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An analysis of the commercialisation barriers of self-healing concrete

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Abstract. Interest in more sustainable construction has grown in recent years. Evidence indicates that larger societal trends and the economic climate have an impact on the transfer of new technologies in the construction sector from university to industry. The transition to sustainability and concerns regarding climate change represent pressing issues to innovate in the sector. In order to decrease CO_2 emissions from cement production, strategies have been developed to reduce the environmental burdens, such as the use of smart materials. The goal is to use more durable materials. Significant research has been performed into the development of self-healing technologies for concrete as a smart material. The advantages of self-healing concrete are many and can be significant to all stakeholders, including researchers, companies and end users. In spite of the progress made by past research, the commercialisation of self-healing concrete is still in its infancy. To fulfil this need, our study examines the commercialisation of self-healing concrete as a process complicated by divergent barriers. By carrying out semi-structured interviews with stakeholders, this study generates its contribution: the development of the self-healing concrete value chain identifying the commercialisation barriers as well as the analysis of these barriers that the innovation encounters along its value chain.

1 Introduction

In Europe, the construction industry has often been considered a mature, traditional industry (1), that is conservative and attached to familiar technologies (2). At the same time, the construction industry is challenged by increased global competition, urging firms in this industry to engage in innovation (3).

Interest in more sustainable construction has grown in recent years. This is due to the fact that the construction industry is in charge of 32% natural resource extraction and 39% of energy and process-related carbon dioxide (CO2) emissions (4; 5). There has been more focus on reducing CO2 emissions from cement production within the subsector of the cement industry (6; 7). As a result, plans have been made to reduce the environmental burdens. For instance, the goal of sustainability is pursued through using more durable materials in the concrete sector (8) such as smart materials (9) and consequently reducing CO2 emissions. Among these materials, self-healing concrete has gained recognition as a technological advance that has the potential to influence the direction of the construction sector in the future since it enables concrete repair without human intervention (10). The advantages of self-healing concrete are many and can be significant to all stakeholders, including researchers, companies and end users. In fact, self-healing concrete is a breakthrough that can improve the economy and the environment by increasing the durability of concrete and, therefore, increasing the service life of the structure.

Research currently being done in the construction industry still mostly focuses on technological development rather than commercialisation aspects (11). Additionally, commercialisation is a complex and diverse phenomenon by its very nature, requiring in-depth research and understanding of the business environment in order to achieve the desired outcomes (12). In spite of the progress made by past research on the development of self-healing concrete for bringing environmental and economic benefits, the stakeholders and activities involved in its value chain remains rather vague and the commercialisation is still in its infancy. To fulfil this need, our study aims at identifying the barriers influencing the commercialisation of self-healing concrete. Shedding light on the barriers encountered on the commercialisation of self-healing concrete enables to develop an action plan to overcome these barriers and to have a more widespread adoption in the construction sector, in addition to contributing to a more sustainable construction.

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1.1 The benefits of self-healing concrete

Technologies that promote self-healing get their inspiration from biological systems that have the capacity to repair damaged parts on their own. As cracks begin to form, the technology releases its content to repair, partially or completely restoring the host matrix's properties (13). The strength, stiffness, durability, and service life of concrete structures are all threatened by cracks (14). On the one hand, self-healing concrete enables the construction process to use less material, reduces the cost of maintenance and repair, extends the service life of the structure, and reduces the environmental impact of concrete production (15). On the other hand, because the concrete has healing agents added, the initial construction cost requires a higher investment. The use of self-healing concrete could, however, reduce costs. Repairs are costly because they require expert personnel need and specific products, in addition to indirect costs such as temporary loss of function (16). Additionally, as stated by 17, repaired concrete may only have a limited service life if it was poorly designed, executed, or if it had not been inspected before the repair, which could result in an inefficient repair and the damage reappearing after a relatively short period of time. This could further increase the life cycle cost of repair services, which could be reduced or even avoided with the use of self-healing concrete.

The increased durability of structures using self-healing concrete dictates that the maintenance will be reduced or the lifespan will be increased when considering the entire life cycle of the structure. Self-healing concrete can therefore be one of the complementary strategies for reducing global warming potential.

