedicated spreading equipment. This could involve devices similar to manual seeders used in agriculture, specifically designed for the proper containment and distribution of the capsules, or alternatively time-controlled dispensers directly integrated into the concrete pumping system.

[35] (Hermawan H. , et al., 2024)

3.2.3 Third strategy: random placement

The simplest way to integrate the capsules would be to add them directly into the mix, treating them as just another "ingredient" of the concrete, alongside aggregates, sand, cement or water. This approach would greatly simplify the design phase, as it would only require determining the desired quantity of healing agent and, consequently, the corresponding number of capsules. At the same time, it would have no impact on the procedures or timelines already established for construction.

Moreover, the data collected during the sperimentation reflect perfectly the reality, as the procedures adopted in the laboratory correspond exactly to those that would be implemented on-site. Even in this case, to avoid interference, the use of capsules that approximates the shape and size of the coarse aggregate fraction is recommended.

Figure 9 - Third strategy, random placement

However, this procedure raises a number of issues, including the inability to control either the concentration or the localized placement of the capsules. For this reason, it is necessary to overestimate the number of capsules to be added, effectively meaning that not 100% of the material is utilized efficiently, in order to ensure that capsules are present in the desired locations.

Moreover, there is a possibility that during concrete vibration the capsules, being less dense, may rise to the surface, so the execution of these procedures must be carefully evaluated. Finally, capsules may also be damaged during mixing and casting operations, which makes it necessary to design a capsule capable of withstanding these processes while still being able to break when a crack occurs.

From the previous considerations, it is evident that this approach is more suitable in situations where widespread cracking is expected, and it is practically applicable only if the cost of the capsule element is low enough to allow for increased dosage without significantly impacting the overall cost of the structure.

4. Original comparative experimental study

While all three approaches show promising potential, the fact that the three of them could offer comparable performances cannot be assumed. To properly assess their efficiency, it is essential to carry out a comparative evaluation under controlled experimental conditions, that consider the most important aspects previously discussed and offer an exhaustive panoramic of each behavior enabling an evaluation of their suitability across different potential applications.

The diagram below is a schematic overview that summarize the main steps carried out during the experimental phase:

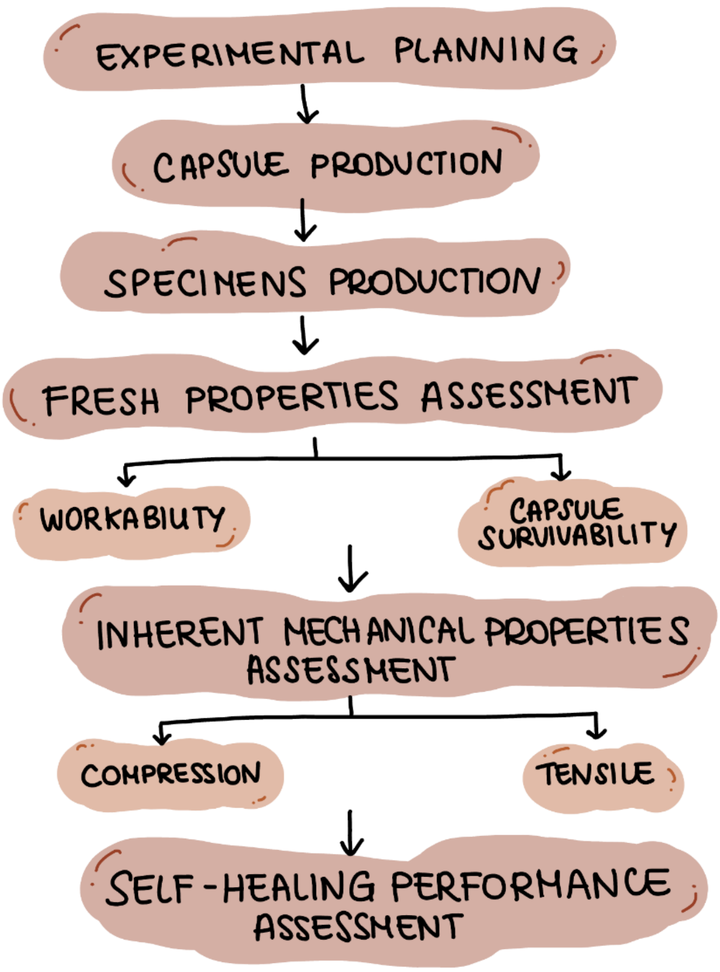


Figure 10 – Scheme of the main experimental steps

4.1 Experimental planning

To translate the approach described so far into an experimental framework, the first step was to define which kind of specimens has to be produced and in what quantities. To ensure their identifiability throughout the entire process is then essential define labels assigning them a coherent nomenclature. The logical scheme used was: SPECIMEN TYPE – STRATEGY TYPE – IDENTIFICATION NUMBER.

Subsequently, the type of capsule used and the number of capsules to be produced was estimated. Since, at the end of production, some specimens or capsules may need to be discarded due to defects that could affect the test results, it is necessary at this stage to overestimate the number of units to ensure sufficient availability to complete the entire experimental campaign.

4.1.1 Test to be performed

The main elements that we want to evaluate are:

- For the third strategy, the *survivability* ratio of the capsules when mixed with the other concrete components. Although no standardized procedure exists for this assessment, it is sufficient to simulate a casting process, introducing a known quantity of capsules into the mix and then gradually extracting fresh concrete from the mixer in order to recover the capsules counting how many have survived;
- Still for the third strategy, the *fresh properties* of the mix, such as workability, to evaluate the consistency class of the material. This can be assessed by performing a slump cone test (Abram's cone test) following the UNI EN 12350-2:2019
- For all three strategies, it is important to evaluate how the insertion of the capsules affects the inherent mechanical properties of the material. A compressive strength test, performed according to UNI EN 12390-

3:2019, can be used to assess potential changes in *compressive strength*, while a splitting tensile test, following EN 12390-6:2023, can be conducted to estimate the *tensile capacity*.

- For all three strategies, it is also essential to evaluate the *healing/sealing properties*, which depend on the type of healing agent used. In this study, a water-repellent agent was encapsulated, and its effectiveness upon release was assessed through a water absorption test carried out according to UNI EN 13057:2003, measuring the amount of water absorbed by the concrete matrix in correspondence with the crack.

4.1.2 Types and number of specimens to be produced

In order to obtain representative results, minimize the impact of random errors, and enable a reliable statistical analysis, it is necessary to produce an adequate number of specimens to use for each test.

To meet these requirements, the following specimens should be produced:

- 18 specimens without capsules, to be used as reference in the various tests, labeled as REF-L-xx[36];
- 12 specimens with manually placed capsules (first strategy), labeled as CAP-L-xx;
- 12 specimens with a controlled number of capsules (second strategy), labeled as CAP-N-xx;
- 12 specimens with capsules randomly integrated into the mix (third strategy), labeled as CAP-R-xx.

[36] The "L" in this nomenclature does not refer to the presence of any type of capsule; rather, it indicates that the concrete mix used to produce these specimens is the same as that used for the specimens with L-type capsules.

4.1.3 Type and number of capsules to be produced

The capsules used have a cementitious shell and contain a water-repellent healing agent capable of sealing cracks and preventing the ingress of water or aggressive agents from the outside. To ensure the correct application of the different strategies, two types of capsules were produced: a longer one (CAP40) [37] for controlled placement, and a shorter one (CAP10)[33] for the other two strategies.

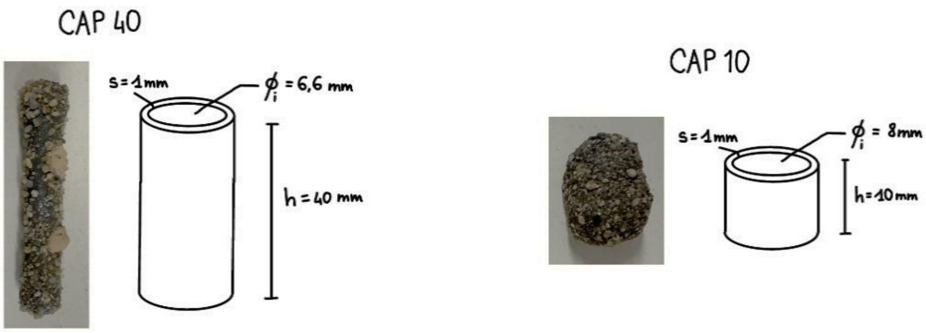


Figure 11 - Capsules type and dimensions

To estimate the required quantities, a similar approach to that used by Harry et al. (2023) was followed. Starting from choosing a replacement percentage with respect to the coarse aggregate in the mix and knowing the volume occupied by a single capsule, the number of capsules needed for each specimen was calculated.

In our case, aiming for a replacement rate between 4% and 5%, it was estimated that each 1 dm^2 specimen required the inclusion of 4 CAP40 and 14 CAP10. This made it necessary to produce at least 48 long capsules and 336 short capsules for the specimen tests, plus around forty additional

[37] The number refers to the length of the capsule in millimeters.

capsules for the survivability test, resulting in a total of approximately 380 CAP10 capsules.[38]

4.2 Capsules production

The production of both CAP40 and CAP10 followed the same procedure, carried out manually in the laboratory. The main phases, described in detail below, included the fabrication of the shell made of cement paste, its internal waterproofing, the sealing of one end, the filling with the healing agent, the sealing of the second end, and the external coating.

4.2.1 Materials

The materials and mix proportions are reported with reference to a “standard dose” of production. A standard dose is defined as the quantity of material that, at the laboratory scale, was found to be manageable for capsule manufacturing, ensuring process efficiency while minimizing waste due to premature hardening of the mix before shaping.

The procedure was therefore repeated as many times as necessary to produce a number of capsules exceeding the required target.

According to estimates derived from previous laboratory campaigns, the average yield of a standard batch is approximately 180 CAP10 and 45 CAP40.

4.2.1.1 External rigid shell

To produce the shell, a mix of solid and liquid components was used to form a paste with the consistency of clay, which can be easily modeled by hand. In fact, a cement paste made just by cement and water should be casted in molds

[38] (For further details on the calculation methods, refer to the Excel file: *Attachement4_Capsule cost and price analysis*, sheet “Mix design”.)

that are difficult to manage for these dimensions, so a polymer modified cement paste is used instead.

The solid components are:

- 108,5g of Ordinary Portland Cement, type CEM I 52.5 R. The “I” means pure Portland Cement, with a percentage of clinker that overcome the 95% and only minor addiction. The “52,5” refers to the characteristic compressive strength (in MPa, measured on standardized specimens at 28 days) attended, while finally, the R stands for rapid, meaning that the cement develops its mechanical strength quickly, just after a few days of curing.
- 50g of Calcium Carbonate ($CaCO_3$), used to act as a filler in the mix reducing the porosity and permeability of the hardened cement paste. It also provides more compactness, contributing to increase the strength reducing the quantity of cement used.
- 0.8g of Metakaolin, used to improve the workability of the paste and enhance its mechanical properties and durability. It’s a natural clay calcinated at high temperature to make it more reactive and it’s a source of aluminum silicate.
- 1.7g of (Hydroxypropyl)methyl cellulose (HPMC), is a viscosity adjusters used to improve the homogeneity of the mix reducing the segregation between the components. The commercial product Sigma-Aldrich H8384 was used.

The liquid components are:

- 50g of demineralized water;
- 4g of Polyethylene glycole (PEG) used for reducing the shrinkage without affecting the strength of the paste thanks to his surface-tension reducing properties.

- 40g of Acryl Resin PRIMAL B60A, a copolymer of ethylacrylate and methylmethacrylate (EA/MMA) that provides plasticity and workability to the mix by reducing the water to cement ratio. The use of this polymer improves the survivability of the capsules during the mechanical mixing procedures.

4.2.1.2 Coating

Due to the inherent porosity of cement, an internal and external coating is required to prevent any leakage of the healing agent inserted inside the shell before capsule rupture, as well as to avoid undesired reactions caused by the moisture normally present in the matrix and the surrounding environment.

This protection is achieved using an epoxy coating, consisting of a base and a hardener mixed in a 2:1 ratio, with the addition of a small amount of water to improve fluidity.

A very thin layer of coating is sufficient to cover the inside of the shell making it impermeable, while for the outside, the finished capsule is also rolled in sand after being covered with resin. This process enhances adhesion between the capsule and the concrete used to produce the specimens, while also making the capsule easier to handle once completed. A fine sand (< 2mm) was used.

4.2.1.3 End capping

To seal the two extremity of the capsule a two-component epoxy-based plaster from Bostik was used. It has high mechanical strength, short curing times, isn't shrinkage sensitive and is able to cure even in contact with liquids, making it particularly suitable for sealing the capsule ends, even after they have been filled with the healing agent.

4.2.1.4 Healing agent

As aforementioned, a wide range of healing agents can be used depending on the type of properties that are aimed to be restored once a crack occurs. Considering that the literature already provides numerous studies demonstrating the efficiency of this mechanism, and given that this is not the main focus of this work, a water repellent was selected as the agent for filling the capsules, keeping the healing and testing procedures simple, time-efficient, and low-cost.

In particular, Sikagard-705L, a one-component reactive liquid impregnating agent characterized by low viscosity, was used. This substance forms a layer on the surface of the crack and the surrounding material, reducing capillary water absorption, ensuring long-term efficiency and deep penetration, providing exceptional resistance to stresses caused by freeze-thaw cycles, de-icing salts, and chloride attack in marine environments, while also protecting the rebars from degradation.

4.2.2 Procedure

To create the capsules, the subsequent procedure was used.

All the solid components together were weighted and mixed in a bowl, eliminating any clumps. The same thing was done for all the liquid ingredients in another bowl, keeping the water separate. Then the solid and liquid were combined using a stick, gradually adding the water up to the specified maximum amount, until the paste reached the desired consistency, finishing the kneading by hand.

