Brussels, 12 February 2016

COST 003/16

DECISION

Subject: **Memorandum of Understanding for the implementation of the COST Action "Self-healing As preventive Repair of COncrete Structures" (SARCOS) CA15202**

The COST Member Countries and/or the COST Cooperating State will find attached the Memorandum of Understanding for the COST Action Self-healing As preventive Repair of COncrete Structures approved by the Committee of Senior Officials through written procedure on 12 February 2016.

MEMORANDUM OF UNDERSTANDING

For the implementation of a COST Action designated as

COST Action CA15202
SELF-HEALING AS PREVENTIVE REPAIR OF CONCRETE STRUCTURES (SARCOS)

The COST Member Countries and/or the COST Cooperating State, accepting the present Memorandum of Understanding (MoU) wish to undertake joint activities of mutual interest and declare their common intention to participate in the COST Action (the Action), referred to above and described in the Technical Annex of this MoU.

The Action will be carried out in accordance with the set of COST Implementation Rules approved by the Committee of Senior Officials (CSO), or any new document amending or replacing them:

a. "Rules for Participation in and Implementation of COST Activities" (COST 132/14);
b. "COST Action Proposal Submission, Evaluation, Selection and Approval" (COST 133/14);
c. "COST Action Management, Monitoring and Final Assessment" (COST 134/14);
d. "COST International Cooperation and Specific Organisations Participation" (COST 135/14).

The main aim and objective of the Action is to SARCOS is to deal with new concepts and advanced solutions for the preventive repair of concrete structures, from designing smart "healing promoter additives and technologies" to defining standards for performance evaluation, with the final challenge to contribute to advance towards the sustainable development of the European construction industry. This will be achieved through the specific objectives detailed in the Technical Annex.

The economic dimension of the activities carried out under the Action has been estimated, on the basis of information available during the planning of the Action, at EUR 36 million in 2015.

The MoU will enter into force once at least five (5) COST Member Countries and/or COST Cooperating State have accepted it, and the corresponding Management Committee Members have been appointed, as described in the CSO Decision COST 134/14.

The COST Action will start from the date of the first Management Committee meeting and shall be implemented for a period of four (4) years, unless an extension is approved by the CSO following the procedure described in the CSO Decision COST 134/14.

TECHNICAL ANNEX

OVERVIEW

Summary
The search for smart self-healing materials and preventive repair methods is justified by the increasing sustainability and safety requirements of structures. The appearance of small cracks in concrete is unavoidable, not necessarily causing a risk of collapse for the structure, but certainly accelerating its degradation and diminishing the service life and sustainability of constructions. That loss of performance and functionality promote an increasing investment on maintenance and/or intensive repair/strengthening works. The critical nature of such requirements is signified by their inclusion as priority challenges in the European Research Program.

The first focus of this proposal is to compare the use of self-healing capabilities of concrete with the use of external healing methods for repairing existing concrete elements. Despite the promising potential of the developed healing technologies, they will be real competitive alternatives only when sound and comparative characterization techniques for performance verification are developed, being this SARCOS's second focus. The third focus deals with modelling the healing mechanisms taking place for the different designs and with predicting the service life increase achieved by these methods.

SARCOS COST Action will be leaded by research institutions searching on different self-healing technologies and repair solutions for extending service life of new and existing concrete structures, with high expertise in developing characterization techniques. Also specialists on modelling healing mechanisms and experts on numerical service life prediction models contribute for the Action's success. This composition provides a solid framework to advance in implementing innovative and sustainable solutions for extending the service life of concrete structures.

Areas of Expertise Relevant for the Action	**Keywords**
● Civil engineering: Sustainable engineering, adaptation to long-term environmental changes ● Civil engineering: Construction engineering ● Materials engineering: Cement ● Materials engineering: Sustainable engineering ● Chemical engineering: Characterization methods of materials	● Methodologies for preventive repair of concrete ● Healing approaches for cement-based materials ● Durability performance of repaired structures ● Modelling crack healing and service life prediction ● Standards in characterization methods

Specific Objectives
To achieve the main objective described in this MoU, the following specific objectives shall be accomplished:

Research Coordination

● To produce an updated state-of-the-art for the three main pillars: 1) self-healing concrete and external healing-based repair methods, 2) characterization techniques for the performance assessment of the different strategies, 3) modelling the healing phenomena and service life prediction for structures after a preventive healing-based repair action.

● To coordinate, compare and bring together results of related research with the aim of defining optimized global methodologies to improve the performance of concrete structures when preventive repair actions are required, both for new constructions and in-service structures.

● To establish recommendations and guidelines suggesting the optimal healing-based preventive repair approach for different types of concrete structures and exposure conditions and identifying limitations and possibilities for each preventive repair solution, contrasting the point of view of a wide range of international researchers from the field participating in SARCOS Action.

● To propose agreed methodologies by comparing and bringing together experimental procedures and criteria for the evaluation of self-healing/repair ability.

● To coordinate the development of numerical models and in-situ monitoring tools for assessing and predicting the self-healing performance and service life extension associated with healing-based preventive repair technologies. This will allow overcoming the gap between models and real engineering applications, bringing together experimentalists and modellers.

<u>Capacity Building</u>

● To promote interdisciplinary work streams using the synergies between the participating groups for an efficient exchange of knowledge by taking advantage of the different COST tools.

● To contribute to human resources training in new technologies based on healing concept for concrete repair within an international framework, favouring the organization of Training Schools, Workshops and STSM to create an open network of knowledge and professionals with differentiated skills in the proposed advanced technologies.

● To promote the compliance with COST policies: involving ITC in network activities (meetings organization and application for STSM), assuring gender balance in tasks with responsibilities and promoting ECI participation as independent researchers (trainers in Training Schools, Lectures in Workshops, STSM).

● To increase the soundness and visibility of the Action’s outputs coordinating the dissemination activities through a specific Working Group: publishing joint scientific and technical articles, inviting industry to the Action’s workshops, assisting at Construction Forums, updating the website and organizing a show-room as final activity of the Action.

● To bridge networks with international bodies and associations, such as the European Materials Modelling Council, RILEM Committees and ICSHM (International Conference on Self-Healing Materials) conference participants dealing with the topic of self-healing and preventive repair, thus ensuring the visibility of the SARCOS Action in meetings and conferences.

