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Integral Solutions for Sustainable Construction (IS2C)
A Structural Health Monitoring Program in The Netherlands

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ABSTRACT: In the early beginning of 2010, a comprehensive structural health monitoring program has been launched in The Netherlands with the title "Integral Solutions for Sustainable Construction" (IS2C). IS2C is a National STW[2] (www.stw.nl/programmas/is2c) and company (25%) program that aims to encourage new technologies and innovations on durability and service-life assessment for the building and construction sector in general and for the infrastructure sector in particular. With the IS2C program, it is the objective to generate advanced knowledge for the elements necessary to development a next generation "*predictive SImulation Model for service-LIFE assessment*" (SIMLIFE). These elements are the building blocks for the simulation model and should generate knowledge in the field of, key performance indicators, degradation mechanisms, monitoring degradation, material / structural performance, monitoring structural performance, and data management. The research projects are expected to be strongly integrated and cover at least two of the three following main research directions, i.e. Sensing & Monitoring, Degradation mechanisms and Materials & Structures and should address a level of research knowledge that goes beyond state of the art of these research directions. The IS2C program is aiming to enforce new innovations in the current state of the art of service-life assessment and to set a new standard for sustainable construction. Projects that were selected and currently run under the program address the following issues: 1) Integral chloride sensor development, 2) Chloride in cracked concrete, 3) Rapid Chloride Migration method, 4) Li-based ASR remediation, 5) ASR performance assessment tool development, 6) Durable repair materials, 7) Post casting systems, 8) Proof loading of aged concrete structures, and 9) Data Management. The paper will provide an overview of the state of the art of the IS2C program.

1 INTRODUCTION

Structural Health Monitoring for infrastructural assets as a research direction is getting more and more the attention of the international research society. The aging stock of concrete road and railway infrastructure in the western world is piling up to significant levels and threaten the reliability of our mobility and, with this, has huge impact on the growth of the western

[2] STW = Stichting Technische Wetenschappen resembles the Dutch National Science Foundation.

economies. The aging and associating deterioration of the building materials over its service life is a very moderate process of destruction that affects a structures' durability, integrity as well as the traffics' network reliability. The durability of traditional concrete structures using traditional materials is relatively well covered by existing codes and regulations. Properly designed and build structures are expected not have major durability problems during their overall life in service. Major financial risks ensuing from structures expressed in terms of maintenance requirements may be caused by improper construction, bad design or flaws in building codes as well as by (over) loading the structural capacity due to intensified traffic. Therefore, in terms of structural health monitoring and service-life assessment of concrete structures, the robustness of durability predictions is an issue that is of paramount importance.

With the structural health monitoring program developed in The Netherlands called "Integral Solutions for Sustainable Construction" (IS2C) it is the ambition to enforce a breakthrough in the urge to achieve a proactive prediction and monitoring system for a reliable assessment of the (remnant) technical service-life of railway and road infrastructure, and to quantify the associating repair and maintenance demands. With the IS2C program, it is the objective to develop a new vision and knowledge to define the elements necessary to development a next generation "predictive **SI**mulation **M**odel for service-**LIFE** assessment" (SIMLIFE). These elements are the building blocks for the simulation model and generate the knowledge in the field of, key performance indicators, degradation mechanisms, monitoring degradation, material / structural performance, monitoring structural performance, and data management. The program attracted projects that covered all the research issues addressed above and is now aiming at enforcing new cutting edge developments in the current state of the art of service-life assessment and to set a new standard for sustainable construction.

2 SETTING AND RELEVANCE

It is envisioned that the IS2C program contributes to the ambition of the Dutch infra-asset managers to develop new and innovative solutions that can be used to preserve the vital part of the national economy, *viz.* the national road and railway infrastructure. The Netherlands is dealing with a mature stock of bridges, tunnels and other infrastructural assets that were mainly built between in the past, between the 1960s and 1980s (about 30 to 40 years of age). For these assets significant maintenance is to be expected within the decades to come. Besides, these uncertainties, governments substantially started boosting their spending in infrastructure in order to stimulate the economic activities. Based on these facts, a situation has araised where durability, maintenance and (residual) service life assessment are key issues that should be addressed in view of achieving a sustainable society.