Some plastic straws, which served as the inner cores of the capsules, were pre-treated with a thin layer of oil. These straws must have the same diameter as the desired internal diameter of the capsules.

The cementitious paste was wrapped around the straws to create tubular capsules approximately 1 mm thick. (See *Chapter 4.2.3* for the evaluation on the uniformity of final diameters).

Figure 12 - Capsule making 1

Using a cutting system set to the required length (1 cm for CAP10 and 4 cm for CAP40) the tubular paste was engraved to give them the wanted length. In the end, the tubular elements were closed in a container with some water to ensure the proper humidity for the curing process of the capsules and left to dry.

Figure 13 - Capsule making 2

After a few days, once completely hardened, the capsules were carefully removed from the straws, taking care not to apply excessive force at this delicate stage, which is the main cause of capsule breakage.

After separating the shells one from the other, the ends felt a little indented, so they were smoothed with sandpaper to facilitate the subsequent sealing operations.

Figure 14 - Capsule making 3

At this point the epoxy coating was prepared by mixing the base and the hardener in a container, in a sufficient amount to cover the inside of the shell.

To cover the inside, a small amount of coating was taken from the container using a toothpick and applied to the inner surface of the shell, making sure not to leave any gaps and not to thicken the layer excessively, as this would significantly reduce the capsule's internal diameter and consequently the amount of healing agent it can contain.

Then the coating was left to dry placing the shell in vertical position.

Figure 15 - Capsule making 4

At this point, a small amount at a time of the bi-component plaster was first mixed and then applied to seal one end of the shell, forming a cap. Once it had dried, the healing agent was carefully collected with a pipette and poured into the shell, which now functioned as a small container, taking care to avoid spilling it on the outside. Any spillage could make sealing the opposite end more difficult, as the healing agent is oil-based and prevents proper adhesion of the epoxy plaster. The capsules were left to dry in a vertical position to prevent any spillage.

Once the cap dried the capsules were inspected to understand if any leakage could be spotted on the outside. In that case the capsule was discharge. In the end the outside covering was made using the same epoxy resin used to impermeabilize the inside and then spread with sand to properly finish the external surface.

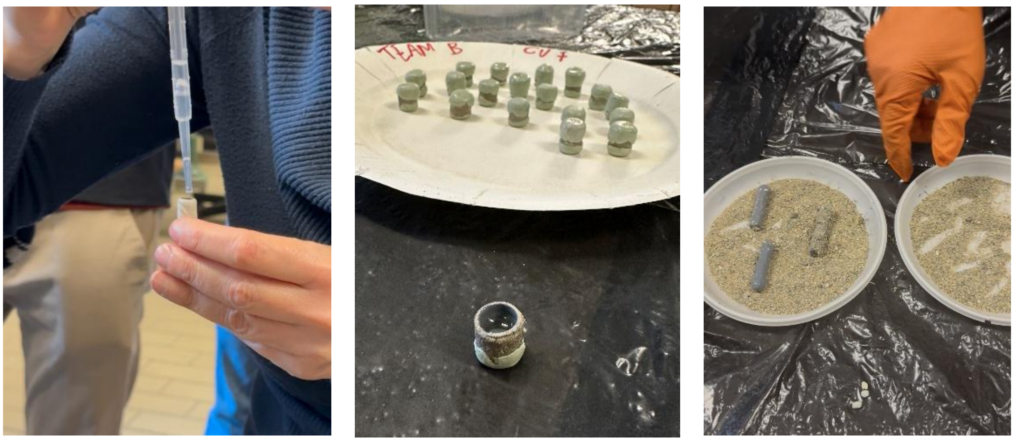


Figure 16 - Capsule making 5

In the following image, a finished CAP40 and a CAP10 can be seen, ready to be used within the specimens.

It can be observed how the CAP10 closely resembles a coarse aggregate, while the CAP40 is equivalent in size and healing agent content to approximately three CAP10.


Figure 17 - CAP 40 and CAP10

4.2.3 Evaluation of capsule dimensional variability

To understand how the manual production process affects the geometric variability of the capsules, it is important to know their final dimensions, as these will directly interfere with the concrete mix.

This aspect was specifically investigated for the CAP10 capsules, as this is the first study in which they were produced, while for the CAP40, historical data from previous research campaigns can be referenced.

Starting from an internal diameter of 8 mm and aiming to maintain a shell thickness of approximately 1 mm, an expected external diameter of around 10 mm was anticipated.

For each capsule, three measurements were taken along its length, and the average was calculated to obtain a representative value. Measurements were repeated on a sample of 408 capsules (see *Attachment1_Capsule dimension survey*), resulting in an average external diameter of 10.28 mm, with a standard deviation of 0.45 mm and a coefficient of variation of 4%.

Such a result demonstrates a certain level of production uniformity despite the manual manufacturing process, with only minimal dimensional differences compared to the expected values.

4.3 Specimens production

Once all the capsules required for the experimentation were available, the production of the specimens was carried out in the predefined quantities. Specifically, 10×10×10 cm concrete cubes were chosen.

This geometry is particularly suitable for the intended tests, as it allows direct verification, through compression testing, of whether the introduction of the capsules affects the declared compressive strength of the concrete. Moreover, the cubic shape is also well suited for splitting tests, while the chosen dimensions are optimal with respect to the particle size distribution of aggregates used, ensuring compliance with UNI EN 12390-1:2021 regarding the ratio between the maximum aggregate size and the specimen side, and at the same time providing specimens that are practical and easy to handle in the laboratory.

Before carrying out the castings, it was necessary to prepare the support system for fixing the CAP40 capsules and to divide the capsules for the CAP-N specimens into precise quantities, in order to ensure the correct number of capsules inside each specimen.

To produce all the specimens required and to carry out the tests on the fresh properties, based on the available equipment and in order to ensure the best possible result while avoiding the risk that the mix could begin setting before being properly cast into the molds, it was necessary to perform two separate castings, thus dividing the work over two days.

On Day 1, the casting was carried out for the production of REF-L and CAP-L specimens. For both of these specimen types, the casting did not involve inserting capsules directly into the mixer; therefore, workability was tested through the slump test in order to obtain a representative reference value for the concrete used.

On Day 2, the casting was carried out for the production of CAP-N and CAP-R specimens. After taking the required amount of concrete to form the CAP-N specimens, where the capsules were inserted manually, the predetermined quantity of capsules (see *Chapter 4.3.2*) was added directly into the mixer. Before forming the CAP-R specimens, however, a slump test was performed to verify how much the workability of the mix had changed.

On the same day, a second smaller casting was also carried out to perform the survivability test.

4.3.1 Particle size distribution of aggregate

For the castings, a pre-dosed fiber-reinforced concrete for structural use (Rck 30 N/mm²) was employed. This product is supplied in bags where cement and aggregates are already premixed in a moist state; however, the technical sheet does not specify either the particle size distribution of the aggregates or the water content.

Nevertheless, for our purposes it is essential to know these two parameters in order to define the percentage of coarse aggregate to be replaced with capsules.

To achieve this, the content of one 25 kg bag was analyzed: the aggregates were extracted and weighed, resulting in a value of 23.359 kg (humid weight). At this point, the material was divided into several containers and dried in an oven at 110 ± 5 °C for 70 hours until constant mass was reached, in accordance with UNI EN 933-1:2012, but skipping the washing step since the information on the finest fraction of aggregate was not considered particularly relevant for our purposes.

Figure 18 - Aggregate drying process

The sieving was carried out in accordance with the standard, selecting sieve diameters of 14, 10, 8, 4, 2, 1, 0.5, 0.25, and 0.063 mm, considered significant for the purpose of reconstructing the particle size distribution of the material.

Figure 19 - Sieving

Once the sieving process was completed, the different particle size fractions, now separated, were weighed individually (*Fig. 20*) in order to reconstruct the dry weight of the aggregate and its initial water content.

The percentages of each particle size fraction relative to the total and the corresponding cumulative values were then calculated to reconstruct the particle size distribution curve (see *Attachment2_Aggregate weight*).

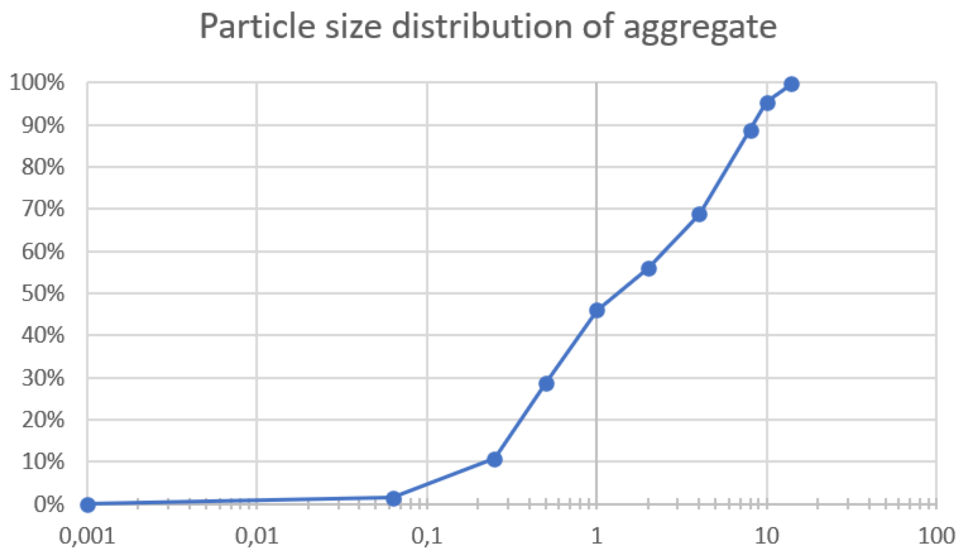


Figure 20 - Particle size distribution curve

The particle size distribution curve indicates a well-graded aggregate, showing a balanced proportion of fine and coarse fractions that ensures good packing and workability in the concrete mix.

However, for our purposes, it is not necessary to maintain the data partition according to the sieve sizes used; it is sufficient to group them into Sand 0 - 4 mm and Gravel 4 -16 mm, following a methodology similar to that adopted by Harry et al. (2023), and make the appropriate considerations to estimate the number of capsules to be used based on these values.

The final measured dry weights are reported in the following table:

SIEVE TEST							
Test date:		24-apr					
diam	tare	weight (cont+material)	retained weight	mu	percentage on total	cumulative percentage	complement to 100
14	476	550	74	g	0,33%	0,33%	99,67%
10	448	1416	968	g	4,35%	4,69%	95,31%
8	653	2098	1445	g	6,50%	11,18%	88,82%
4	330	4765	4435	g	19,94%	31,12%	68,88%
2	795	3672	2877	g	12,94%	44,06%	55,94%
1	573	2786	2213	g	9,95%	54,01%	45,99%
0,5	797	4655	3858	g	17,35%	71,36%	28,64%
0,25	770	4751	3981	g	17,90%	89,26%	10,74%
0,063	430	2497	2067	g	9,29%	98,55%	1,45%
0,001	1130	1452	322	g	1,45%	100,00%	0,00%
			22240	g			
			22,24	kg			
Sand 0-4			15318	g			
Gravel 4-16			6922	g			

Figure 21 - Sieve test results

From the collected data, it was therefore possible not only to reconstruct the particle size distribution of the mix but also to determine its water content, which amounts to 1.126 kg.

4.3.2 Mix design proportions

Thanks to the data collected from the sieving test, it was possible to determine the mix proportions referred to one cubic meter of material, which served as the starting point for estimating the actual quantities of capsules to be used.

As for the cement and water dosages in relation to the quantities of aggregates, since this was a predefined mixture, the mix design provided by the manufacturer in the product's technical data sheet was followed.

Baseline concrete mix proportions			
Material	*Dosage*	*Density*	*Volume proportions*
	[kg/m^3]	*[kg/m^3]*	*[m^3/m^3]*
CEM - type 42.5 R	370,0	2900	0,128
Sand 0-4	1286,7	2670	0,482
Gravel 4-16	536,1	2600	0,206
Added water	126,0	1000	0,126
Water from moisture content in aggregates	94,1	1000	0,094

Figure 22 - Baseline concrete mix proportions

At this stage, it was possible to reconstruct the water-to-cement ratio characterizing the mix by considering both water contributions (added water and water contained in the wet aggregates).

Features of the starting mix	*mu*	
W/C ratio	/	0,59
Percentage of coarse aggregate by volume	m^3/m^3	20,6%

Figure 23 - Features of the starting mix

To estimate the quantities of capsules to be used, the volume percentage of coarse aggregate in one cubic meter was first calculated. Then, knowing the geometries of the two types of capsules, a replacement percentage of 4–5% was established, and the actual volume occupied by the capsules was calculated to determine by how much the coarse aggregate dosage should be reduced (see *Attachment4_Capsule cost and price analysis, Mix design* sheet).

From these considerations, it was determined that 4 CAP40 capsules and 14 CAP10 capsules are needed to achieve exactly the same amount of healing agent within the specimens (0.005 L/dm³), resulting in a volume occupancy of 0.82% for the CAP40 and 1.07% for the CAP10.