● To connect at the national and international level (including H2020) with projects dealing with the topic, and to consolidate a strong consortium of research groups with complementary potential future research lines in order to increase the success rate in future proposals within the HORIZON 2020 framework.

DESCRIPTION OF THE COST ACTION

1. S&T EXCELLENCE

1.1. Challenge

1.1.1. Description of the Challenge (Main Aim)

The sustainable development of industrialized countries is a key priority, being mandatory the implementation of innovative solutions able to answer to highly demanding societies. Transversal challenges such as minimizing the consumption of natural resources and raw materials, improving and guaranteeing durability performance and optimizing efficiency must be addressed in the construction business. A new concept for repair in construction industry, based on the preventive treatment of incipient cracks, ranging from new constructions to the existing ones, is required for reaching such transversal challenges.

Self-healing of cement-based construction materials represents a valuable and cutting edge asset because of their inborn capacity to repair damages once they occur. External repair methods based on incorporating “healing promoter additives”, compatible with the existing cementitious substrate, are also innovative solutions beyond the know-how for the repair and rehabilitation of the existing building and infrastructures’ stock. These preventive repair solutions aim at extending the service life of structures and infrastructures while keeping their level of pristine performance.

A COST Action dealing with these new concepts and advanced solutions, from the design of smart “healing promoter additives” to the definition of standards for performance evaluation, will favour the development of a breakthrough scientific research. Furthermore, assessment of the durability of repaired concrete structures, development of monitoring techniques and implementation of environmentally friendly repair strategies, are critical aspects for strengthening Europe’s potential by incorporating excellence and innovation into the construction industry, which represents a significant share of the continent and world global gross domestic product (GDP).

To this purpose, the present Action will promote mobility among established researchers, junior scientists and students working on self-healing technologies for cement-based construction materials and on external treatments with healing ability due to the compatibility with the repaired substrate. Cross-fertilization between different disciplines and research streams will be created by taking advantage of COST Network tools: workshops, meetings, dissemination activities, participation in specialized conferences, and coordination of ongoing research collaboration projects. The Short Term Scientific Missions (STSMs) will be focused on a transversal exchange of knowledge between the different groups involved in this Action with complementary expertise in several aspects concerning the preventive repair of cementitious materials. This Network creates a consolidated interdisciplinary and international environment for the advanced training of PhD students and for the capacity building of Early Career Investigators (ECI), supported by a solid network of experienced researchers, within a highly challenging topic for the European construction industry, looking for enhancing the competitiveness and the stabilization of the new generation of researchers.

The progress obtained in the framework of this Action will generate new knowledge on the development of self-healing approaches and novel strategies for concrete repair, for both new and existing constructions. The Action will actively pursue and facilitate the definition and calibration of robust methodologies for the comparative assessment and quantification of the benefits yielded by different preventive repair techniques based on healing concept. This COST Action will promote the positioning of the European construction business as point of reference at worldwide level in implementing high quality and durable solutions within a sustainable and efficient development.

1.1.2. Relevance and timeliness

Construction industry deals with the huge volume of raw materials required for new constructions and with the increasing maintenance and repair costs of aged concrete structures; thus, looking for more efficient and durable solutions with lower costs has become a prioritized challenge. The relevance of this COST Network lays on the connection between high-quality research groups specialized in different aspects of self-healing construction materials and smart repair methods as promising alternatives for improving sustainability in the construction industry. A new concept for concrete repair based on innovative solutions to recover the durability performance is introduced, promoting the service life increase of concrete structures for both new and existing constructions. These solutions range from producing new advanced cementitious materials with self-healing ability to implementing non-destructive technologies with healing properties for repairing concrete structures already in service. Advanced methods for characterizing the performance of the repaired concretes will also be implemented, aiming at defining standard procedures for the comparative assessment of the different technologies investigated.

In this framework, the collaborative work of research groups dealing with preventive repair techniques based on self-healing functionalities, together with groups focusing on novel external repair solutions incorporating healing properties for existing structures, ensures an innovative global vision and a new concept of the durable and sustainable repair of concrete structures. Furthermore, the implementation of robust techniques for characterizing the self-healing capacity of the designed concretes and for evaluating the efficiency of the developed repair methodologies in extending the service life of concrete structures will have a great relevance to guarantee the successful incorporation of such promising solutions in the construction market.

The participation of the most well recognized research groups working on self-healing, combined with groups with an outstanding knowledge of concrete durability, ensures the timeliness of this Action. Furthermore, specialists on modelling healing mechanisms together with specialists in developing numerical approaches for service life prediction are also actively involved in the Action, thus adapting the findings of this Action to the digital European future as introduced by the European Materials Modelling Council. Although the topic is in an early-development stage, there is enough experience to bring together the different approaches for preventive repair, homogenizing criteria and defining new methods and research lines. This Action will contribute to a shared vision and effort to positioning Europe as world-leader in implementing new concepts and innovative solutions in such a strategic economic sector as the construction industry.

The composition of the Network, including groups with synergic expertise and dealing with complementary objectives and challenges, increases the possibilities for the Action's success and spans its impact over several streams of work, contributing to extend lifetime of concrete structures and to improve their durability and long-term performance. To establish a unique framework with the whole spectrum of technologies available nowadays for the early repair of concrete structures is an exceptional opportunity to advance in their efficient implementation, based on performance criteria and/or new functionalities, identifying the optimum scenario for each solution, self -healing and/or external repair at incipient stages of deterioration.

1.2. Specific Objectives

1.2.1. Research Coordination Objectives

The main objective of this Action is to favour international interest in developing a shared understanding on healing-based preventive repair technologies for concrete structures. This will be carried out through the sharing of the technical and scientific skills of the different research teams of the network, as well as their existing facilities. The Research Coordination Objectives are:

- To produce and updated state-of-the-art for the three main pillars: 1) self-healing concrete and external healing-based repair methods, 2) characterization techniques for evaluating the healing ability of the different strategies, 3) modelling of the healing phenomena and prediction of service life for structures with self-healing abilities and/or after a preventive external repair action. This will include the applicability and state of development of each approach, settling the basis for further improvements and for their introduction in real constructions..