The owners of infrastructural assets always have to balance their maintenance decisions based upon financial and operation priorities. Owners lack knowledge about the relationship between the technical state of a structure expressed in terms of durability, and, the financial and operational consequences regarding the maintenance demand. This lack of knowledge is commencing from the state of the material in relation to the structural integrity, i.e. the technical service-life performance. So far, the actual knowledge of the material, expressed in terms of degradation, is considered the key information necessary for the asset owner to decide upon the maintenance priorities. Knowledge among the relation between the actual state of a structure and the repair requirements to keep the structure operational is, at this moment, not reliable enough to predict the financial consequences of structures reliably. It provides the clear demand for the need to generate more knowledge on these particular subjects which have also been the basis for the research issues addressed in this IS2C program.

With the introduction of the Design-Build-Finance-and-Maintenance (DBFM) contracts for large infrastructural assets, the government has the objective to shift key responsibilities with respect to the construction and maintenance progressively towards the private sector. As a consequence, consortia consisting of government, builders and investors are working together in Private, Public, Partnerships (PPP) and bearing long-term predefined maintenance responsibilities from 5 up to 25 years. Within the building and construction sector, this has let to a significant change in the situation that infrastructural assets are now judged more and more in terms of service-life assessment and less in terms of product specifications, i.e. from "functional design" toward "defined performance design". This has turned out to be the initiation of an enormous demand for innovation within the construction sector.

In order to encourage for new innovations in the area of interest, three main research directions were selected, i.e. Sensing & Monitoring, Degradation mechanisms and Materials & Structures, (see Fig. 1) that will come together in the IS2C program with the ambition to stimulate the development of innovative and integral solutions for sustainable construction in general and to generate new knowledge in the field of service-life assessment of infrastructural assets in particular. Emphasis is on the overlapping area of the three disciplines and on the interfaces between the individual disciplines. New innovations in these challenging research areas will directly contribute to the innovative level of the building and construction sector as well as to an improvement of the ability to manage our infrastructural assets in a sustainable way. Besides, it contributes to an efficient and sustainable use of construction materials and in relation to the design life of structures and its maintenance demand.

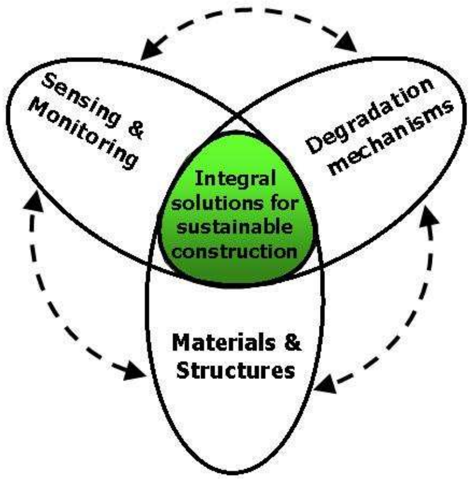

Figure 1. Schematic representation of the structural health monitoring program IS2C.

With the IS2C program, it is envisioned to fill-up the missing link in a long-list of already finished and many currently running activities in the field of service-life assessment and long term performance of infrastructure by introducing an integral approach. In view of the relation with public and other privately funded programs, many initiatives have been launched all with their own unique perspective, resulting in new information on targeted fields of interest. The main goal of the IS2C program is to generate new innovations and to link together the three dominant research fields in this arena, i.e. Monitoring & Sensing, Degradation Mechanisms, and Materials & Structures, and to accomplish an integrated approach that will play a central role in all running activities. The projects that were developed within the IS2C framework associate the same vision and cover a variety of research areas. An overview of these projects will be provided in a later section of this paper.

3 PROGRAM SETUP

The IS2C program was launched with the ambition to generate the elements necessary to development a next generation "*predictive SImulation Model for service-LIFE assessment*" (SIMLIFE), in view of sustainable construction. These elements should generate advanced knowledge in the field of six pre-selected research areas, covering key performance indicators, degradation mechanisms, monitoring degradation, material / structural performance, monitoring structural performance, and data management. With the setup addressed above, the program aims to generate knowledge by developing projects that cover all research issues addressed above. The research projects are expected to be strongly integrated and covered at least two of the three following main research directions of the IS2C program, i.e. Sensing & Monitoring, Degradation mechanisms and Materials & Structures and address a level of research knowledge that goes beyond state of the art.