Consequently, the final mix designs are:

Final mix design			
CONCRETE MIX DESIGN WITH CAP40			
Material	***Dosage*** [kg/m³]	***Density*** [kg/m³]	***Volume proportions*** [m³/m³]
CEM - type 42.5 R	370,0	2900	0,128
Sand 0-4	1286,7	2670	0,482
Gravel 4-16	514,7	2590	0,199
Added water	126,0	1000	0,126
Water from moisture content in aggregates	94,1	1000	0,094
CONCRETE MIX DESIGN WITH CAP10			
Material	***Dosage*** [kg/m³]	***Density*** [kg/m³]	***Volume proportions*** [m³/m³]
CEM - type 42.5 R	370,0	2900	0,128
Sand 0-4	1286,7	2670	0,482
Gravel 4-16	508,2	2590	0,196
Added water	126,0	1000	0,126
Water from moisture content in aggregates	94,1	1000	0,094

Figure 24 - Final mix design

4.3.3 Molds preparation

Before the actual casting of the concrete specimens, a preparatory phase was necessary to ensure that the different strategies could be properly applied. In particular, a support system was created within the CAP-L molds to host the four CAP40 capsules, while pre-packed sets of 14 CAP10 capsules were prepared to guarantee a controlled placement inside the CAP-N specimens.

To facilitate the preparation of this support system, polystyrene molds were used.

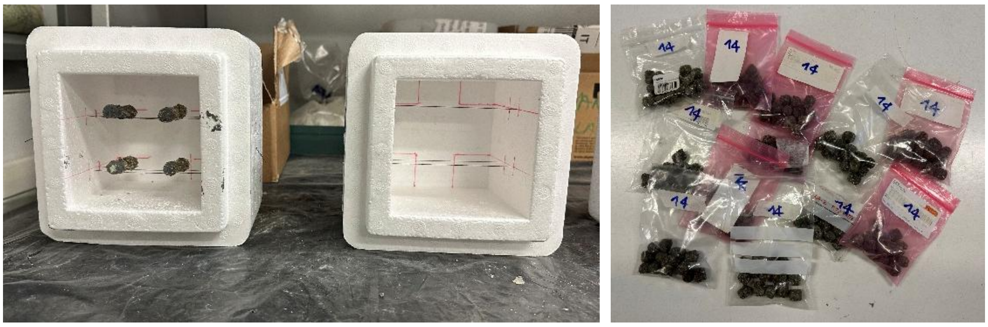


Figure 26 - CAP-L molds preparation and CAP-N capsule pre-packing

The wire was placed symmetrically, as shown in the following figure, using spacers to ensure compliance with the designed distances, while also maintaining the correct concrete cover and proper spacing between the capsules themselves.

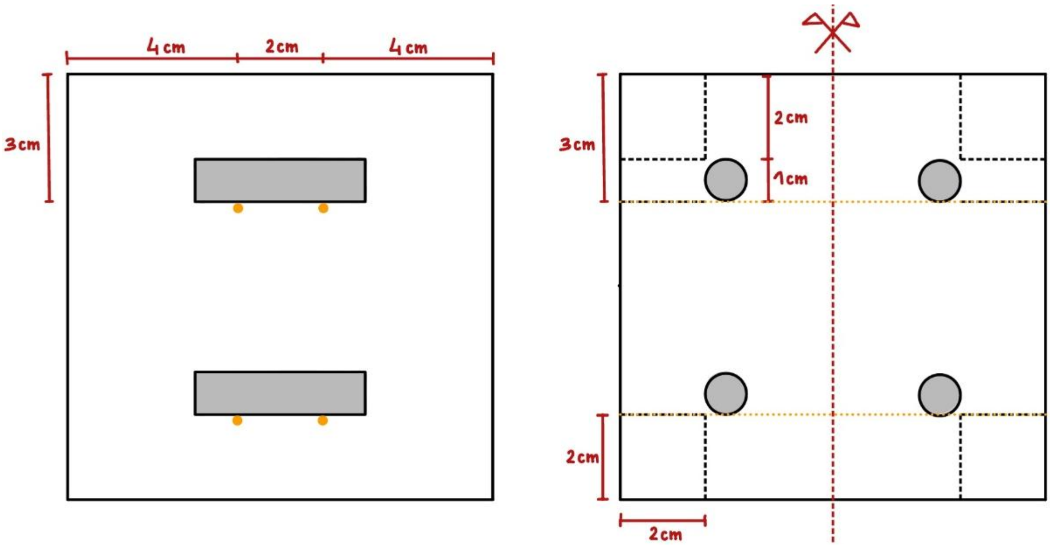


Figure 25 - Scheme for mold preparation of CAP-L specimens

This placement method is rudimentary but effective. It is certainly not directly applicable on a large scale, given the high level of precision required to mark the positions for threading the wire and the long execution times. However, it is a method that can be easily adapted, as suggested in *Chapter 3.2.1*.

4.3.4 Casting procedures

On the first day, three pre-mixed bags were blended in a concrete mixer according to the previously reported proportions, with the addition of 5 L of extra water. A mixing time slightly above 3 minutes was adopted, which allowed the desired consistency to be reached.

Once the concrete was collected and the slump test was performed (see *Chapter 4.4.1*), the molds for the REF-L and CAP-L specimens were filled using a trowel. For the CAP-L specimens, thanks to the arrangement of the support system, the casting direction was parallel to the axis of the capsules, thus allowing the subsequent tests to be carried out with the capsules always aligned longitudinally with respect to the testing surface. This configuration complies with standards requiring the testing surface to differ from the casting surface in order to avoid anisotropic effects.

Figure 27 - Casting procedures, day 1

Finally, the molds were vibrated using a shaking table for approximately 5 minutes to minimize potential voids remaining in the filling.

For the second day, before performing the casting, it was necessary to reduce the amount of coarse aggregate contained in the pre-mixed bags according to the dosages previously reported. The operation was carried out manually by selecting the aggregates that most closely resembled the CAP10 capsules in size and shape, in order to achieve the most homogeneous replacement possible and to minimize differences within the particle packing.

Figure 28- 5% coarse aggregate replacement by volume with CAP10 capsules

The casting required more water than on the previous day, namely 3.6 liters for 2 bags, most likely because the capsules were added to the mix in dry condition and the aggregate itself was slightly drier, as the selection and removal of the particles to be replaced with capsules had been carried out about a day before casting.

First, the mix was prepared using only cement, water, and aggregates; from this, the appropriate amount was taken to produce the CAP-N specimens, where the capsules were manually inserted in the pre-defined number prepared in advance in small bags. The remaining capsules were then added directly into the concrete mixer to produce the CAP-R specimens. The workability of the mix was tested by means of the slump test, and finally, the molds were filled. As in the previous case, the specimens were compacted using a shaking table.

Once the specimens were filled and vibrated, the molds were closed to preserve the proper humidity conditions for curing and maturation of the concrete, and they were left in a controlled environment for 28 days.

4.4 Fresh properties

As previously discussed, testing the fresh properties of the mix provides valuable insights into how the introduction of capsules directly into the mixture may alter some essential characteristics, potentially impacting both standard procedures and expected performance.

Workability, for instance, defines how easily the material can be transported, placed, and made to flow around reinforcement within formworks being directly linked to the rheological properties of the material, which are determined by stability, compactability, and mobility.

In this context, *stability* refers to the ability of fresh concrete to remain homogeneous without external forces, typically measured through bleeding and segregation. *Compactability* refers to the ease with which fresh concrete can be compacted using vibration, while *mobility* describes the viscosity of the mix as influenced by cohesion and internal friction.

At the same time, it is crucial to assess whether the capsules themselves, as designed, can resist the mixing process. In fact, the mechanical action of the blades and the energy imparted during mixing may cause the premature breakage of a significant portion of the capsules, thereby reducing the effective number of functioning capsules and, consequently, the overall efficiency of the self-healing system.

4.4.1 Workability assessment

Several methods are available to measure workability, but the most widely used due to its simplicity is the slump test, standardized in UNI EN 12350–2:2019. The procedure consists of measuring the vertical settlement (slump) of fresh concrete once it is removed from a truncated metal cone (Abram's cone), compared to the initial height of the concrete that has been compacted in a standardized manner inside the 300 mm-high cone.

The standard defines five consistency classes, identified by the letter S followed by a number from 1 to 5, corresponding to mixes of increasing fluidity.

The tests were conducted on the mixes produced on both casting days, in order to obtain a reference value for the base mix without capsules (day 1) and a corresponding value for the mix with the introduction of CAP10 capsules at a substitution rate of 4–5% (day 2). The test was performed in accordance with the standard, recording a slump of 70 mm for the mix without capsules and 35 mm for the mix with capsules.

The 70 mm value recorded on the first day corresponds to consistency class S2. However, it should be noted that the shape of the slump did not fully match the typical form considered acceptable, likely due to the presence of fibers within the mix.

Figure 29 - Slump test, day

According to the manufacturer's technical data sheet[39], the use of 1.5–2 L of water for a bag should correspond to a consistency class S4.

The value of 35 mm recorded on the second day for the mixture containing the capsules corresponds to a consistency class S1, indicating in fact a reduction in the workability of the mix making it less fluid and potentially more challenging to handle.

Figure 30 - Slump test, day 2

These results underline how becomes really important considering the capsule inclusion at the mix design stage, to redefine the mix itself, probably adding superplasticizers to compensate for the loss of workability and ensure adequate fresh concrete performance.

4.4.2 Capsules survivability assessment

There is no standardized methodology for testing capsule survivability. However, replicating the mixing procedures normally used in conventional concrete production as closely as possible can be considered to be representative of the stress experienced by the capsules. This allows us to

[39] https://www.grascalce.it/prodotti/calcestruzzi/calcestruzzo-predosato-fibrato/

assess whether their design enables direct integration into the concrete matrix or whether they are too fragile.

For this reason, a batch of concrete was prepared using one 25 kg pre-mixed bag into which 39 CAP10 capsules, previously covered with fluorescent green paint to make them more visually recognizable, were added. A tilting drum mixer was employed: first, cement and aggregates were mixed with water for three minutes, after which the capsules were introduced and mixing continued for an additional three minutes.

The survivability test was performed by gradually removing fresh concrete from the mixer, diluting it with water, and spreading it over plastic sheets to better distinguish and recover the intact capsules. These were then rinsed with water, collected, and manually counted.

Figure 31 - Survivability test

Out of the 39 capsules introduced into the mix, 38 were found intact, while just one capsule was not recovered during the inspection of the concrete. The missing capsule may have either adhered to the inner walls of the mixer or been lost during the inspection process, but no fragments of a damaged capsule were identified.

The survival ratio was therefore calculated as the number of intact capsules over the total number of capsules originally added, expressed as a percentage, yielding a result of ≥ 97%.

Previous studies on capsule survivability, such as those conducted by Hermawan et al. (2023), adopted very similar procedures but replaced manual recovery with a more accurate sieving method. In their experiments, survival ratios of 100% were obtained for samples containing 40 and 80 capsules, respectively.

These findings indicate that the capsules are sufficiently robust to withstand the mixing process and can be effectively integrated into the concrete matrix while remaining functional.

4.5 Post-curing specimens selection

After 28 days of curing (or 27 for CAP-N and CAP-R that were casted one day after), the specimens were demolded and labeled in order to make them recognizable through the entire process of testing.

At this stage we had:

- 18 REF-L
- 12 CAP-L
- 12 CAP-N
- 15 CAP-R[40]

[40] The numbers slightly exceeded the planned quantities, as on the second day a higher yield of the concrete mix was achieved. This was likely due either to the addition of more water or to the greater volume occupied by the capsules inside the specimens, which made it possible to cast three additional CAP-R specimens beyond the initial plan.

At this stage, some defects that could affect the testing results were observed.

First, the molds did not hold their shape properly, resulting in specimens with angles not exactly equal to 90 degrees and side lengths slightly different from the intended 10 cm. This may lead to an underestimation of compressive strength and to test surfaces that are not perfectly parallel, which is particularly problematic for compression tests.

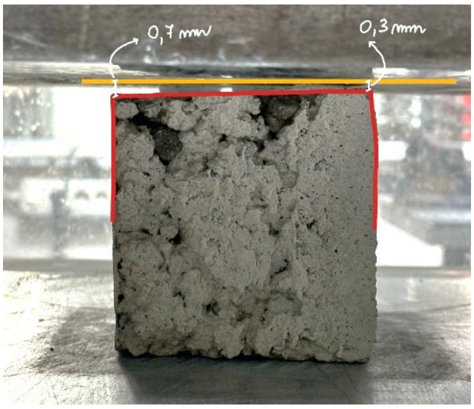


Figure 32 - Dimensional defects

In addition, some specimens exhibited defects such as voids, likely caused by uneven vibration. To prevent this issue, it would probably have been necessary to better adjust the vibration settings and sturdily secure the molds to the shaking table using barriers, ensuring that the vibration was effective and correctly transmitted.

Figure 33 - Difference between a specimen with vibration defects and a properly compacted one

To avoid compromising the reliability of the results, the worst specimens were discarded, while the remaining ones were selected for testing based on their condition, ensuring nevertheless a sufficient number of samples to provide statistically meaningful data.

The following testing plan was therefore adopted:

- *Compression tests*: 3 specimens per type (12 specimens in total, plus 3 used for preliminary machine setup).
- *Splitting tensile and absorption tests*: 5 REF-L+5 REF-L-U[41], 7 CAP-L, 5 CAP-N, and 9 CAP-R specimens (31 specimens in total, plus 2 used for preliminary machine setup).

All remaining specimens were discarded.

4.6 Inherent mechanical properties

The mechanical properties of concrete such as compressive, tensile, and flexural strength, along with the modulus of elasticity, are fundamental in assessing the material's ability to resist applied loads and stresses. These properties not are not only fundamental to determine the structural integrity of concrete constructions but also dictate their durability and safety[42].

By performing the following tests, we aimed to evaluate whether the introduction of capsules, which could represent a weak point within the matrix, actually alters the concrete's properties.