- To coordinate, compare and bring together results of related research with the aim of defining optimized global methodologies to improve the performance of concrete structures when preventive repair actions are required, both for new constructions and in-service structures.
- To establish recommendations and guidelines suggesting the optimal healing-based preventive repair approach for different types of concrete structures and exposure conditions and identifying limitations and possibilities for each preventive repair solution, contrasting the point of view of a wide range of international researcher from the field participating in the SARCOS Action.
- To proposed agreed methodologies by comparing and bringing together experimental procedures and criteria for the evaluation of self-healing/repair ability.
- To coordinate the development of numerical models and in-situ monitoring tools for assessing and predicting the self-healing performance and service life extension associated with healing-based preventive repair technologies. This will allow overcoming the gap between models and real engineering applications, bringing together experimentalists and modellers.

1.2.2. Capacity-building Objectives

The Action has two general capacity-building objectives: to deal with building critical mass through the training of highly-skilled professionals in the emerging topic of healing-based repair technologies, and to create bridges for approaching the developed solutions to the stakeholders. The following specific aspects will be tracked:

- To promote interdisciplinary work streams using the synergies between the participating groups for an efficient exchange of knowledge by taking advantage of the different COST tools.
- To contribute to human resources training in new technologies based on healing concept for concrete repair within an international framework, favouring the organization of Training Schools, Workshops and STSM to create an open network of knowledge and professionals with differentiated skills in the proposed advanced technologies.
- To promote the compliance with COST policies: involving ITC in network activities (meetings organization and application for STSM), assuring gender balance in tasks with responsibilities and promoting ECI participation as independent researchers (trainers in Training Schools, Lectures in Workshops, STSM).
- To increase the soundness and visibility of the Action’s outputs coordinating the dissemination activities through a specific Working Group: publishing joint scientific and technical articles, inviting industry to the Action’s workshops, assisting at Construction Forums, updating the website and organizing a show-room as final activity of the Action.
- To bridge networks with international bodies and associations, such as the European Materials Modelling Council, RILEM Committees and ICSHM (International Conference on Self-Healing Materials) conference participants dealing with the topic of self-healing and preventive repair, thus ensuring the visibility of the SARCOS Action in meetings and conferences.
- To connect at the national and international level (including H2020) with projects dealing with the topic, and to consolidate a strong consortium of research groups with complementary potential future research lines in order to increase the success rate in future proposals within the HORIZON 2020 framework.

1.3. Progress beyond the state-of-the-art and Innovation Potential

1.3.1. Description of the state-of-the-art

Different self-healing approaches and external preventive repair methods: Incorporating self-healing materials in concrete appears as a promising sustainable alternative for extending the service life of new structures, lowering maintenance costs and avoiding complicated repairs, by filling cracks at the earliest stage of damage and allowing the recovery of properties, whether physical or

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mechanical. There are two main approaches for self-healing in concrete: autogenous healing and autonomous healing. The first is a natural process, intrinsic to the properties of the material itself, mainly caused by the continuous hydration of cement and by the calcium carbonate precipitation. The second is an engineered process to improve the self-healing properties of a concrete element. There are different strategies for designing autonomous healing methods depending on the method for incorporating the self-healing properties or on the healing agent.

Introduction Method → / Healing agent nature ↓	Without encapsulation	Dispersed encapsulation	Localized encapsulation
Cement	Autogenous healing	Encapsulation of water by superabsorbent polymers or by porous fibres	
Chemical agent	Admixtures such as: crystalline admixtures	(Micro-) capsules, impregnated porous aggregates or fibres containing the chemical or bacterial solution	Porous networks, encapsulating vessels containing the chemical or bacterial solution
Biological agent	Bacteria		

The **autonomous healing** approaches to achieve a self-healing ability can improve autogeneous healing concrete ability and/or provide different healing properties. One of the main challenges of such technologies is to protect healing agents inside concrete and activate them only when required. With this purpose, several encapsulation techniques are still being developed, both for bacterial and for chemical solutions; but capsules have to survive during mixing and casting of concrete. Placing encapsulation vessels before pouring the concrete can partially avoid that problem, but they have to resist the concrete impact at the moment of pouring while must be activated by cracking (or other type of damages, like change of the pH in the vicinity of cracks). Also the use of biological agents (bacterial solutions) needs certain encapsulation in order to provide to the microorganisms the necessary space for their development and to protect them from the high alkalinity of the aqueous phase of concrete. Because of these difficulties, different research groups have studied the use of admixtures with designed activation (crystalline admixtures) and impregnated fibres or aggregates. These self-healing methods have also been applied as **surface treatments** for concrete structures in service, where the composition of existing concrete elements does not include the presence of healing agents. The autogenous self-healing ability of concrete has been reported for promoting the healing of cracks due to the precipitation of non-soluble products inside the crack. Applying colloidal nanosilica on the hardened concrete surface has shown to be able to penetrate through the pores to the concrete bulk, refining the porous skeleton of the original material due to the chemical interaction with the solid matrix and creating new calcium silicate hydrates, compatible with the existing substrate, that densify the cementitious matrix. Recently, the application of self-healing functionalities has been proposed for increasing the efficiency of sealing existing cracks.

Characterization techniques for evaluating structures' health and healing effectiveness: Currently, there is **no standard methodology** to evaluate the self-healing capacity of a cementitious material. Each research group uses its own test methods to evaluate the healing efficiency of the different approaches. These differences in methodology are further compounded with differences in materials' composition, thus making it hard to establish sound and reliable comparisons between the reported studies. Therefore, a prior standardization step will be required in order to provide a common point of comparison.

Both the healing ability of the preventive repair methods and the associated performance regain must be characterized for the effective incorporation of such repair solutions in real concrete structures. The healing ability has been characterized by analysing the products of the healing reactions and their interaction with the cementitious matrix, studying both the physical properties and the chemical composition of the repair products. This knowledge is related to how they protect the structure and, thus, to the performance enhancement that they provide, either durability - or mechanical-related. The main tests available in the literature for evaluating the performance enhancement of a concrete structure due to the healing processes can be divided in two groups: 1) durability-related tests, focusing on the measurement of crack closure, on the evaluation of the permeability of cracked specimens and on the porosity changes, 2) mechanical-related tests which usually compare the capacity of load recovery or the recovery of stiffness. The highest interest for novel developments in characterization is related to the application of indirect or non-destructive measurements for measuring different properties and to the development of sensors for the continuous monitoring of such properties. The challenge of such innovative alternatives will be also analysed for the purpose of this Action.