As illustrated above, the IS2C program combines the efforts of experimental physicists, sensor developers, materials scientists and structural engineers in order to realize its ambitions. For each project running under this program, it is considered vital that numerical/theoretical analyses are combined with experimental characterizations and validations.

Focus

The focus of the three main research directions is:

- Sensing & Monitoring: Robustness and endurance of the sensor systems.
- Degradation Mechanisms: Chloride ingress and Alkali Silica Reaction.
- Materials & Structures: Concrete and/or composite structures.

Goal and main deliverables: Elements for SIMLIFE

The goal of the IS2C program is to generate new knowledge on service-life assessment that goes far beyond the methods and procedures that are currently used in the daily practice of the construction sector. The elements to be generated within the scope of the IS2C program are the necessary building blocks for the development of the next generation simulation model that is based on an overall vision on service-life assessment, and will overrule all currently available prediction models. In order to limit the scope of the IS2C program and to structure the projects that run under the IS2C umbrella, the dominant elements of the simulation model are pre-selected and are considered as the main research areas of this program. In total, six different research areas have been preselected addressing the research areas of the key elements. In short, these elements hold:

Key elements:

1 - Key Performance Indicators
2 - Degradation mechanisms
3 - Monitoring degradation
4 - Material / Structural performance
5 - Monitoring structural performance
6 - Data management

These key elements are considered to set the boarders of the framework of the IS2C program. In order to address the scope of these key elements a detailed description of the scope that indicates the focus of the key elements has been elaborated and comprises:

1 - Key Performance Indicators:
Determining the criteria at which degradation initiation occurs. Quantifying the state of durability at a moment of initiation and determine the reduction of performance in the propagation phase in relation to the design parameters. Nanotechnology and/or miniaturize sensor-based systems to measure the actual state of degradation in relation to the critical performance criteria are considered within this key element as well.

2 - Degradation mechanisms:
Determining the degradation mechanisms in cement based materials, limited to chloride ingress and alkali silica reaction (ASR). Determining the critical parameters and processes that activate stimulate and/or promote the deterioration of existing and or new types of (blended) cements and concrete. Associated effects induced by coupled factors such as (micro) cracking due to thermal, mechanical and/or imposed deformations are considered in this key element as well.

3 - Monitoring degradation (chemical / physical):
Determining monitoring systems for measuring the actual state of degradation by using advanced sensing technologies (RFID, MEMS, Lab-on-Chip), that can operate in a distributed sensor network, while requiring low power supply only. The monitored actual state of degradation provides feedback data from real structures to the SIMLIFE model.

4 - Material / Structural performance:
Determining the effect of degradation processes on the actual material properties and determine its effect on the residual performance of structures. These effects should be determined for both existing aged and newly build and/or repaired structures and include the effect of “hidden” bearing mechanisms and its effect on the service-life assessment. It accounts for tolerances and non-conformities during construction on the material properties and structural performance.

5 - Monitoring structural performance (mechanical):
Determining monitoring systems for measuring the actual performance of structures using advanced sensing technologies (MEMS, etc) that can operate in a distributed sensor network, requiring low power supply only. It includes for relationships between the internal effects of materials degradation and the external changes in structural performance. Providing the ability to generate feedback to the SIMLIFE model, and generate decision info for actual performance.

6 - Data management:
Determining system info for data management necessary to organize the input for the SIMLIFE model, i.e. input necessary to assess the service-life of structures based on the indicated degradation mechanisms, the materials and structural performance and including the feedback of data coming from monitoring / sensing of degradation mechanisms and structural performance. It includes effects of local spatial monitoring and global systems response. The system should account for the management of the expected large amounts of data generated by the monitoring systems and include decision making algorithms that can account for the effect of damage and/or deterioration of sensors and its consequences for the quality of the input data.

Towards a coherent portfolio of projects
With the IS2C program it is the ambition to create a coherent portfolio of projects that deliver the key elements of SIMLIFE and contribute to the overall IS2C objective. Consequently, projects should comply with the structure of the IS2C program (see Fig.1) and integrate in a way at least two of the three key elements addressed above. More schematically, projects are selected on a basis that they cover the issues as outlined in accordance with the scheme presented in Table 1. In this Table, a preferred selection of links between the main research directions and the key elements has been provided. The scheme indicates the basic structure of the integrated projects that run under the IS2C structural health monitoring plan.