[41] U stands for *uncracked*. Used as a reference for the absorption test

[42] (Makul, 2025)

In particular we investigated:

- *compressive strength*, the ability of concrete to withstand compressive loads. It is determined through tests on cylindrical or cubic specimens, according to the UNI EN 12390-3 standard, and depends on several factors such as the water-to-cement ratio, curing conditions, aggregate quality, and mix design.
  For ordinary structural concrete, typical compressive strength values range from 20 to 50 MPa developed after 28 days, while high-performance concretes may reach values well above 100 MPa.
- *tensile strength*, the ability of concrete to resist tension forces. It is typically much lower than compressive strength due to the brittle nature of the material and is determined using methods such as the splitting tensile test (UNI EN 12390-6) or flexural test (UNI EN 12390-5). Tensile strength mainly depends on factors like aggregate-matrix bond, curing, and mix composition.
  For ordinary structural concrete, it usually ranges between 2 and 5 MPa, corresponding to about 10% of the compressive strength.

4.6.1 Compression test

Specimens were tested in a direction orthogonal to the casting direction to avoid introducing anisotropic effects that could influence the test results.

The testing machine used for determining compressive strength was equipped with an automatic system for controlling the loading or displacement rate, as well as data acquisition equipment, which required preliminary calibration tests before the actual measurements.

A standard scheme[43] of how the machine is mainly composed is reported in the following figure:

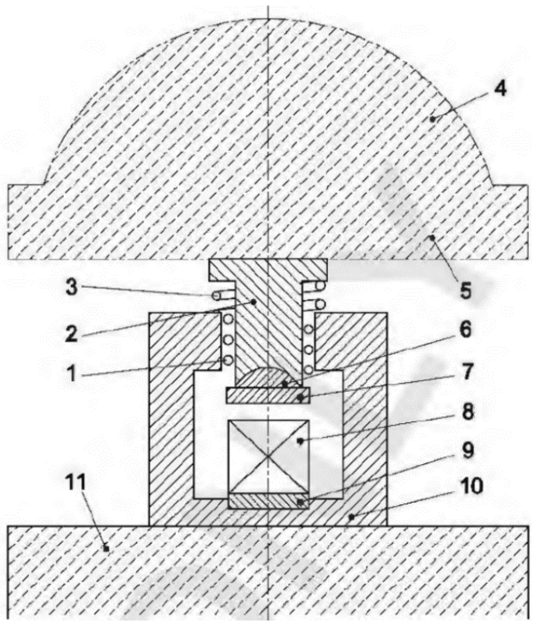


Figure 34 - Typical machine used for compressive tests on concrete cubes (UNI EN 196-1:2016)

It can be observed that the setup is equipped with a head joint and a press, allowing fine adjustments and ensuring that the load is transferred as uniformly as possible.

According to the standard, the test should be performed by applying a load and recording the corresponding deformation. In our case, however, the press was operated under displacement control, measuring the applied force and thus the stress. This approach was chosen in order to capture the softening branch of the stress–strain curve, which would not be observable under pure load control.

[43] *image legend*: 1 - ball bearings, 2 - sliding assemble, 3 - return spring, 4 - spherical seating of machine, 5 - up per platen of machine, 6 - spherical seating of the jig, 7 - upper platen of the jig, 8 - specimen, 9 - lower platen of the jig, 10 - jig, 11 - lower platen of the machine

A preliminary calibration of the testing machine was carried out on REF-L-9 specimen by applying first a load up to 70 kN, which on a 100 × 100 mm cube corresponds to approximately 7 MPa and then proceeding under displacement control at a rate of 0.1 mm/min, equivalent to about 1.66 µm/s. The maximum load recorded was 135 kN, after which unloading occurred at 72.8 kN with a piston displacement of 1.75 mm. An approximate strain of 2% and a load drop of about 46% from the peak value was than evaluated.

Figure 35 - Results of preliminary calibration test on REF-L-9

From the graphs shown in the previous figure, it is possible to observe the variation of applied load over time as well as the relationship between load and deformation.

To speed up the testing process, the settings were adjusted to a load of 70 kN with displacement control at 0.2 mm/min, and the test was repeated on specimen CAP-N-5. Despite doubling the loading rate, the collected data were considered equally representative; therefore, this loading rate was adopted for the subsequent tests recording for each specimens the maximum compressive load applied.

The compressive strength σ_c was than calculated using the following formula:

$$\sigma_c = \frac{F_{max,c}}{A}$$

Where:

- σ_c = compressive strength [MPa]
- $F_{max,c}$ = maximum breaking load [N]
- A = area of the specimen in contact with the plate [mm^2]

By testing three specimens for each type, the mean value obtained from the individual results was considered representative of the category.

The following table reports the calculated compressive strength values, together with statistical coefficients that provide an indication of the variability of the collected data. In addition, the difference between the values of the specimens containing capsules and those of the reference material without capsules was calculated.

Specimen type	Mean compressive strenght	Standard deviation	CoV (coefficient of variation)	Difference from reference	Variation percentage
	N/mm^2 - MPa	/	%	/	%
REF-L	20,65	1,37	6,6%	Ref value	Ref value
CAP-L	19,89	0,63	3,2%	-0,76	-3,68%
CAP-N	21,51	1,52	7,1%	0,86	+4,14%
CAP-R	22,34	1,26	5,6%	1,69	+8,16%

Figure 36 - Results of compressive test

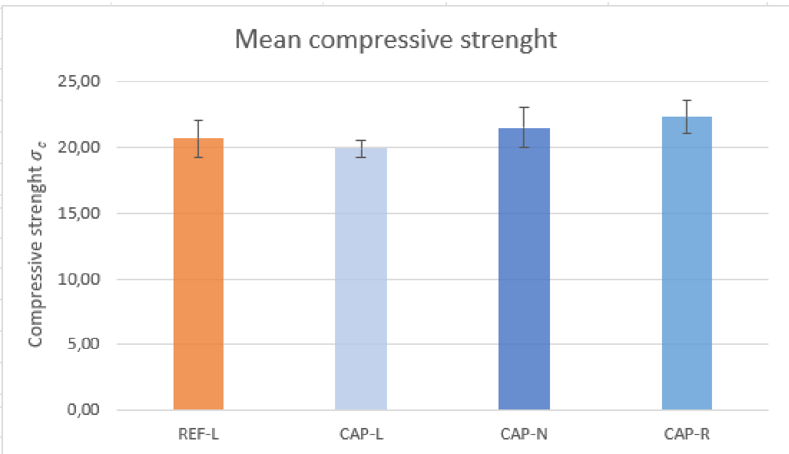


Figure 37 - Graph of the mean compressive strength

Some representative pictures of the broken specimens are shown, illustrating how even a compressive rupture can successfully intersect the capsules within the matrix:

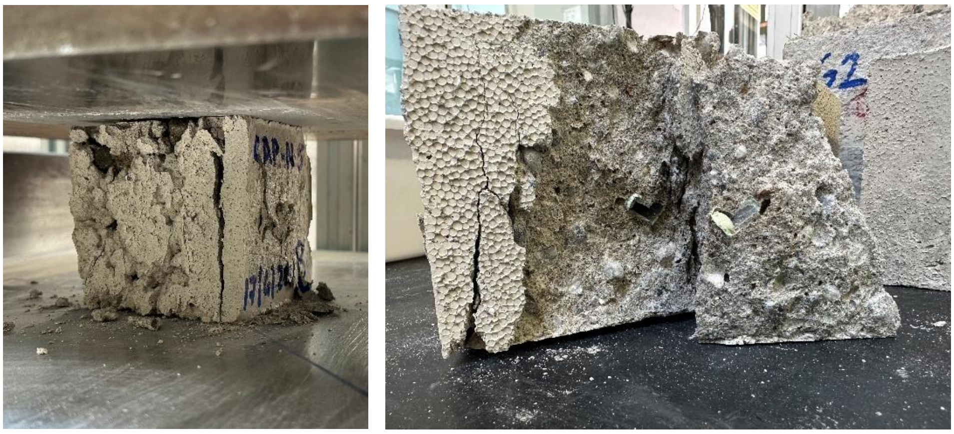


Figure 38 - Broken specimens after compressive test with capsule interception

4.6.2 Splitting test

Assessing the self-healing effect requires the introduction of preliminary damage. While the compressive strength test essentially destroys the specimen making the further testing more difficult, especially if the healing agent used does not provide strength recovery, the splitting test provides a single representative crack, ensuring consistency in crack width and location so as to minimize variability among specimens but at the same time allows us to evaluate the tensile strength of the material.

For this reason, the splitting tensile test following the BS EN 12390-6:2023 standard was adopted. In this configuration, the specimen is placed between two supports and subjected to a concentrated load applied from above, while the base remains fixed. This induces compressive deformation which, as can be observed in a force–deformation graph, initially increases linearly until reaching a peak load, followed by a sudden drop corresponding to crack formation.

The test was conducted under displacement control, with an imposed rate of 0.2 mm/min. Once the load drop was observed, the machine was stopped. This procedure generated a distinct fracture, splitting the specimen into two halves which, however, did not remain naturally attached.

Figure 39 – Preliminary calibration for splitting test

To overcome this problem and to simulate the confining action of steel reinforcement in reinforced concrete, the specimens were confined with different types of confinements such as plastic and duct tape or cable ties. The cable ties, due to their high ductility and some difficulties in assuring a correct positioning provided insufficient stiffness, while the duct tape performed well but it was an unjustified expensive solution; the final choice of wrapping the specimens with 4 layers of plastic tape ensured adequate confinement without significantly altering crack propagation. In addition, the fibers embedded in the concrete matrix contributed to maintaining some cohesion even after crack formation.

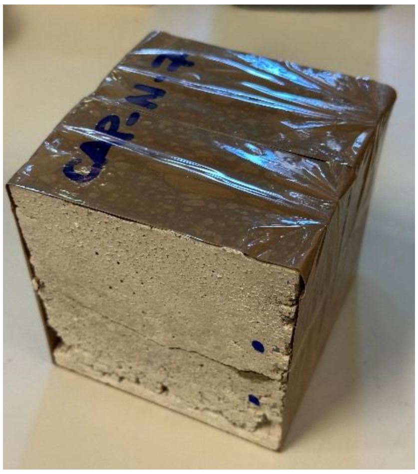


Figure 40 - Specimen wrapped in plastic tape for splitting test

To calculate the tensile splitting strength the following formula from the BS EN 12390-6:2023 standard was used:

$$f_{ct} = \frac{2 * F}{\pi * L * d}$$

Where:

- f_{ct} is the tensile strength [MPa];
- F is the maximum load [N];
- L is the length of the line in contact of the specimen [mm];
- d is the designated cross-sectional dimension [mm].

By testing 5 to 9 (depending on availability) specimens for each type, the mean value obtained from the individual results was considered representative of the category.

As for the compressive test, the following table reports the calculated tensile strength values, together with statistical coefficients that provide an indication of the variability of the collected data. In addition, the difference between the values of the specimens containing capsules and those of the reference material without capsules was calculated.

Specimen type	Mean tensile strenght	Standard deviation	CoV (coefficient of variation)	Difference from reference value	Variation percentage
	N/mm² - MPa	/	%	/	%
REF-L	2,17	0,10	4,8%	Ref value	Ref value
CAP-L	1,99	0,09	4,6%	-0,18	-8,38%
CAP-N	2,03	0,24	11,7%	-0,14	-+6,53%
CAP-R	2,30	0,20	8,5%	0,13	+5,81%

Figure 42 - Results of tensile splitting test

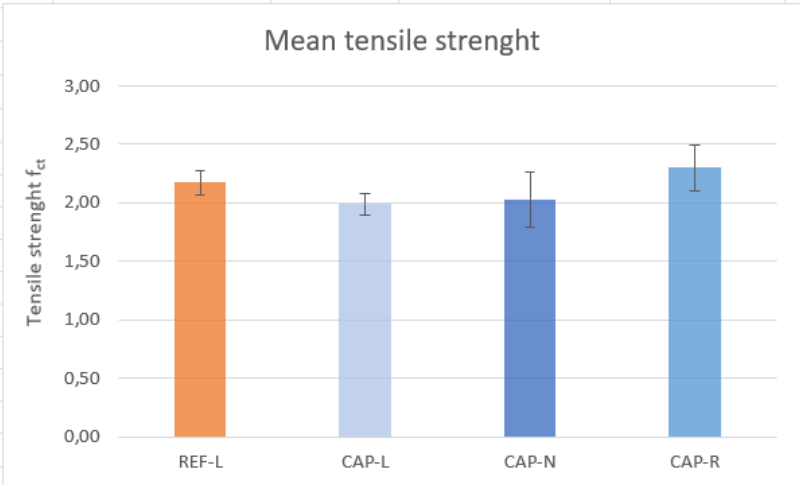


Figure 41 - Graph of the mean tensile strength

As with the results obtained from the compression tests, no significant differences were observed between the reference samples and those containing capsules in this test either. However, from empirical observations, it is noted that for concrete the tensile strength is approximately one-tenth of the compressive strength, and this ratio is here respected.

4.7 Self-healing performance

As previously explained in detail, the presence of cracks increases the ability of water and harmful substances to penetrate the concrete element, ultimately leading to reinforcement degradation.

When in contact with water, the porous nature of the concrete matrix allows liquid to be drawn into narrow spaces due to the combined effects of surface tension and adhesive forces between the liquid and the solid. In the absence of damage, the entire surface is uniformly exposed to water; however, the formation of a crack creates a preferential pathway that adds to the overall surface exposure. If the crack is healed, on the other hand, the expected behavior should be comparable to, or at least close to, that of the uncracked case.