Modelling of self-healing and prediction of the increase in service life: Modelling of self-healing mechanisms will contribute to a deeper, faster and cheaper development of concepts. Calcium carbonate precipitation within small cracks can be described and replicated computationally through a set of diffusion-reaction equations coupled through a mass balance argument. The effect of capsule distribution on the release of agents has been addressed from a physicochemical perspective for a moisture-absorbing matrix. Cracking/damaged behaviour of concrete can be modelled by mechanical-physical-chemical models adopting the reaction degree as the main variable for simulating aging of concrete. The mechanical properties of healing products and prediction of the autogeneous healing efficiency of concrete can be simulated by developing macroscopic hydro-chemo-mechanical models considering a self-healing mechanism coupling hydration products with the evolution of a continuous damage variable. The use of cohesive finite elements allows modelling the mechanical recovery due to self-healing processes, and the microscale healing phenomena can be linked to continuum models via Representative Volume Elements (RVS/SVE).

Finally, **life-cycle analysis** of concrete structures is included in standards, such as the Model Code. Life cycle models predict deterioration and service life of structures and can be seen as an optimization problem, which can seek for minimizing costs or environmental impacts, maximizing the service life of a structure, or finding a compromise point with benefit for most factors.

1.3.2. Progress beyond the state-of-the-art

The Network will work on surpassing the limitations of the three main topics of this Action focusing on: comparing the self-healing and non-invasive external repair approaches, assessing methodologies for standardizing the evaluation of healing efficiency, and implementing coupled models representing the whole phenomena and allowing to predict the increase in service life; all of them being in the frontiers of the knowledge. In fact, the latter will need results from the two first topics in order to calibrate and verify the models, and the modelling results feedback will be used to define the standardized characterization techniques. Discussions between researchers working with the same objective, which involves a better comprehension and application of preventive repair techniques, will strengthen the knowledge and understanding of the topic. This will be enhanced by the expected synergies between the three main views.

First, the complementary application of an external repair/healing action to control an incipient damage and a preventive repair based on a self-healing approach in order to reach the best solution for different scenarios involves a development beyond the state-of-the art. The Action will work on achieving a better knowledge of the available self-healing/repair methods, including their optimal application and/or their practical limits for an effective application in the construction industry. This will pave the way to new designs and improvements for increasing the recovery of properties or the efficiency of the healing/repair methods.

Second, the definition of common criteria regarding self-healing of new structures and compatible healing of existing structures will be considered as an indicator of the COST Action success, associated to the clear progress beyond the current knowledge of these innovative preventive repair solutions. At this moment, there are almost as many methods as laboratories working on this topic. Thus, an analysis of their advantages, disadvantages and optimal applications will lead to the establishment of common standard methodologies, or at least will settle the basis for the creation of guides; for the achievement of this goal it is proposed a Round Robin Test campaign (RRT). This aspect is essential to achieve a proper comparison between self-healing and preventive external repair approaches and an effective evaluation for future constructions.
At last, the use of standardized monitoring and characterizing methods together with the calibrated models of healing, performance and service life of concrete is one of the main challenges to be tackled. Much work needs to be done to couple mechanical (and micro-mechanical) fracture models with the breaching of microcapsules and transport of reactive throughout the matrix and the crack. This includes scale linking (e.g. via RVE) and bridging of methods limitations. Likewise, the calibration of the proposed models is of the utmost importance in order to tackle aspects such as the "crack opening limit", the maximum healing capacity of the material and durability-based design approaches. This COST Action presents an excellent opportunity to overcome the gap between models and real engineering applications by bringing together experimentalists and modellers on one platform.

1.3.3. Innovation in tackling the challenge

The innovation of this COST Action lays on different aspects of the proposal:

- The cross-disciplinary concept of the project, with three main parts (experimental development of advanced approaches, characterization and modelling of such developments), is an innovative way to incorporate all the steps involved in the design of self -healing materials and structures, which is required to achieve their effective penetration into the construction market.
- The global vision of the preventive repair, not only for new constructions with self-healing capacity but also considering the repair of existing constructions with an incipient damage, by external repair techniques based on healing properties (which could even include the self-healing concept), is a clear innovation in tackling the challenge.
- To tailor and to adapt specifically designed "healing promoting additives" for concrete attending to the specificities of its chemistry, local environment and type of construction is a novel approach in this topic, which will promote real applications in the short-term.
- The implementation of standardized testing procedures among the different research groups will allow the quantification of the repair efficiency, durability and performance, answering one of the current limitations for the application of these technologies as competitive alternatives.
- The monitoring and computational modelling of the phenomenon will allow forecasting the recovery of properties, helping to introduce the studied methodologies into sound design approaches and strengthening Europe's competitiveness in implementing this cutting edge field for construction industry as also introduced by the European Materials Modelling Council.
- The exchange of researchers and expertise between laboratories in a relatively new topic would pave the way to build up a common framework for pursuing more effectively further research, from which also the "marketability" of the ideas and results will be benefited.
- To promote the generation of high-level professionals to guarantee the success in implementing such innovative solutions in European and worldwide construction business.

1.4. Added value of networking

1.4.1. In relation to the Challenge

The added value of networking in this COST Action mainly lays in the expertise exchange between the most recognized international research groups working in the topic. The discussion at international level between worldwide leading groups will cover a wide range of approaches, methodologies and applications, ensuring the objective of creating guidelines and recommendations for real applications. The transversal network, involving different types of countries and research groups with well-differentiated expertise in the several areas of engineering, will be a pillar to guarantee the high quality and the impact of the Action's results.

The broad number of participating institutions guarantees a multifold perspective on the topic. The perspectives and the expectations from construction industry partners will be continuously checked, and they will be invited to join during the development of the Action. The consortium as a whole will benefit from good relations that each partner has with prominent multinational construction companies and material producers, which represent an added value to the Action.