Table 1: Preferred outline for a coherent project portfolio.

KE / MRD	Key Performance Indicators	Degradation Mechanisms	Monitoring Degradation	Materials / Structural Performance	Monitoring Structural Performanc	Data Management
Sensing & Monitoring	√	√	√		√	√
Degradation Mechanisms	√	√	√	√		√
Materials & Structures	√			√	√	

KE = Key Elements; MRD = Main Research Directions

4 PROJECTS SELECTED

In line with the STW procedures and after a thorough peer reviewing process, 9 projects (23 PhD positions) were selected that complied with the vision and structure of the IS2C program. In short, these projects comprise: 1) Integral chloride sensor development, 2) Chloride in cracked concrete, 3) Rapid Chloride Migration method, 4) Li-based ASR remediation, 5) ASR performance assessment tool development, 6) Durable repair materials, 7) Post casting systems, 8) Proof loading of aged concrete structures, and 9) Data Management. In this section brief summaries of these projects will be provided and the main research issues will be addressed.

1: An integral in-situ chloride sensing and monitoring system for concrete structures
In order to come to a reliable sensor for in-situ measurement of chloride concentrations a full integral approach is proposed where the sensor development, the chloride induced degradation mechanism and the materials performance are developed simultaneously by three PhDs. The first project will be on the development of a Cl sensor that can measure the actual chloride concentration directly from its in-situ condition in a porous network of cement-based materials. The second project puts emphasis on the various transport mechanisms of Cl in concrete and its relation to damage mechanisms. The third and last project is on the morphological changes of the microstructure and its consequences for the chloride measurements. In order to come up with a sensor with long term stability it is foreseen to make use a of sensor technologies such as employed by lab-on-a-chip systems.

2: Measuring, modelling and monitoring chloride ingress and corrosion initiation in cracked concrete
Chloride ingress and subsequent reinforcement corrosion determine for a large part the service life of concrete structures. Various factors are highly uncertain, however, so far, research has addressed chloride ingress models and test procedures that are available for concrete which is not loaded and not cracked. In practice, all concrete structures are loaded and cracked to a certain extent. In comparison with chloride diffusion, chloride transport through cracks happens very fast, potentially causing early corrosion of reinforcement. In practice, corrosion at cracks is considered less severe, however, the local conditions responsible for chloride corrosion are not well understood. Apparently counteracting factors exist that mitigate corrosion in cracks, possibly due to (self)healing and/or blocking of corrosion products. Presently there is no non-destructive measurement technique available for studying chloride transport in concrete. NMR promises to provide such a technique. Main influencing factors are only known qualitatively. Experimental work on micro and meso level will be done to elucidate the mechanism.

3: Chloride penetration in cracked and uncracked concrete structures (RCM method)
In recent years, there is a clear trend towards design for durability of concrete structures. This requires the development and subsequent introduction of performance criteria as a design tool for practice. For existing concrete structures, the chloride profiles obtained reflect the real exposure conditions prevailing during the preceding period. This information forms the basis for the quantification of key parameters (apparent surface concentration, diffusion coefficient and aging factor), featuring in models that describe combined moisture (in surface zone) and chloride transport. Evaluation of laboratory accelerated migration tests is eventually resulting in a straightforward test procedure. This includes a comparison between the migration coefficients determined on labcrete (potential quality) as opposed to the migration coefficient on realcrete (using iodide as migrating ion), while including the effect of cracks.

4: Modelling, non-destructive testing and Li-based remediation of deleterious Alkali-Silica Reaction in concrete structures

Alkali Silica Reaction (ASR) is a silent killer of concrete as it often becomes apparent only five to 15 or more years after placement, and is also often misdiagnosed. Left untreated, ASR can continue to cause further expansion and cracking, which negatively influences tensile strength and affecting its structural capacity. Secondly, ASR may render the affected concrete vulnerable to additional deterioration, such as increased penetration of chloride which causes corrosion of reinforcing steel, attack by freezing and thawing and sulphates. Hence, detection, prevention and mitigation of ASR is of critical concern when designing structures for long-term durability. This is the objective of this research project, covering the complete knowledge chain from fundamentals of degradation up to underpinned remediation methods.