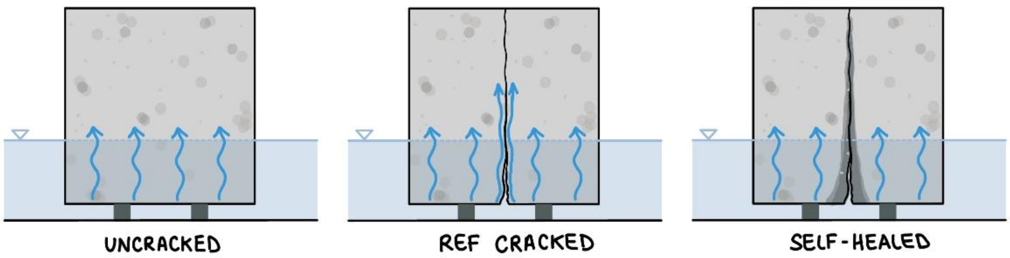


Figure 43 - Capillary absorption scheme

To evaluate the effectiveness of the proposed solutions, it is necessary to adopt a methodology that allows for a quantitative assessment, in order to capture potential performance differences among the options. For this purpose, the specimens previously cracked through the splitting test, along with five uncracked reference specimens, were subjected to an *absorption test*.

On average, the splitting test produced cracks of about 0.5 mm in width in the specimens, which are considered significant for our purposes, since the NTC prescribes a maximum limit of 0.4 mm even under ordinary environmental conditions.

4.7.1 Crack width measurements with optical microscopy test

We aim to evaluate if any correlation exists between crack width and consequently the exposed surface of the specimen, and its absorption capacity. For this reason, the crack openings of each specimen were measured using an optical microscope, performing five measurements along the crack to assess the homogeneity or heterogeneity of the collected data.

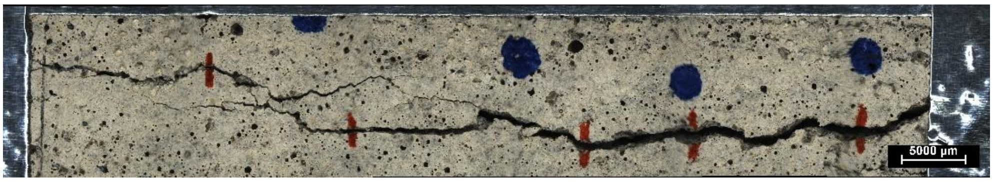


Figure 44 - CAP-L-2 crack on optical microscope observation

In the table below are shown the mean values measured for each specimen category together with their standard deviations and coefficients of variation.

Specimen type	Mean crack width	Standard deviation	CoV (coefficient of variation)
	µm	/	%
REF-L	441,44	121,22	27,5%
CAP-L	549,49	141,90	25,8%
CAP-N	468,40	341,05	72,8%
CAP-R	571,73	202,71	35,5%

Figure 45 - Results of crack width measurements

In all four categories, the average crack width is around 0.5 mm, indicating that despite the variability of individual measurements, the absorption test data can be reliably compared across the different strategies and reference specimens. However, the variability of the individual results originates from the heterogeneity of each crack along the specimen's length, as shown in Fig.

43, and from the unique features of each crack, which explain the relatively high standard deviations.

Moreover, the use of the optical microscope allowed for a more detailed observation of the crack morphology and any specific effects arising during propagation. For example, in the following figure, it can be seen how the presence of a fiber aligned with the crack direction influenced its path.

Figure 46 – Crack with visible fiber

In contrast, the following image shows how, in the presence of defects in the matrix caused by the vibration process, the crack propagated precisely from those weak points.

Figure 47 - Crack starting from a matrix defect

From the following macro image, it can be observed that not only the crack itself but also the presence of large pores may act as preferential absorption pathways.

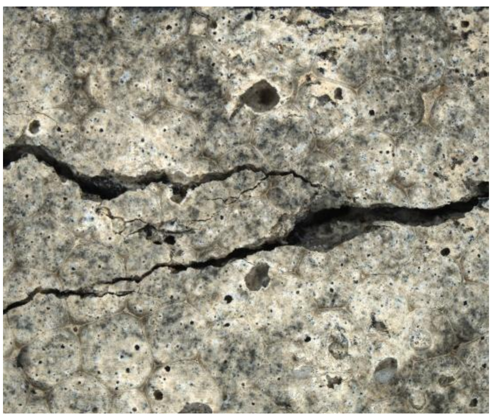


Figure 48 - Macro picture of a cracked matrix with pores

4.7.2 Absorption test

To quantify whether, and to what extent, the different strategies are able to repair the crack and restore impermeability against the penetration of external substances, an absorption test was conducted following UNI EN 13057:2003.

To minimize the influence of the matrix and emphasize the effect of the crack, only the cracked area was exposed to water, while the remaining surfaces of the specimen were sealed with adhesive aluminum foil.

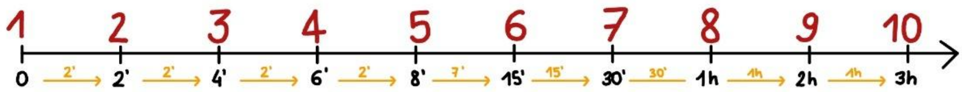
Figure 49 - Specimen preparation for absorption test

The initial condition of the specimens is crucial, particularly for ensuring repeatability and comparability of the results. For this reason, the specimens were first dried in a curing cabinet set at 40 °C with controlled humidity and ventilation for five days. Conventionally, this procedure is assumed to provide sufficient drying; however, to ensure accuracy, the weight of each specimen was repeatedly measured until a constant mass was reached.

During testing, the samples were partially submerged in 5 mm of water for multiple time intervals, and the variation in weight was recorded. A higher number of intervals was applied at the beginning of the test, as the dry specimens were expected to absorb water more rapidly.

Figure 50 - Absorption test

The following schedule has been followed:



The balance used for weighing had a load capacity at least twice the maximum specimen weight and sufficient resolution to capture small weight variations. In this case, a scale with a capacity of up to 5 kg and a resolution of 0.1 g was employed.

To represent the data collected during the test, the difference in mass recorded at each step for each specimen can be plotted against the cumulative time. However, previous studies have shown that plotting the square root (or the fourth root) of time against the change in mass produces a linear trend.

This approach is particularly useful because it allows to measure the slope of the line, providing a quantitative indicator that can be directly compared across the different series, thereby serving as a reliable measure of the system's behavior.

For each time step of the test we can identify the *sorptivity* measured as*:*

$$S = \frac{\Delta m}{\Delta \sqrt{t}}$$

Where:

- Δm is the delta in mass between two consequent measurements [g];
- $\Delta \sqrt{t}$ is the delta of the square root of time between two consequent measurements [s].

In the following graph we can see how the mean sorptivity of the 5 different kinds of specimens tested varies over time:

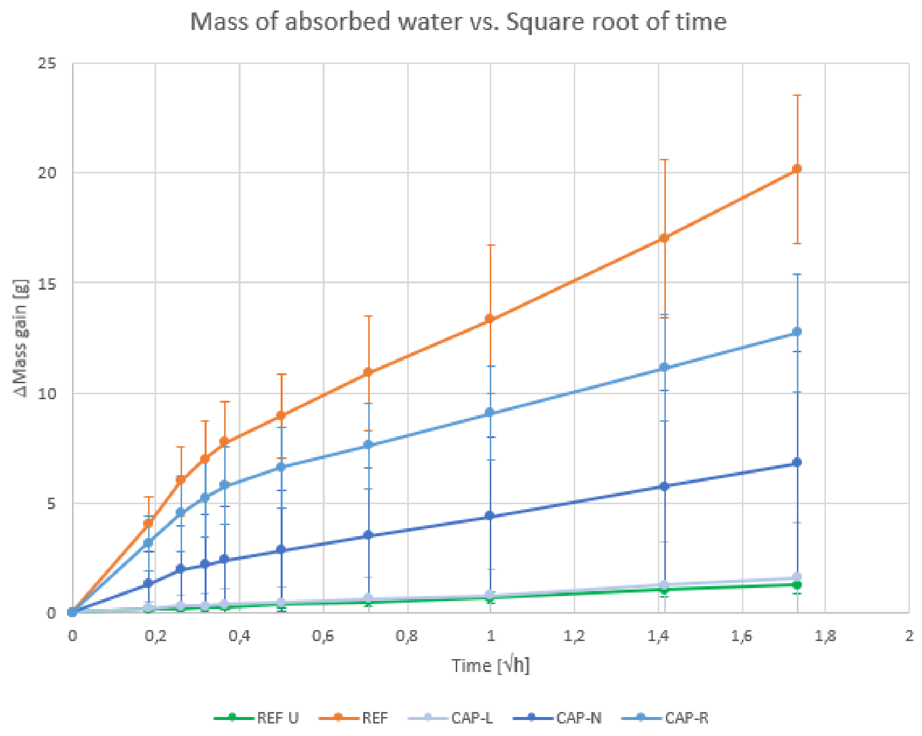


Figure 51 – Trends of mean values of absorption test results

The trend observed for the uncracked specimens (REF-L-U) provides an indication of the absorption attributable only to the intrinsic porosity of the material and thus represents the target values to be achieved through crack repair.

Conversely, the trend of the cracked REF-L specimens highlights how the presence of a crack significantly increases the absorption capacity of the material.

The fact that the three capsule-based strategies fall between these two limiting trends demonstrates that, regardless of the approach adopted, the absorption capacity of the material is improved. In particular, the higher the quality of capsule positioning control, the better the performance achieved, with the CAP-L specimens in some cases even slightly improving the behavior of the uncracked REF-L-U samples.

To compare the efficiency of different strategy another indicator called *sealing efficiency* is calculated as:

$$SE = \frac{\bar{S}_{REF} - \bar{S}_i}{\bar{S}_{REF} - \bar{S}_{UNCR}}$$

Where:

- $\bar{S}_{REF}$ is the mean value of the sorptivity recorded for REF-L specimens;
- S_i is the mean value of the sorptivity recorded for each strategy (CAP-L, CAP-N and CAP-R);
- $\bar{S}_{UNCR}$ is the mean value of the sorptivity recorded for REF-L-U specimens.

If the crack is completely restored, we expect a *Self-Healing Efficiency* (SE) of 1, corresponding to 100%. However, values exceeding 100% are also possible, as the healing agent may not only seal the crack but also reduce the initial porosity of the matrix, leading to results that surpass the original condition.

Since we see a change of slope in the curve after approximately 8 minutes from the starting of the test, we calculated an initial sorption coefficient with the correspondent sealing efficiency and the late ones:

Series	Initial Sorption Coefficient [g/√h] (*)	Initial Sealing efficiency [%] (°)
REF U	1,04	
REF	21,68	
CAP-L	1,03	100,05%
CAP-N	6,71	72,52%
CAP-R	16,13	26,87%

Series	Late Sorption Coefficient [g/√h] (*)	Late Sealing efficiency [%] (°)
REF U	1,12	
REF	8,99	
CAP-L	0,88	103,05%
CAP-N	3,19	73,75%
CAP-R	5,03	50,35%

Figure 52 - Initial and late values for sorptivity and sealing efficiency

The calculated values give us an even clearer indication of what was already apparent from the trends in the graphs.

The best performance was achieved with the CAP-L strategy, both in the initial stage and at the end of the test, reaching a final sealing efficiency that exceeded 100%.

The CAP-N strategy achieved a sealing efficiency of 74%, which is quite promising considering the limited effort required for its implementation. Meanwhile, the CAP-R strategy, although showing only 27% sealing efficiency within the first 8 minutes, was still able to reach 50% by the end of the test, providing a substantial improvement compared to the absence of any healing strategy.

By plotting the initial sorption coefficient for each specimen of a given type against the corresponding average crack width, it is than possible to evaluate whether a correlation exists between the two parameters.

Specifically, if both values increase together, it would indicate that greater crack widths lead to higher capillary absorption of the material. This would imply that the results of the absorption test should be interpreted in relation to the actual crack width of each specimen. However, as shown in the following graphs, no clear correlation emerges between these two variables.