The concept of identification and evaluation of the optimal preventive repair approach, ranging from several self-healing solutions for new constructions and smart repair methods for existing constructions, involves a significant benefit of networking. In order to face these challenges, the implementation and consolidation of robust methodologies is required for quantifying the repair ability. In this sense, strong networking tools are needed to include and to compare the different methodologies, with the final purpose of standardization and prediction of the service life increase for the repaired concrete structures. The modelling part paves the way for integration of Materials Modelling in Business Decision Processes to enhance effective industrial decision-making and thus increasing the competitiveness of the European industry.

Finally, the most important value of the Network will be the coordinated work and sharing of ideas, data, test results, case studies and experience in order to create synergies for achieving a more effective and quicker introduction of the developed technologies and methods into the industry. These aspects will be also promoted by conducting a Round Robin Test campaign.

To this purpose, the Action will use the following COST instruments:

- Internal Meetings of the Management Committee and the Working Group leaders.
- Workshops for knowledge exchange, promoting participation of PhD students and ECIs.
- Final Show-Room meeting with invitation of the industry and stakeholders for approaching the different developments to potential end-users.
- STSM and Training Schools, focusing on the scientific career development of ECI participants and on the students exchange between the participating groups.
- Dissemination of knowledge by joint publications in scientific journals, using an own website and promoting social networks.
- Preparation of a manuscript summarizing recommended laboratory practices and evaluation of their "pros and cons", drafting of recommendations and guidelines, and dissemination to the scientific community as well as the interested stakeholders.

1.4.2. In relation to existing efforts at European and/or international level

The efforts at European and international level mainly focus on specific aspects of the topic of this Action, such as self-healing approaches and development of monitoring and characterization techniques. This COST Action does not overlap with those projects but is complementary in many aspects. Some of the complementary running projects and networks at international level are:

- HEALCON: Self-healing concrete to create durable and sustainable concrete structures (NMP 2012.2.1-3 – Self-healing materials for prolonged lifetime).
- RILEM Technical Committee 253-MCI (Microorganisms - Cementitious Materials Interactions).
- fib Task Groups, T8.3 Operational document to support Service Life Design, and T8.4 Life cycle cost (LCC) - Design life and/or replacement cycle.

- COST-TUD1404 Towards the next generation of standards for service life of cement -based materials and structures.
  CAPDESIGN: Encapsulation of polymeric healing agents in self-healing concrete: capsule design (supported by the EU funded network M-era.Net).

2. IMPACT

2.1. Expected Impact

2.1.1. Short-term and long-term scientific, technological, and/or socioeconomic impacts

Self-healing capacity is one of the features that smart advanced materials can possess. The HORIZON 2020 Research and Innovation Programme includes the development of materials with advanced functionalities as a priority within NMP challenge, which indicates the importance of this topic for Europe.

The **scientific impact** is expected to be of a great importance at short and long term, as only for the network of proposers (from the beginning of the Action), 16 different scientific centres from 10 countries are supporting the proposal. Since self-healing is a hot topic in materials science, the amount of research centres involved is expected to increase significantly during the running of the Action, reaching more than 70-80 participants. It will be relatively easy for the whole network of researchers to publish in total around 10 scientific and technical papers and 15 conference papers per year about the challenges tackled in this Action, thanks to the parallel funding of each centre and the synergic collaborations that will be guaranteed within this Action. The training of PhD students in this topic will be encouraged in the different research centres participating in the Action, and thus around 10 doctoral theses can be expected during the development of the Action, some of them in collaboration between different groups thanks to the Short Term Training Missions. These activities will help to consolidate a consortium of research groups for future collaborations.

The main **technological impacts** are related to the advance beyond the frontiers of knowledge in the construction field, looking for a high-level profile for the construction business. At short-term, the organization of a Round Robin Test campaign (see 3.1) will imply a high impact for the wide range of laboratories and companies involved, as they will need to prepare the facilities for dealing with self-healing methods/tests. This also will set the foundation for a more efficient introduction of the techniques in the construction industry, and for more ambitious projects such as full-scale tests and prototypes development. At long-term, these aspects will provide new market opportunities improving the participants' competitiveness by incorporating advanced repair technologies to give an answer to the market demand. This will promote concrete as a smart material of high added value due to a proper introduction of these new properties in concrete structures.

From the **sustainability** point of view, self-healing concretes and preventive repair of structures will grant an arrest or at least slow down the development of cracks, even achieving in the best cases a decrease in crack width with associated benefits for the structures. These approaches are also associated to the optimal application of different repair technologies, involving environmentally friendly technologies, and to the minimization of the use of raw materials and of the worker's risk associated to traditional repair operations, which will benefit at long-term. The new functionalities included in these advanced cement based materials and the higher performance, associated to the developed methodologies, are expected to delay the ageing of concrete structures built with these materials, thus leading not only to higher service life but also to better performance in more aggressive environments and under more demanding conditions.

Regarding the **socioeconomic impact**, this novel concept of preventive repair will lead to a significant enhancement of the durability and performance of future concrete structures, avoiding additional monetary cost due to the cease of service during traditional maintenance and repair operations, positioning of Europe as the reference point at worldwide level in this economic sector. The self-healing approaches, in general, are not yet really introduced in the construction market; however, the interest of the industry in healing properties of construction materials is increasing. Thus, a new and promising market of products appears with a clear benefit for all involved stakeholders, from the producers of admixtures and cements to the end users. The quantitative and practice-oriented vision of the network, looking for realistic methodologies able to give a reliable guarantee of the efficiency and performance of these innovative repair solutions, is focused to ensure the applicability of the results for cement-based constructions and their incorporation into the construction market in the medium term.

2.2. Measures to Maximise Impact

2.2.1. Plan for involving the most relevant stakeholders

Companies related to the construction industry have already shown interest in the development of this new type of preventive repair approaches, since their long-term performance is guaranteed. This interest is present in construction companies as well as government agencies, but also for chemical and biochemical manufacturers. The favourable behaviour of self-healing materials for long-term and for special conditions, such as deep-sea constructions, offshore platforms, heat- storage facilities, etc. can economize some complicated projects, benefiting all the involved parts. In a similar way, the repair of existing constructions by using high performance and sustainable methods based on healing concepts is of a high interest for these companies.