1.2 Research approach

Using the literature on value chains as background, the main stages of the self-healing concrete value chain were identified and validated throughout the interviews. A process-oriented model to identify the gaps in bringing self-healing concrete to market for each stage of the value chain is proposed. Specifically, 44 semi-structured interviews were conducted with university researchers (professors), consultants, engineers, CEOs, entrepreneurs and tech transfer officers working on self-healing in the construction industry in Europe.

The semi-structured interviews were conducted both in person and online (due to the fact that some of the interviews took place during the covid-19 pandemic) with experts in the field of self-healing concrete and commercialisation of innovative technologies in the construction sector. All interviews took place during the period from May 2021 to October 2022. To analyse the data collected, all interviews were transcribed, and the interview notes were transferred to a coding frame.

2 Commercialisation barriers

We initially identify two barriers that are more general to the construction industry and relevant to all stages of the value chain for self-healing concrete.

First, the *lack of standards and certification* is identified as a significant barrier relevant to all stages of the self-healing concrete value chain. In particular, the innovative technology must adhere to codes and standards since clients need require guarantees on construction projects. In line with the literature (18; 19; 20) that has highlighted the importance of standards for a technology's success as well as in supporting major technological and societal developments, compliance with standards is therefore a crucial strategy to gain market credibility and persuade potential clients. To this end, 16 argue that the lack of standardized test methods for self-healing concrete (at both the development and certification levels) hinders international collaboration and impedes further development because it makes it difficult to compare the outcomes of different self-healing agents on an even playing field. Certification gives an endorsement to place the product in the market. As mentioned by 21, asset owners are beginning to demand technical evidence that their structures can meet service life standards and are becoming less willing to accept black-box construction solutions. In fact, the World Bank Group's study (22) considers standardization as a process that influences the construction value chain as whole.

Second, stakeholders are typically unwilling to take the risks associated with uncertainties about the benefits of a new technology, therefore this presents a barrier at all stages. *Risk aversion* thus prevents innovation in the construction industry. The tight margins that the construction sector often operates under further add to the pressure to stick to proven methods and technologies, which further strengthens this barrier. The literature indicates that it is often difficult to get innovations accepted into civil engineering practice (23). Moreover, the extent to which firms are able to embrace and adopt new technologies is largely contingent on their dynamic capabilities, enabling them to adapt, integrate and reconfigure their organizational competences and resources in order to reach a fit with the changing business environment (24; 25). Furthermore, construction firms are challenged by the integration of new technologies into their project-based structure, which is typical for the construction industry (25).

2.1 Research and Development (R&D) stage

In the first stage of the self-healing concrete value chain, R&D, the activities embedded range from carrying out basic research and technology development to IP protection and dissemination of results, through the execution of lab tests and construction of demonstration projects. The players at this stage are the parties in research (universities and research institutes) and the companies collaborating with the research parties, known as university-industry collaboration. At this stage, two barriers were identified: the *lack of demonstration projects* and the *lack of R&D funding*.

For the construction industry specifically, it is crucial to invest in demonstration projects as part of the technology transfer process to validate assumptions in a real scale concrete structure, such as water tanks, or structural elements, such as beams, slabs and pillars. The lack of demonstration projects contributes to the second barrier, a lack of R&D funding. Building demonstration projects could be accomplished with such an investment.

2.2 Technology manufacturing stage

In the second stage of the value chain, technology manufacturing, the main players are both existing and new manufacturing companies. Here, we identified three barriers.

The first barrier identified is the *difficulty to convince mid/end users* to adopt the innovation. The mid users are manufacturing companies' direct clients: concrete plants and precast concrete factories, whereas the end users are the indirect ones and refer to the owners of the structure (private asset owners or the government in the case of civil works, such as tunnels, bridges or roads).

Another barrier is the *lack of long-term data*. Given that concrete structures have a long service life (typically at least 50 years) and that most deterioration mechanisms (such as corrosion due to carbonation and/or chloride ingress) take time to develop, it will take time to gather long-term data to demonstrate that cracking is a problem for concrete structures that causes deterioration, and that self-healing can prevent deterioration. It is a drawback that long-term testing to assess the material performance in real conditions are needed to collect data for self-healing concrete. In fact, the influence of other innovations such as superplasticizers may be seen very quickly, namely between the concrete production and casting (26), which facilitates its take-up.