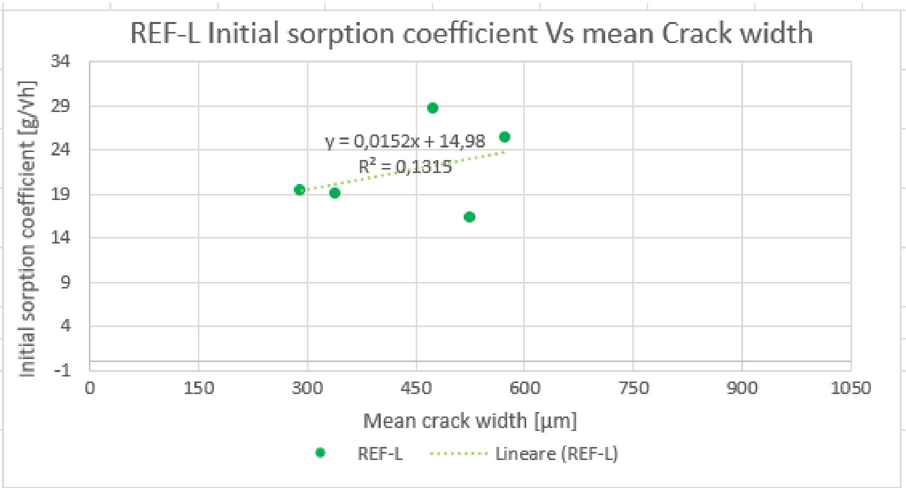


Figure 54 - Correlation between crack width of REF-L and their initial sorption coefficient

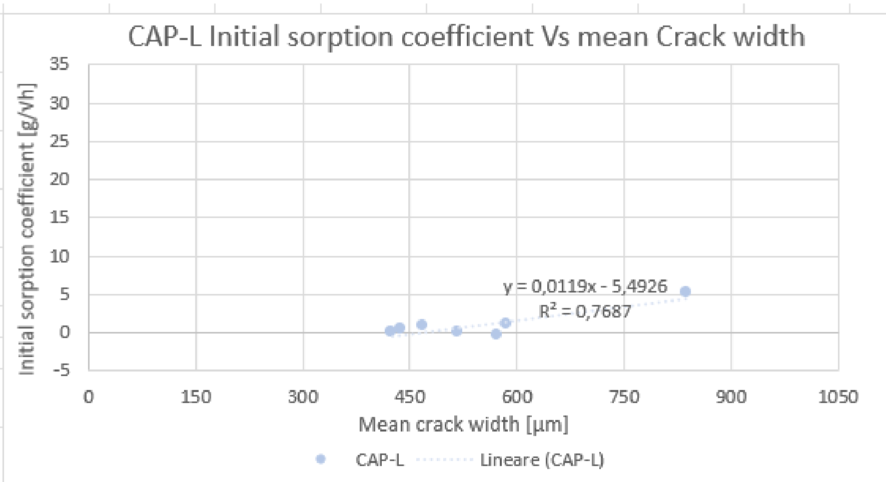


Figure 53- Correlation between crack width of CAP-L and their initial sorption coefficient

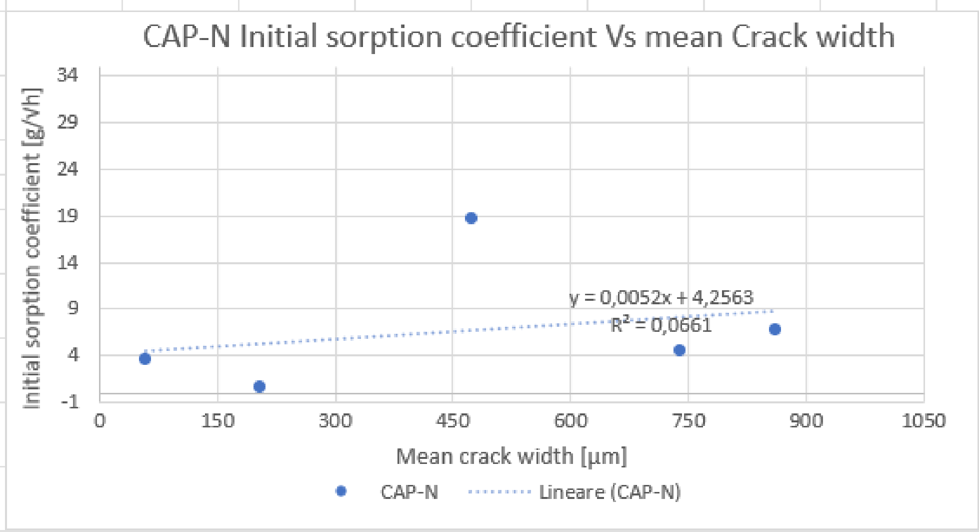


Figure 56- Correlation between crack width of CAP-N and their initial sorption coefficient

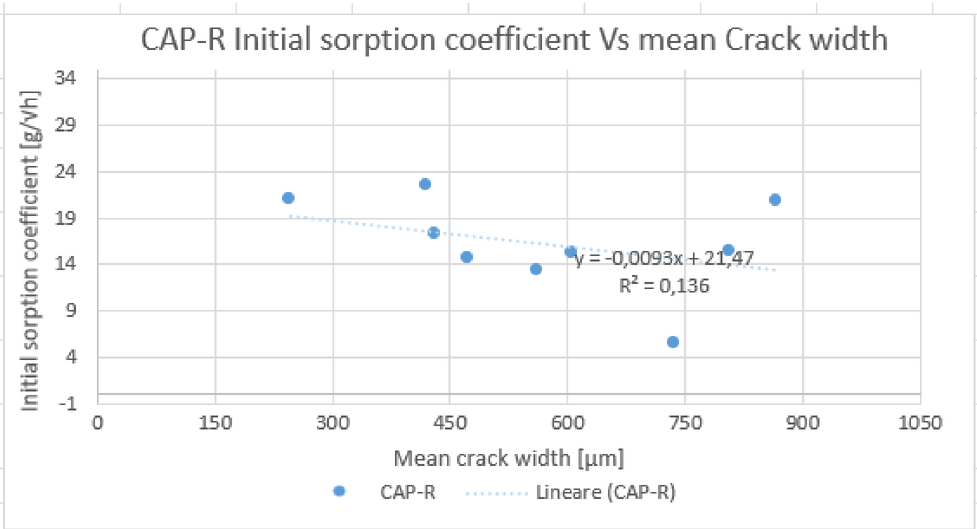


Figure 55 - Correlation between crack width of CAP-R and their initial sorption coefficient

4.7.3 Specimens inspection

By opening the two halves of the specimens, which were held together by tape, it is possible to observe the degree of absorption for each specimen and the number of capsules intercepted by the crack in the cases of semi-controlled or random placement.

The following images clearly show what was quantitatively recorded in the absorption test. Indeed, we observe an almost completely dry surface in the case of CAP-L, a surface with two different levels of wetting in the CAP-N and CAP-R specimens, and an almost entirely wet surface in the REF-L specimens.

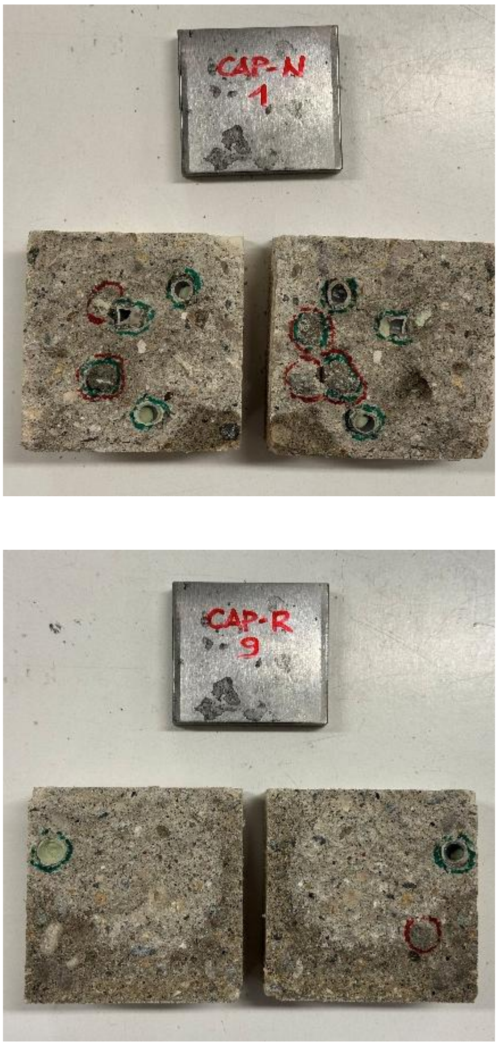


Figure 57 - Specimens inspection after absorption test

It can also be observed that with semi-controlled positioning, where at least the number of capsules in each specimen is controlled, the probability of the crack intercepting a capsule is higher, resulting in improved performance.

By using LiDAR, a mapping technology that employs laser light to measure the distance from a target surface and easily generate a 3D map of any object, it was possible to digitally reconstruct the specimens while preserving the data for potential future analyses.

Nowadays, anyone with a smartphone equipped with LiDAR can perform this kind of operation, as there are many apps, such as *Scaniverse*, that allow for the rapid collection and processing of data for small objects. When working with larger elements or requiring a higher degree of accuracy, however, professional-grade instruments become necessary.

This approach enabled the digital reconstruction of the specimen surfaces, both in their intact form and as two separate parts resulting from the fracture. The accuracy of the models produced depends on factors such as the instrument used, the density of recorded points, and the quality of the processing.

Nevertheless, this represents a very promising method for storing and comparing data across different stages of experimentation, while also enabling further investigations. For instance, one possible application could be the digital reconstruction and evaluation of surface roughness to explore potential correlations with healing performance. Although this analysis was not carried out in the present study, it could be pursued in future researches.

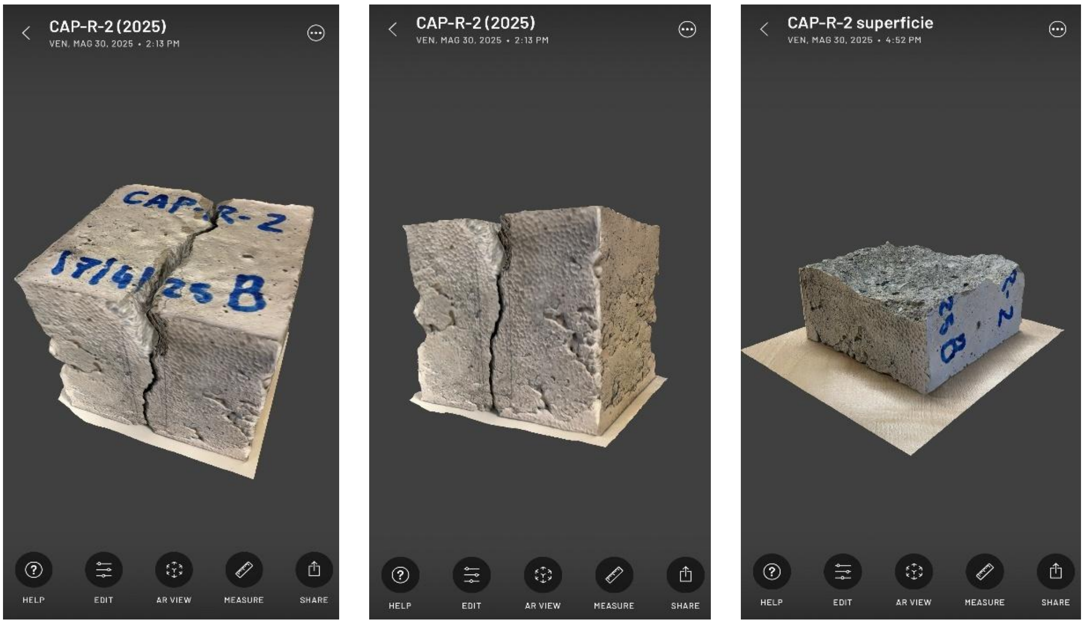


Figure 58 - 3D reconstruction of tested specimens

4.8 Results discussion

The tests carried out so far allow for a comparative evaluation of the most relevant aspects that characterize each strategy, ranging from their practical applicability to their influence on standard conditions and, ultimately, their overall efficiency.

A summary of all the results obtained is provided in the following table:

	EXPERIMENTAL TEST RESULTS							
	Fresh properties		Hardened properties		Self-healing properties			
Speciments name	Workability (Slump test)	Capsules' survivability	Compressive strenght	Tensile splitting strenght	Initial sorption coefficient	Initial Sealing efficiency	Late sorption coefficient	Late Sealing efficiency
	consistency class]	[%]	[N/mm²] - [MPa]	[N/mm²] - [MPa]	[g/√h]	[%]	[g/√h]	[%]
REF-L	S2	-	20,65	2,17	21,68	-	8,99	-
CAP-L	S2	100%	19,89	1,99	1,03	100,05%	0,88	103,05%
CAP-N	-	100%	21,51	2,03	6,71	72,52%	3,19	73,75%
CAP-R	S1	97%	22,34	2,30	16,13	26,87%	5,03	50,35%

Figure 59 - Results summary

The results obtained on fresh properties tests indicate that the capsules are sufficiently robust to withstand the mixing process. Consequently, the third strategy (random positioning) that appears to be the least demanding from an operational perspective, as it treats the capsules simply as an additional component of the mix design without requiring any modification of standard procedures or the use of additional equipment, is readily applicable in practice.

However, particular attention must be paid to the redefinition of certain mix parameters, as the presence of capsules slightly alters the workability of the fresh concrete. Likewise, dimensional aspects of the structures, such as the concrete cover, should be reconsidered in relation to the capsule size.

With regard to the intrinsic mechanical properties, no significant variations were observed that would require a reduction of cross-sections or a redesign of the reinforcement. Nevertheless, a more detailed analysis should be carried out considering the specific type of capsule and the quantities employed.

In this respect, the need for reference standards to guide both the design and validation of these solutions becomes evident.

Compression and splitting tests also allowed for direct visual observation of the release of the healing agent, which temporarily wets and impregnates the matrix, providing it with water-repellent properties. This effect is clearly reflected in the absorption test results. In particular, in the case of the controlled positioning strategy (CAP-L), the release of the agent was more uniform along the crack, leading to a more consistent impregnation and, consequently, superior performance than for other strategies as shown in the following figures:

Figure 60 - Visual leakage of healing agent in different kinds of specimens

The absorption test clearly highlighted a hierarchy of efficiency among the three strategies, directly linked to the degree of control over capsule positioning where the controlled positioning offers the best performance, followed by the semi-controlled and the random positioning.

However, it still remains to be assessed whether the three strategies are comparable in terms of cost, and, considering their varying levels of scalability, whether it is more appropriate to adopt one strategy over another depending on the specific application context.

5. Cost assessment

For the widespread adoption of a new technology, cost is a crucial factor. This aspect has indeed been identified as a limitation by Barros et al. (2023) in their analysis of the potential barriers to the commercialization of self-healing technologies.

On the one hand, concrete manufacturing companies are discouraged from investing in scaling processes due to uncertainties related to the required procedures, the scale of production, and the quantification of the necessary investments.

On the other hand, since the initial cost of employing self-healing technology would inevitably be higher compared to traditional concrete, contractors are reluctant to propose such solutions to their clients. This is because self-healing provides benefits over the long term, while contractors are typically responsible for the structure only for a limited period, which is not long enough to appreciate these advantages.