This Action will work on the establishment of guidelines that could be preliminary or first standards for the topic and it will settle the basis for the identification and verification of the healing effects. This objective will be enriched with an involvement of the relevant stakeholders in order to investigate new approaches or techniques. Relevant stakeholders will be invited to the activities of the Action in order to create synergies between the research and commercial parts of the topic.

In fact, the final activity for this Action is a show-room, involving researchers from the Network and relevant stakeholders (such as producers of additives and cements, concrete manufacturers, end users, industry and public administration), in order to disseminate the most practical aspects reached within the COST Action and to facilitate the application of the preventive repair approaches into real applications, both for new and existing constructions.

2.2.2. Dissemination and/or Exploitation Plan

The measures and strategy to ensure the dissemination of results beyond the network, during the lifetime of the Action but also afterwards, are:

- To prepare publicity and news for the general public, construction companies, public administration, etc. in order to grant easily understandable information but of high quality.
- To publish joint articles in high-quality scientific journals and technical magazines.
- To manage the knowledge and intellectual property through creation of patents and transfer of technology to industrial users and even encouraging the participating groups to get involved in the creation of spin-off companies.
- To create a project website with updated information of the progresses of each WG.
- To use the results as starting points for further research about self-healing materials and sustainable preventive repair technologies.
- To guide the construction industry towards the beneficial performance as well as to solve potential risks in the case of inaccurate execution of construction work of these types of advanced materials and technologies by drafting recommendations and guidelines.
- To elaborate deliverables which represent recommendations that can be preliminary codes both, surface-applied repairs and self-healing materials in new constructions.

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- To evaluate the healing effect in real applications and to define cases of high interest for application, depending on the relation between the risks, the potential damage expected and the advantages given by the type of construction.
- To interact with the European Materials Modelling Council to foster digital engineering and to extend collaboration with software owners, multi-scale modellers and end-users.
- To create a catalogue of potential applications in order to facilitate the dissemination of results and to quantify economically the favourable effects for each case.
- To participate in competitive calls of HORIZON 2020 to consolidate the Network joint work by reaching the economic support needed for the experimental and scientific advances.

2.3. Potential for Innovation versus Risk Level

2.3.1. Potential for scientific, technological and/or socioeconomic innovation breakthroughs

Innovation always entails a certain risk; nevertheless, the concept of smart healing materials with significant added advantages has a high potential to overcome the risks mainly associated to currently high costs of these solutions involving expensive materials and novel developments. Moreover, self-healing cement-based materials are a promising field due to their potentially high consumption in the construction industry and to the ever more demanding challenges of this industry, even if a complete success is not achieved. The main potentials are focused on structures that require ensuring a certain performance, such as facilities working in severe operating environments. Also on structures demanding high levels of security of watertight, in which the higher cost will be compensated with the high quality concrete, this implicates that the introduction of this technology on the precast industry would be the first step.

The organization of a Round Robin Test campaign also implies certain level of risks, as it is necessary to guarantee the active participation of different laboratories. Nevertheless, the high interest on this topic and the involvement of related companies will facilitate the task.

Scientific innovation breakthroughs:

- Improvement of smart cement-based materials with ad hoc designed properties focused on high sustainability and service life extension.
- Enhancement and optimization of self-healing capabilities in cement-based materials.
- Smart active reparation of cement-based materials in new and/or existing structures.
- Better knowledge of the healing phenomena in cement-based materials, allowing the description and prediction of the involved processes.
- Enabling and improving predictive modelling on a level with industrial impact.

Technological innovation breakthroughs:

- Improvement of the decision process about the optimal preventive repair approach for
- Different situations, working on both new and existing concrete structures.
- Reduction of risky repair actions that could put in danger construction workers or that could need difficult and expensive techniques.
- Increase of the performance of structures due to the active healing of small damages.

Socioeconomic innovation breakthroughs:

- Reduction of reparation and maintenance costs and time, in its optimum extent even eliminating the need for repair and maintenance at all.
- Reduction of the ceases of service time due to reparation and related indirect costs.
- Increase of service life of structures and their sustainability.
- Increase of the perception of quality by the users of the structure.

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- Production of new professional profiles highly qualified, which answers to an increasingly demanding construction industry.

3. IMPLEMENTATION

3.1. Description of the Work Plan

3.1.1. Description of Working Groups

The Work Plan will be divided in three WG; a general summary of each WG is detailed below.

WG1: Self-healing concrete and external healing repair methods: this WG will compare and analyse the current state of the different approaches for the preventive repair of concrete structures, both in new and in existing constructions. The experimental development concerning the design of advanced "healing promoting additives" for concrete and the optimization of such technologies is also a challenge for this WG. Two main tasks are defined in this WG, depending on the type of treatment carried out:

Task 1.1. Self-healing concrete for new constructions. This task includes all approaches to achieve self-healing concrete. In order to consolidate the effort of the research groups working on similar mechanisms the task will be divided in three subtasks according the type of agent.

- Subtask 1.1.1. Autogenous and non-encapsulated autonomous self-healing concrete, based on the enhancement of autogenous healing by the use of mineral additions, crystalline admixtures or by the inclusion of water reservoirs inside the concrete matrix.
- Subtask 1.1.2. Encapsulation and activation of the self -healing reactions by developing and improving the use of micro- and macro- capsules in concrete and repair mortars.
- Subtask 1.1.3. Self-healing bio-concrete dealing with the selection and protection of the microorganisms to guarantee their life and metabolic activity inside concrete.

Task 1.2. External healing repair methods for existing constructions. This task will focus on the set-up of non-invasive treatments for the preventive repair of concrete structures, including strengthening and repair of topping layers. Different solutions based on the incorporation of nanoparticles compatible with the cementitious hardened substrate and/or the penetration of additives with self-healing functionality to seal cracks in hardened concrete will be evaluated.

Milestones (M) and deliverables (D):

- M1-1: Analysis of the current state of the different methods considered (M1 – M6).
- M1-2: Enhancement of the efficiency of the studied preventive repair technologies, considering also the optimization with hybrid solutions (M7 - M24).
- D1-1: Report with the current state of the art for the different technologies (M12).
- D1-2: Guidelines and recommendations for the different methods, including the identification of the optimal applying conditions of the evaluated approaches, even considering the implementation of hybrid solutions (M30).