5: Development of a Performance Assessment Tool for Alkali Silica Reaction (PATASR)
PATASR is proposed as a unique platform for engineers, where vital material, environment and structural parameters can be processed to review ASR related performance of a particular structure during its service life. The outcome provides a full-scale technical report as well as financial implications of the desired concrete design. PATASR is also proposed as a tool for inspection and rehabilitation projects of already ASR affected structures, where it could be possible to obtain realistic information on the remaining performance. An additional feature of the tool is that it acts as a database for aggregate, cement and environment profile information centre, which enables transfer of knowledge to the future projects and generations in a user-friendly platform.

6: Durable Repair and Radical Protection of Concrete Structures in View of Sustainable Construction
Areas with poor quality concrete are susceptible to penetration of hazardous substances, like CO2 and chloride ions, resulting in premature deterioration of the concrete and corrosion of the reinforcing steel. In areas where the concrete quality is really poor repair may be required. An ideal situation would be if manual repair can totally refrained by applying a robust cement-based self-healing coating. These two approaches will be considered in this project, i.e. firstly the development of durable and predictable concrete repair and, secondly, the development of cement-based self healing coating. The starting point for this study is the Engineered Cementitious Composite (ECC) with emphasis on the fundamental knowledge of the bond properties between ECC and the substrate interface. The acquired fundamental knowledge of bond properties will then be used as basis for the development of a cement-based self-healing coating. It will be investigated how the self-healing potential of ECC can be ensured in a robust way, even if the thickness of the ECC-based coating is not more than a few millimeters and can contribute to enhanced long-term performance of concrete structures.

7: Post-Casting effects on Concrete Durability

When considering the whole concrete execution process, the issues of packing and curing are considered to be of paramount importance. Packing of concrete directly affects the concrete quality from the interior and determines both the distance at which the aggregates are situated to each other and the volume of entrapped air. Vibration techniques are used to improve the concrete compaction and promote the release of the pockets of entrained air captured in the concrete during the casting. Curing techniques are basically applied to affect the concrete quality from the exterior using surface treatment agents. Emphasis of the current research project is on improving and optimizing the in- and external techniques to improve the quality and durability performance of in-situ concrete.

8: Smart proofloading of concrete structures

Proof loading of existing concrete structures is a method that is used to make sure that a structure can resist at least the legal load, prescribed by design codes. The method is applied if there are doubts on the bearing capacity of a structure, which is damaged by deterioration processes (ASR, Cl) or has been designed according to old design methods which are not in line anymore with modern load requirements. Especially in the USA proof loading is an option that is often chosen for situations that the details of a bridge (like type, amount and location of the reinforcement) are not accurately known. The project is on the questions with regard to the bearing capacity of bridges in Europe address the level of proof loading in relation to prevent irreversible damage and to ensure sufficient safety during proof loading.

9: InfraWatch: Data Management for Monitoring Infrastructural Performance

In terms of condition assessment of infrastructural assets, sensor systems are mounted to structures in order to monitor the environmental as well as the internal performance. Environmental conditions are related to the climatic changes in which the structure has to be operational, and, in terms of performance, the external and internal actions acting on the structure are to be recorded. Long and enduring 24/7 monitoring systems are necessary that generate large amounts of data that needs to be evaluated in a smart way such that relevant changes in the data will be noticed and that asset management systems will be informed and/or alarmed efficiently. Managing the huge amounts of data, extracted from the monitoring systems, requires integral knowledge in the field of data management. With the current research project it is the objective to design, develop and optimize a data management system for measuring and reporting the actual performance of large infrastructural projects.

5 CONCLUSIONS

The outline of the structural health monitoring project for infrastructural assets that currently runs in The Netherlands, called “Integral Solutions for Sustainable Construction” (IS2C), is addressed in this paper. An overview is provided about the setting and relevance of the program followed by a description of the program setup. Focus of the program is the integration of three main research directions, i.e. <u>Sensing & Monitoring</u>, <u>Degradation mechanisms</u> and <u>Materials & Structures</u>, and should generate new and cutting edge research results necessary for the six key elements being the building blocks for the SIMLIFE model. The model is considered to be able to generate technical knowledge to asset management systems regarding the long-term behaviour of the cementitious construction material.

The IS2C program is a National research program that was only possible with strong support of STW and the indispensible support the Dutch and companies. The program strengthens the ties between academia and industry and contributes to a durable and innovative construction sector.