Nevertheless, the multiple benefits of adopting this technology throughout the entire life cycle of the structure have already been highlighted, particularly in terms of long-term savings when considering the substantial costs associated with maintenance operations.[44-45]

In an effort to minimize the impact of the capsules on the final cost of the concrete element, several studies[46] have explored the possibility of adapting products already available on the market, such as capsules commonly used in

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[44] (Barros, Knockaert, & Filho, Towards a more sustainable construction industry: Bridging the gap between technical progress and commercialization of self-healing concrete , 2023)

[45] (Panza Uguzzoni, et al., 2023)

[46] (Kannikachalam, Cailleux, Belie, & Ferrara, 2023)

the pharmaceutical industry, for self-healing purposes. The results have been promising, although the integration of this type of capsule introduces additional effects within the matrix, such as a reduction of the mechanical capacity to about 85% and a capsule failure mode not fully compatible with the concrete matrix, due to an excessively ductile rupture.

Having obtained excellent experimental results with cement-based capsules, our next objective is to estimate the potential cost of implementing the three different strategies.

It is well known that, in order to evaluate the overall cost of a construction project, a *computo metrico estimativo* (detailed cost estimate) is typically prepared. This procedure starts from the dimensional data of the various construction elements and associates them with unit prices, which are usually taken from official regional price lists.

For example, if we wanted to estimate the cost of concrete works for a residential building of a given type, we would need to evaluate each construction element (foundations, columns, beams, walls, staircases…), determine their quantities expressed in cubic meters, square meters, or linear meters, identify the corresponding item in the reference price list, multiply the unit price by the quantity, and sum all partial costs.

However, this procedure is only possible for standard construction works, for which price analyses have already been conducted and unit prices are readily available in regional catalogs. When dealing with an innovative construction process, as in our case, it becomes necessary to prepare a new price analysis from scratch, as required by *art. 32 of DPR 207/2010*. Such analysis must account for all the relevant cost components, including materials, labor, equipment, rentals and transportation, overheads, and profit margins necessary for the specific process under examination.

Conducting a price analysis for the three types of construction processes required to implement the different strategies, would allow us to understand the cost differences between them, identify the factors that have the greatest impact, and determine whether the three solutions, given the same dosage levels, can be considered economically equivalent or not. This aspect is of particular interest, since from a performance point of view the strategies are clearly not equivalent.

Since, in this cost analysis, the capsule would be treated as just another material component of the concrete mix (requiring knowledge of its unit cost to multiply by the applied dosage) it is first necessary to estimate the cost for both types of capsules used in the experimentation (CAP10 and CAP40).

To arrive at this estimate, as previously mentioned, many uncertainties arise due to the lack of data and the difficulty of defining an actual production scale. However, a methodology was developed that started from the available data and proceeded by assumptions to determine the maximum unit cost that a capsule could reach based on market limits.

By then including this value in the cost analysis, it was possible to evaluate scenarios in which the final cost of the works is driven primarily either by the capsule itself or by the additional items or procedures required for implementing the technology.

This approach allowed for a comparison of the cost differences among the various options, taking into account both the performance they provide and the additional challenges involved in their practical implementation.

5.1 Capsule cost evaluation

To correctly estimate the unit cost of a capsule, it would be necessary to account not only for the direct and indirect costs associated with the industrial production process, but also for aspects related to economies of scale and non-recurring expenses.

For example, among the direct costs, in addition to the cost of raw materials, it would be important to include packaging, direct labor, and energy consumption per unit. Indirect costs, on the other hand, would need to cover equipment depreciation, plant and facility expenses, maintenance, and indirect labor related to administrative and supervisory staff.

Furthermore, for an industrial production to operate in compliance with regulations, funds must be allocated for product certifications and approvals, quality controls on actual production, as well as research and development investments needed for prototyping and process optimization. Finally, all cost items related to logistics, management, overheads, and a desired profit margin should be considered.

At this stage, however, defining a realistic production scale and assigning meaningful values to each of these categories proves extremely challenging, due to the many uncertainties and the limited data available. For this reason, an alternative approach has been explored to arrive at an estimate of the capsule unit price.

Starting from the available data, a reverse approach was adopted, based on defining the maximum possible unit cost that the capsule could reach while still keeping the total process costs within market limits.

The following scheme provides an overview of the procedure adopted:

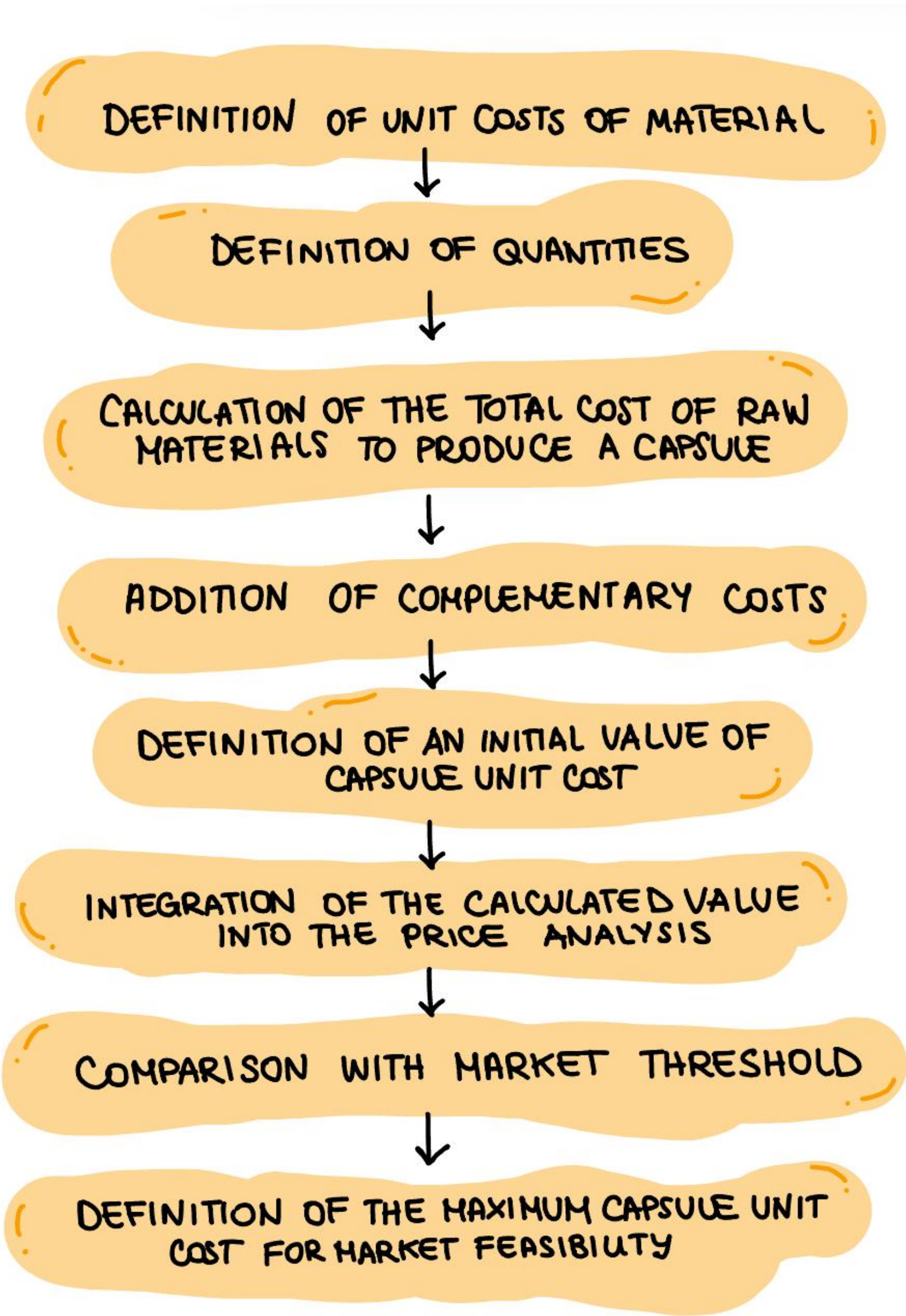

Figure 61 - Scheme of the capsule cost evaluation procedure

5.1.1 Definition of the unit costs of materials

The analysis started from what was known, namely the purchase data for the materials used in laboratory-scale production. These prices obviously reflect small-quantity purchases, while industrial-scale procurement would result in a significant reduction of unit costs. For this reason, a cross-check of market prices for the same raw materials was performed, considering, where available, bulk formats (e.g., 1000 L tanks or 100 kg bags) to estimate a unit cost as representative as possible of large-scale purchases.

All identified raw material prices were subsequently adjusted to exclude VAT, applying a rate of 22% or 10% depending on the provisions of Italian tax law for construction products. The goal was to obtain a net cost of the raw materials consistent with the criteria used in quantity take-off analyses and standard accounting practices in the sector, where VAT does not represent an actual cost but a fiscally neutral item for the company.

For reference, check *Attachment4_Capsule cost and price analysis,* sheet *"Capsule cost"*.

5.1.2 Definition of quantities

The quantities of material required to produce a single capsule were estimated based on the dosages used at the laboratory scale, specifically referring to a standard batch.

The term "standard batch" refers to the amount of material that, at the laboratory level, proved manageable and was used for capsule production, ensuring an efficient process while minimizing waste caused by premature hardening of the mixture before molding. From this standard batch, and using data collected during previous laboratory campaigns, the actual production yield was estimated (that is, the number of capsules effectively obtained) distinguishing between the two types, CAP10 and CAP40.

It is acknowledged that laboratory-scale production yields are significantly lower than those achievable at industrial scale, due to various risk factors introduced in the process (inexperienced labor, rudimentary equipment, operator delicacy, accidental events, etc.). However, since this parameter provides a conservative estimate, effectively overestimating the final cost of a single capsule, this laboratory yield was retained for the analysis.

For reference, check *Attachment4_Capsule cost and price analysis,* sheet *"Capsule cost"*.

5.1.3 Calculation of the total cost of raw materials for a capsule

By multiplying the unit cost of each material by its corresponding quantity and summing the resulting values, it is possible to determine the total cost of the raw materials needed to produce a single capsule.

Assuming that this value should be relatively low for the overall analysis to make sense, the same calculation was also performed for a standard pack containing 1000 capsules, almost to emulate the way pasta is purchased in bulk. In such a case, the unit cost of a single piece becomes less meaningful, while what can be more effectively appreciated is the total cost of the pack containing a defined number of units.

	CAP 10 unit cost	pack of 1000 CAP 10	CAP 40 unit cost	pack of 1000 CAP40
total cost of raw materials (VAT excluded)	0,05 €	48,59 €	0,12 €	115,14 €

Figure 62 - Calculation of the total cost of raw materials

5.1.4 Addition of complementary costs and definition of an initial value of capsule unit cost

Regarding all the other costs mentioned earlier, based on economic analyses of production processes carried out by industry experts, it is estimated that, given the small-scale cost of raw materials, these represent approximately 70% of the total product cost. Since detailed information on the actual industrial production process is not available, an additional 30% is added to account for processing and indirect costs, thus arriving at a final unit cost.

By adding these additional costs to the previously calculated raw material costs, a preliminary estimate of the capsule's unit cost was obtained, along with its corresponding value per package.

	CAP 10 unit cost	pack of 1000 CAP	CAP 40 unit cost	pack of 1000 CAP40
Complementary costs	0,01 €	19,44 €	0,03 €	46,06 €
Total cost of capsule (VAT excluded)	0,06 €	68,03 €	0,15 €	161,20 €

Figure 63 - Preliminary estimate of capsule unit cost

5.1.5 Comparison with market threshold

At this stage, this value was used as if it were the unit cost of any of the materials included in the cost analysis of the individual operations required for implementing the three different strategies.

To set up the cost analysis, the following operations were considered, based on the strategies and dosages used during the experimental phase, in order to directly correlate performance with cost:

- *Reference analysis– Standard Concrete (REF-L):* Pouring of ready-mixed concrete produced in a plant, in compliance with technical specifications, transported to site by mixer truck, and executed according to best practices, including unloading, spreading, vibration, and all other necessary operations to complete the work, excluding scaffolding, temporary works, formwork, and steel reinforcement. Applicable to ground-level structures.

- *CAP-L – Concrete pour with 4 cm capsules in controlled positioning:* Pouring of ready-mixed concrete produced in a plant, in compliance with technical specifications, transported to site by mixer truck, and executed according to best practices, including unloading, spreading, vibration, and all other necessary operations to complete the work, excluding scaffolding, temporary works, and steel reinforcement. Formwork preparation includes marking positions, installing support systems, and fixing CAP40 capsules in the predetermined design positions. Applicable to ground-level structures.
- *CAP-N – Concrete pour with 1 cm capsules in semi-controlled positioning:* Pouring of ready-mixed concrete produced in a plant, in compliance with technical specifications, transported to site by mixer truck, and executed according to best practices, including unloading, spreading, vibration, and all other necessary operations to complete the work, excluding scaffolding, temporary works, formwork, and steel reinforcement. Placement of CAP10 capsules according to the predetermined project quantity using a manual seeder-like device. Applicable to ground-level structures.
- *CAP-R – Concrete pour with 1 cm capsules in random positioning directly in the mix:* Pouring of ready-mixed concrete produced in a plant with a project-specified percentage of coarse aggregate replaced by CAP10 capsules, in compliance with technical specifications, transported to site by mixer truck, and executed according to best practices, including unloading, spreading, vibration, and all other

necessary operations to complete the work, excluding scaffolding, temporary works, formwork, and steel reinforcement. Applicable to ground-level structures.

The structure used to develop the cost analysis will be discussed in more detail in Chapter 5.2.