WG2: Verification of the healing ability and assessment of the repair durability: implementation of robust and comparative characterization techniques. This WG will analyse and compare different characterization techniques to quantify the self-healing capability for new structures and the healing efficiency of external repair methods for aged concrete structures. Three main tasks are defined in this WG; two tasks dealing with evaluation of the different approaches and a specific task for the Round Robin Test campaign.

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Task 2.1. Techniques for characterizing the recovery of performance. Study of the mechanical and durability related properties of repaired concrete elements, comparing their behaviour before and after the healing/repair process.

- Subtask 2.1.1. Mechanical performance of concrete elements regarding the healing ability of the preventive repair actions considered.
- Subtask 2.1.2. Durability-related properties of concrete elements after the preventive repair, including the study of the effect of the different studied approaches on corrosion and diffusive properties on mass and reinforced concrete.

Task 2.2. Analysis of healing products and their properties. Study of the physical and chemical properties of the healing products, including their interaction with concrete matrix.

Task 2.3. Definition and conduction of a Round Robin Test campaign. A Round Robin Test will be carried out to verify the different characterization techniques and evaluation criteria on the preventive repair approaches defined in WG1. The outcome of this test campaign will be used as input for the recommendations and guidelines.

Milestones (M) and deliverables (D):

- M2-1: Definition of complementary techniques for a robust characterization of the healed concrete performance, regarding mechanical and durability related properties (M6 - M30).
- M2.2: Definition of characterization methods and the criteria for understanding the healing reactions (M6 - M30).
- M2.3: Analysis of Round Robin Test results (M30 - M48).
- D2.1: Report of the state-of-the-art in techniques, methods and criteria for evaluating crack healing in concrete (M12).
- D2.2: Guidelines for evaluating the healing effectiveness with reference to the recovery of different properties of concrete materials or structural elements, due to self-healing activity of concrete in new structures or to the repair ability of external methods, including the analysis of the Round Robin Test results (M48).

WG3: Modelling of crack healing and service life prediction: the general objective of this WG is to model and computationally simulate healing mechanisms and their impact on the mechanical properties of concrete. Furthermore, this WG will also evaluate the durability of new and existing concrete structures and the increase of service life due to these preventive actions. Two main tasks are defined in this WG. The first task will focus on the development and calibration of self-healing and repair models; the second task will focus on the estimation of the enhanced mechanical properties by structural integrity studies and on the evaluation of service life improvement due to the use of predictive transient approaches based on upscaling (also in time) and complementary experimental validation.

Task 3.1. Crack healing models. Study and development of the targeted models of healing of concrete structures starting from microscale physic-chemical models:

- Subtask 3.1.1. Modelling of cement hydration, calcium carbonate precipitation and other methods of crack healing by physico-chemical models linking chemical reaction modelling to transport and field equations.
- Subtask 3.1.2. Modelling of crack (initiation and) propagation, by use of Interfacial Transition Zone (ITZ) based fracture mechanics models and/or continuum damage models (RVE/SVE).

Task 3.2. Improvements of entire service life due to preventive repair actions. Development of methods to estimate the increase of service life due to the use of these smart materials either for self-healing new constructions or for repairing/improving fault tolerance of existing elements.

- Subtask 3.2.1. Modelling of strength and working performance, applying transient macroscopic and/or multi-scale hydro-mechanical-chemical models and extrapolation of modelling data.

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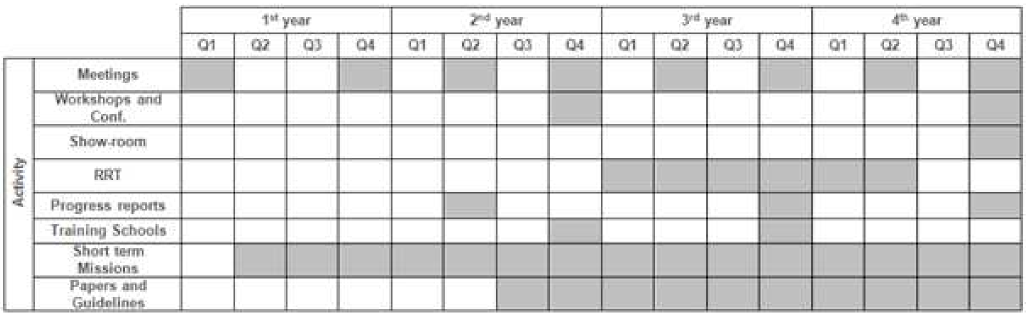
- Subtask 3.2.2. Computational evaluation of sample performance during self -healing cycles (screening) including empirical and statistical approaches.

Milestones and deliverables:

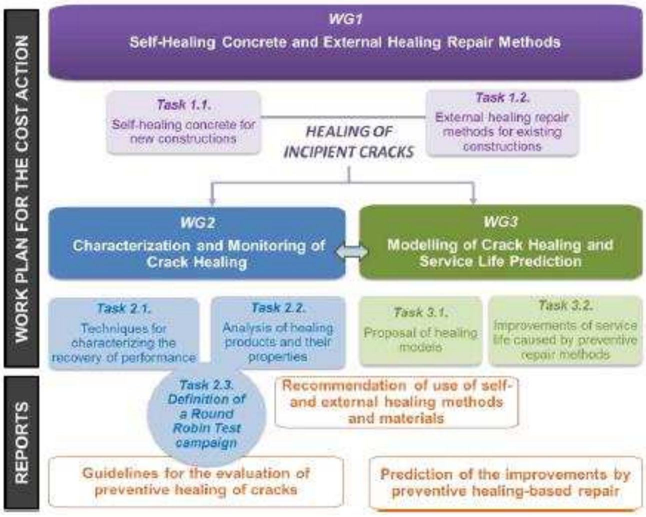
- M3-1: Definition of the targeted self-healing show case, primary linking to existing models and connecting available experimental data for calibration (M1 - M6).
- M3-2: Development of preventive repair models, and prediction of healing capacity via microscale physio-chemical approach (M7 - M26).
- M3-3: Extension and linking to meso-and macroscale via RVE/SVE elements, and prediction of healing capacity and related structural integrity (M18 - M36).
- M3-4: Optimization of self-healing systems for a defined task via computational simulation and design (M37 - M42)
- M3-5: Prediction of the service life enhancement due to the different strategies (M30 – M48).
- D3-1: Report summarizing the variables and models that can be validated with the experimental data delivered by the network (M12).
- D3-2: Report on the modelling performance/accuracy and guidelines to improve the healing performance as a function of the sealing mechanism (M48).
- D3-3: Modified service life prediction models (semi-empirical) including the self-healing abilities of new concretes and the healing properties of the external repair methods. (M48).