In addition to the lack of long-term data, self-healing concrete has a greater initial cost than traditional concrete. Particularly, innovations in the construction sector often require a large initial investment, with effects taking a longer time span to mature and therefore cost is often considered the main barrier for the implementation of new technologies (27; 28). Construction is a *cost-sensitive industry*, making it more challenging for manufacturing companies to market their products. Cost is a significant barrier to the commercial adoption of self-healing concrete because customers prioritize the purchase price of the concrete volume over the life cycle cost.

2.3 Distribution stage

The distribution stage includes the structure design and the concrete production (incorporating the self-healing technology) for use in construction. The actors of these processes are the architects and engineers' consultants, concrete plants and precast concrete companies. In the distribution stage, there are three barriers encountered.

The first barrier is the *lack of quantitative data*, particularly to demonstrate self-healing benefits. Quantitative data includes lab results of the parameters required to make initial estimates on the performance of self-healing concrete.

The second barrier is the *uncertainty about the scaling up* of manufacturing because consultants still lack confidence that manufacturing companies are able to deliver the amount of self-healing needed for the construction of concrete structures. Depending on the size of the company and the costs to adapt its facilities to produce self-healing agents at the construction site, concrete manufacturing companies might be reluctant to invest in scaling production to a commercial scale as the market for self-healing concrete is still very incipient and uncertain.

The *lack of awareness of the innovation by potential end users* is the third barrier, which indicates the fact that self-healing concrete still lacks a better dissemination strategy.

2.4 Use in construction stage

The last and fourth stage is the use in construction, during which either a new structure is built, or an existing one repaired. The actors involved in the construction and repair of structures are contractors and asset owners as end users.

Here, one of the two identified barriers at the use in construction stage is the *lack of requirements/specifications* in the projects from architects and engineers. The expertise of the architects and engineers' consultants is relied upon by contractors and asset owners. Essentially, contractors will only include concrete innovations if this is a demand from architects and engineers or from their customers, which are the asset owners. Contractors are legally responsible for maintenance for a period of time after construction, but not long enough to gain the benefits of self-healing.

As to what the contractors' interest is concerned, these parties often also have a conflict of interest related to the use of self-healing concrete since one of their activities is construction repair. For this reason, the second barrier identified is the *diverging interests between contractors and end users*.

3 Discussion

The inability to set up real scale demonstration projects is the barrier that most directly impacts others and therefore the most critical one, which are relevant to all other stages of the value chain. As this barrier is identified in the first stage of the value chain, R&D, it is the root cause of the barriers identified in the later stages of the value chain. The lack of demonstration projects impacts the lack of standards and certification in addition to impact the barriers encountered in the second and third stage (technology manufacturing and distribution, respectively): the lack of long-term and quantitative data. This is because by monitoring the structures of demonstration projects, tests are done to obtain data beyond lab scale. In addition, the lack of demonstration projects and therefore successful projects might discourage engineers and architects from specifying self-healing concrete in their projects, which is a barrier pointed out in the last stage, use in construction. Thus, the lack of demonstration projects is the bottleneck in the commercialisation of self-healing concrete.

However, the barrier that is most impacted by others is the difficulty to convince mid/end users, identified during the technology manufacturing stage. The lack of requirement and specification also impacts this barrier as it increases the difficulty to convince clients. Obviously, if potential clients are not aware of the technology and if there are diverging interests between contractors and end users, the difficulty increases even more.

Since the construction industry is driven by cost and the initial cost of self-healing concrete is expected to be higher than ordinary concrete, it impacts negatively in the willingness of stakeholders to take risks. The risk aversion of stakeholders also affects the technology scalability because if there is not enough demand, small and medium-sized manufacturers might not want to take the risk to use their production facilities, which can compromise all, to produce only self-healing agents. It should be noted that risk aversion and the fact that the industry is cost sensitive are barriers inherent to the construction sector in general and not specific to self-healing concrete.

4 Concluding remarks

Our study may help stakeholders to understand which barriers exist and may thus contribute to the development of viable business models of self-healing technologies. Solving the key issues can help the transition towards a more environmentally sustainable construction industry. In the end, new technologies, such as self-healing, offer opportunities for the material properties and performance. This may result in capturing economic value and delivering environmental benefits. As a result, it is commonly acknowledged that in order for the construction industry to contribute to climate change targets, more efficient and durable cementitious materials are required.

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