At this stage, it is sufficient to note that by summing the reference values for materials, production, equipment rentals, transport, labor, overhead, and profit margin, it was possible to calculate the total cost of the operations for the three strategies and the reference analysis that are reported in the table below:

	Speciments name	Description	Total cost of the manufact	Construction-site implementation difficulty
			[€]	-
Reference	REF-L	Use of standard concrete	111,77 €	Standard
First strategy	CAP-L	Use of CAP40 with controlled positioning	1.396,70 €	High
Second strategy	CAP-N	Use of CAP10 with semi-controlled positioning	1.664,15 €	Medium
Third strategy	CAP-R	Use of CAP10 with random poistioning	1.737,41 €	Low

Figure 64 - Starting scenario based on preliminary estimate capsule cost

For reference, check *Attachment4_Capsule cost and price analysis,* sheet *"Scen 0 – price analysis"*.

5.1.6 Definition of the maximum capsule unit cost for market feasibility

Observing the calculated values, it becomes evident that the practical applicability of this technology seems far from being market-feasible, as the total cost of operations incorporating capsules is approximately ten times higher than that of the reference analysis.

From previous studies, it is clear that such a starting cost could not be justified even by long-term savings from avoiding additional maintenance interventions, since the canonical maximum value for maintenance-related savings is typically no more than double the initial investment.

Therefore, it is necessary to identify the maximum unit cost that a capsule could have while keeping the overall process within market limits.

To adopt a cautious approach, a threshold equal to twice the cost of the reference operation is set, effectively reducing the initial capsule cost to one-tenth of the value initially considered.[47]

	CAP 10 unit cost	pack of 1000 CAP 10	CAP 40 unit cost	pack of 1000 CAP40
Max unit cost within market limits (VAT excluded)	0,01 €	6,80 €	0,01 €	16,12 €

Figure 65 - Maximum unit cost within market limits

5.2 Price analysis

The unit cost analyses were carried out in accordance with the procedures set out in Art. 32 of DPR 207/2010. Specifically, the cost analysis was performed not only for the three strategies, which, being associated with an innovative process, are not included in the regional price list used for preparing bills of quantities, but also for a standard concrete work, so as to establish a consistent baseline for price comparison.

The various items in the cost analysis, as is customary in professional practice, refer to the generic execution of a concrete pour (either standard or with capsules) and not to the construction of a specific structural element.

[47] As previously anticipated, the initial analysis likely considered prices that were revealed entirely out of scale, reflecting retail-level raw material costs rather than the actual bulk purchase prices achievable in industrial-scale production.

For this reason, formwork costs are not included in these items and have instead been computed separately according to the type of structural element to be built and its location. In particular, considering the most likely applications of self-healing technology, reference was made to a beam, a column, a wall, and a mat foundation.

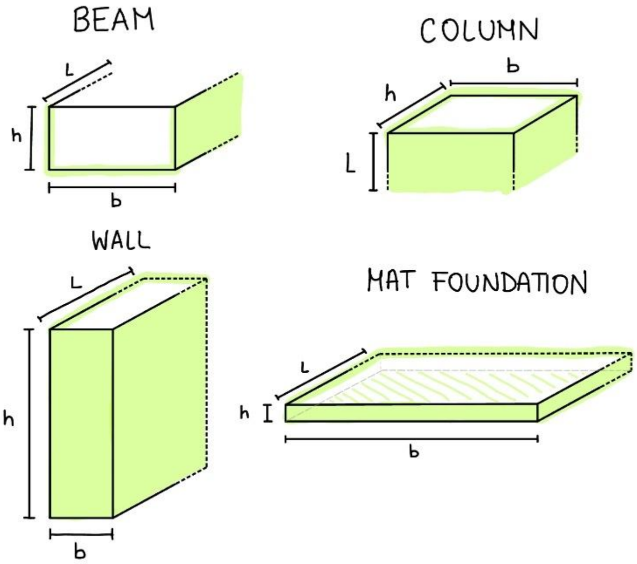

Figure 66 - Dimensional reference for item considered in the analysis

The reference quantity for the work, as is customary, is 1 m^3 of material, which is assumed not to be produced directly on-site, but rather delivered as a ready-mix from the plant via concrete mixer trucks.

It is also assumed that the construction site is located within the Piedmont region, and therefore the cost analysis has been carried out with reference to the *2025 Regional price list for public works*.

For each of the construction operations listed previously (see *Chapter 5.1.5*), the price analysis was carried out as follows:

- for the materials component, the quantities required to produce 1 m^3 of material were calculated based on the same mix proportions used in the experimental phase and multiplied by their respective unit costs;

- for all other costs (production, equipment hire, transportation, labor, etc.), estimates were based on their typical incidence on the final cost.

Since the exact values of these costs were not known due to the significant uncertainties related to process scalability and to avoid making overly specific assumptions regarding the construction site, type of plant, or equipment used, it was deemed appropriate to rely on incidence data obtained from economic analyses of previous projects, conducted using software such as Primus[48] or similar.

Finally, the total derived from summing all these contributions was increased by 15 % for overheads and 10 % for contractor profit, as is standard practice.

For reference, check *Attachment4_Capsule cost and price analysis.*

5.2.1 First scenario – High-impact capsule cost

The results obtained are reported in the following table:

	Speciments name	Description	Total cost of the manufact [€]	Construction-site implementation difficulty -
Reference	REF-L	Use of standard concrete	111,77 €	Standard
First scenery - high impact capsule cost				
First strategy	CAP-L	Use of CAP40 with controlled positioning	226,13 €	High
Second strategy	CAP-N	Use of CAP10 with semi-controlled positioning	236,68 €	Medium
Third strategy	CAP-R	Use of CAP10 with random poistioning	237,94 €	Low

Figure 67 - First scenario - high impact capsule cost

Analyzing in detail which cost items most influence the final price, it is evident that the unit cost of the capsules has a predominant impact compared to the other components.

[48] It is a software widely used in professional practice to prepare cost estimates, as well as to manage construction accounting.

This means that the main factor determining why one strategy is more expensive than another is the dosage used and the type of capsule.

For example, the controlled placement strategy (CAP-L), which uses CAP40 capsules, turns out to be paradoxically the most cost-effective option, even though it requires more labor and time for installation. Conversely, the CAP-R strategy, which involves adding a higher dosage of capsules directly into the mix to ensure proper functionality, does not alter the standard execution procedures but ends up being the most expensive.

5.2.2 Second scenario – Low impact capsule cost

A second scenario is then considered, in which, thanks to optimized production processes and a particularly favorable market for raw material costs, it is possible to produce capsules at an even lower unit cost.

In this case, the capsules are no longer the main cost driver of the process; instead, other items such as labor or additional equipment become the factors that determine the increase in the final cost of the operation.

	Speciments name	Description	Total cost of the manufact	Construction-site implementation difficulty
			[€]	-
Reference	REF-L	Use of standard concrete	111,77 €	Standard
Second scenery - low impact capsule cost				
First strategy	CAP-L	Use of CAP40 with controlled positioning	203,78 €	High
Second strategy	CAP-N	Use of CAP10 with semi-controlled positioning	198,31 €	Medium
Third strategy	CAP-R	Use of CAP10 with random poistioning	194,59 €	Low

Figure 68 - Second scenario - low impact capsule cost

As shown in the previous table, when in addition to the material other cost items also drive the value of the final price, it becomes clear that the strategy that has the least impact on procedures is the most economically advantageous making the CAP-R the most convenient.

5.3 Solutions comparison and result discussion

Knowing at this stage, if the reality is going to be more likely the first or the second scenario is very difficult. All the uncertainties arising from all the factors concerning production costs, raw material prices, and the scalability of the capsule manufacturing process itself, cannot yet be precisely quantified.

As a result, the economic advantage of adopting one strategy over another may vary significantly depending on the eventual conditions encountered in the field.

Considering the experimental results obtained during laboratory testing, it is evident that, in the context of Scenario 1, where the unit cost of the capsules represents the predominant contribution to the overall cost of the operation, the CAP-L strategy would likely emerge as the preferred option. This strategy, characterized by controlled placement of the capsules, ensures the highest performance in terms of crack sealing and sealing efficiency, thus justifying its higher labor and procedural requirements.

However, this preference assumes that no additional risks or operational challenges are encountered during large-scale implementation, such as difficulties in positioning the capsules for the operator, interferences with the rebars or excessive extension of construction time.

On the other hand, in the second scenario, where optimized production processes and favorable market conditions significantly reduced the unit cost of the capsules highlighting the contribution generated by the other cost items, the relative cost differences among the strategies become a little more pronounced even though still not substantial.

Under these conditions, the selection of a particular strategy could be made on a case-by-case basis, balancing the marginal differences in cost with the specific performance benefits offered by each approach.

Overall, comparing the results obtained by the economic analysis and the experimental performance highlights an important insight: while CAP-L consistently demonstrates superior technical efficacy, its adoption may be constrained or influenced by cost considerations depending on the scenario.

On the other hand, strategies like CAP-N or CAP-R, which may offer more flexible implementation and that determine less impact on the variability of standard procedures, could become viable alternatives in contexts where the capsule cost is less dominant and dosages can be easily increased, still providing an improvement if compared to not apply any strategy at all.

Conclusions

The work conducted in this thesis aimed to help bridge the gap between the experimental field and the actual application on real construction site of self-healing capsule-based technology.

The growing interest in this kind of solutions capable of enhance the durability of the material becoming at the same time a tool for sustainability, quality, and cost-effectiveness is justified by the challenges that nowadays we need to deal with as professionals and as human being.

In particular, the focus on the introduction of cementitious macro-capsules in concrete was motivated by the wide range of advantages offered by this technology. These include high versatility (thanks to the possibility of incorporating different repairing or sealing agents), the capacity to address cracks of considerable width due to the large volume of healing agent contained, flexibility in applying either a localized or a distributed healing strategy depending on capsule placement, and full compatibility with the cementitious matrix in terms of both material and mechanical properties.

However, despite the fact that this technology seems very promising, its widespread adoption has not yet taken place. The main barriers identified were related to the uncertainties surrounding the actual large-scale production process of the capsules, the adjustments required within standard construction procedures, and the difficulty in estimating both the magnitude of the necessary investments and the actual final cost of the technology.

In this thesis, three strategies were developed, tested in the laboratory, and economically assessed in order to overcome the main barriers identified.

The first strategy (CAP-L) is based on the controlled placement of larger capsules within the matrix, ensuring precision in the release of the healing agent and the most efficient use of the material.

The second strategy (CAP-N) aims to reduce the practical difficulties associated with the implementation of the first one by introducing a semi-automated process, while still maintaining control over the number of capsules embedded in the elements.

The third strategy (CAP-R), instead, offers a solution in which the production process of concrete elements does not undergo any modification: the capsules are simply mixed directly into the concrete as if they were any other aggregate.

From an experimental perspective, the tests demonstrated that the capsules, as designed, are sufficiently robust to withstand the mixing process, making their introduction into the concrete according to the third strategy technically feasible. At the same time, however, the workability of the mix is slightly altered, meaning that certain aspects of the mix design need to be reconsidered, along with dimensional aspects related to the potential interaction between the capsules and reinforcement bars. On the other hand, no significant variations were observed in the intrinsic mechanical properties of the material.

As for the crack-healing effectiveness of the different technologies, although all three solutions provided excellent results — with each of them achieving at least 50% sealing efficiency at later ages — a clear hierarchy of efficiency emerged among the placement strategies: controlled placement (CAP-L) ensured the best performance, whereas random placement (CAP-R) proved to be the least effective.

The economic analysis, on the other hand, showed that attempting to estimate the unit cost of a capsule based solely on laboratory data leads to results that diverge significantly from what would be acceptable in the market. For this reason, a maximum feasible unit cost was identified by looking for the maximum value acceptable considering the price analysis of an ordinary concrete batch and comparing it with the innovative ones (introducing capsule based self-healing) following the three strategies applied. This led to a value for a single CAP10 capsule of less than 0.006€ and 0.015€ for a CAP40 capsule.

Two scenarios were then developed to assess how the capsule cost impacts the overall price.

In the first scenario, capsules remain the dominant cost component, making the CAP-L strategy not only the most economically convenient among the three, but also the one delivering the best performance. While its implementation is of course more expensive than the reference scenario, the superior performance it ensures clearly outweighs the baseline solution.

In the second scenario, thanks to economies of scale and production optimization, the unit cost of the capsules decreases significantly, reducing the price differences between strategies.

In this case, strategies such as CAP-N or CAP-R, which offer greater flexibility in implementation and cause less impact on standard construction procedures, could become viable alternatives. In fact, their dosages can be easily increased without leading to excessive cost escalation, while still ensuring a significant improvement compared to not applying any strategy at all.

In such a scenario, the decision on which strategy to adopt would depend more on the specific application context than on purely economic considerations.

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Attachments

For reference see the list of attachments below that can be found at: https://doi.org/10.5281/zenodo.17226203

Attachment1_Capsule dimension survey

Attachment2_Aggregate weight

Attachment3_Test and data results

Attachment4_Capsule cost and price analysis

Index of figures

Acknowledgements

When I started this journey almost four years ago, I promised myself that I would do my best to finally understand what my path was meant to be, as if it had already been written somewhere and all I had to do was finding it.

At some point, though, while I was completely lost chasing something that did not truly represent me, I realized that, regardless of the field, what makes me happy is doing something every day that has meaning, something not done just for the sake of doing it, but because it has value.

It may sound obvious, yet one of the most important lessons I have learned in these years is that in the rush to do everything, quickly, perfectly, and in large amounts, we often end up doing nothing meaningful at all.

Choosing a thesis marks an important milestone: the university journey is nearly over, and soon it will be time to look elsewhere. On this occasion, I decided to treasure what life has taught me in recent years and not to compromise, to remain true to myself and to choose what might have been the more complex path, but also the only one that was truly mine.

I consider myself incredibly fortunate. I have been surrounded by extraordinary people who have been a constant support, an inspiration, a friendly voice in the hardest moments, and a motivation to always do my best.

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