3.1.2. GANTT Diagram

The Action will run for 48 months. The MC meetings and Working Group meeting dates will take place twice a year promoting the rotation for the hosting location. WG will coincide (if possible) with workshops and MC meetings. In any case, the MC could modify the schedule for the meetings depending on the Action's advances. Progress Reports will be delivered at months 18, 36 and at the end of the Action. Working Groups will prepare the deliverables defined above and the documents that will form part of the annual progress report of the COST Action. One workshop and one final show-room inviting the different stakeholders related to the development of the action will be organized as final summarizing events. Training Schools will be organized at the end of the second and third year in the same hosting location as the corresponding meetings; the participation of Early Career Investigators will be promoted in these events. The period of time for the STSMs will be during the entire Action, except for the first quarter; the STSM will be mainly based on the exchange of PhD and postdoctorant students between the groups involved in each Working Group to promote the training of specialists with a more global knowledge of the different solutions for the preventive repair of concrete structures.



3.1.3. PERT



3.1.4. Risk and Contingency Plans

The main risks that will confront this Network are intrinsic to all the topics located at the frontiers of the knowledge. The main goal of this Action is not to ensure self-healing structures but to characterize the existing approaches, techniques and methods of characterization and numerical predictive models. Thus, the focus of the Action is the discussion, contrast and evaluation of these aspects. Even if some self-healing approaches are not sufficiently developed for the establishment of guidelines, some of them have enough maturity; in fact, autogenous healing is a phenomenon that has been known for years. This focus will minimize the risks of working on a new topic. Consequently, the concept of this COST Action is to identify trends for the self -healing/repair approaches and products in order to classify and typify them, but also to analyse the techniques for characterizing and evaluating the performance of the considered preventive repair solutions, and the numerical models for predicting the process' behaviour. This will allow the Network to create common criteria for quantifying the effectiveness of the different approaches.

The main risks for this Action are: 1) not achieving consensus for the techniques (that could be due to the differences between the preventive repair methods), 2) a lack of repeatability throughout the Round Robin Test for the self-healing/repair approaches that could difficult their evaluation and 3) the difficulty of trustworthily measuring the specific parameters needed for the numerical models with a minimized risk of systematic errors.

However, the expertise of the participating groups, equilibrated for the three main aspects considered in the Action, with common objectives, will facilitate to answer and manage the difficulties appearing during the Action development due to these inherent risks. Creating a well- balanced Network will favour the consensus towards the definition of guidelines and standards for evaluating the preventive repair methods. The expertise of the participating groups will guarantee to identify difficulties concerning the stability of the different approaches and how to face that from the point of view of the characterization and modelling. Concerning the risk related to the difficulty of measuring specific parameters, this is a great challenge in the topic, and any advance in this sense will be considered as a step towards achieving those goals in a close future.

3.2. Management structures and procedures

This Network's structure with a strong collaboration between the three WG's will help each group to accomplish the goals of each task and WG. The wide range of self-healing methodologies and smart external-repair treatments covered by this network, including the experimental methods to evaluate and models to predict the process, ensures the possibilities of a successful addition of new

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beneficiaries during the lifetime of the Action. All the different groups will have a strong collaboration with researchers from different WG in the definition of criteria to evaluate the healing properties achieved by each method. The presence of some members in two WG will be encouraged in order to ensure a proper transfer of knowledge. Specifically, the characterization and modelling Working Groups (WG2 and WG3) will have a strong collaboration with WG1. There is a strong need for feeding experimental data produced by WG1 into WG2 and especially into WG3 to calibrate the models and to re-define the experimental conditions to carry out the Round Robin Test. WG3 will guide the variables of interest for modelling and simulation that have to be tested by WG1 and WG2. WG4 will be coordinated with WG1, WG2 and WG3 in order to organize the dissemination activities and the relation with the stakeholders. The MC, Chair, Vice-chair and Grant Holder Institution will work to guarantee the success of the coordination of the Network. Each WG will have two leaders, who will be responsible for the coordination of their respective WG. A Core Group will then be formed, consisting of the MC, Chair, Vice-Chair and Working Groups leaders. Each Subtask will have members from at least three different research groups, ensuring effective discussion and evaluation of the results. This increases the possibilities of success for each task. Whenever possible, ECI will be encouraged to be part of responsibility tasks. Gender balance will be maintained in these responsibility positions.

3.3. Network as a whole

Proposers supporting this Action come from nine COST countries: Belgium (BE), Germany (DE), Italy (IT), Israel (IL), Netherlands (NL), Portugal (PT), Romania (RO), Spain (ES) and United Kingdom (UK), and one COST International Partner, Canada. Canada's participation will bring mutual benefits to COST countries, opening further markets for the developments outcoming within the Action, and to Canadian construction business, with strong demand of materials that can perform well in the severe exposure environments of Canada. The Network has a significant presence of COST Inclusiveness Target Countries (22%). The size of the Network is appropriate to promote the participation of each centre in WG and tasks according to its expertise and interest.

In this Network, several Early Career Investigators are involved, which is demonstrated by the presence of seven ECI and an ECI as main proposer. The gender balance is 48% males–52% females, and the Network will encourage the maintenance of this equilibrium from the opening of the Action, considering that the Civil Engineering field has traditionally less percentage of women.

This Action is supported by several research groups from different research centres with a common main profile, Civil Engineering represents 72% of the partners; nevertheless, complementary core expertise are also included (Materials, Chemical and Mechanical Engineering and Chemical Sciences), providing a highly equilibrated network able to successfully solve the challenges of the Action. In fact, the high number of proposers permits to include the wide range of techniques developed recently about self-healing and external healing-based repair methods. Some of the involved countries have also research programs concerning the topic of this Action, which demonstrates their interest.

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