REFURBISHMENT
CONCRETE CORROSION MONITORING SYSTEM

TO BUILD AND MAINTAIN SMARTER, MORE COST-EFFECTIVE, SAFER, AND MORE SUSTAINABLE STRUCTURES

DURAMON

BUILDING TRUST

INFRASTRUCTURE MANAGEMENT CHALLENGES

Sika has joined forces with DuraMon, an ETH Zurich spin-off company, specializing in robust and long-term stable, structural health and corrosion monitoring solutions for reinforced concrete structures. The innovative DuraMon monitoring solutions provide for early detection of corrosion and deterioration processes, enabling cost-efficient, resource-efficient, and safe maintenance strategies for many types of aggressively exposed infrastructure, including bridges, tunnels, and parking garages, etc.

Together, DuraMon and Sika are committed to advancing the field of structural health corrosion monitoring, revolutionizing maintenance strategies, and contributing to the sustainable develop-ment of infrastructure worldwide.

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"SIKA'S STRATEGIC PARTNERSHIP WITH DuraMon IS AN ALIGNMENT OF VISIONS: TOGETHER WE CAN SERVE OUR CUSTOMERS IN THE CONSTRUCTION INDUSTRY WITH A COMPREHENSIVE TECHNOLOGY THAT ENABLES SUSTAINABILITY VIA BOTH THE RATIONALE USE OF CONSTRUCTION MATERIALS AND THE PROPER MAINTENANCE OF INFRASTRUCTURES AND BUILDING STRUCTURES."

Philippe Jost,
Head of Construction and Member of Group Management

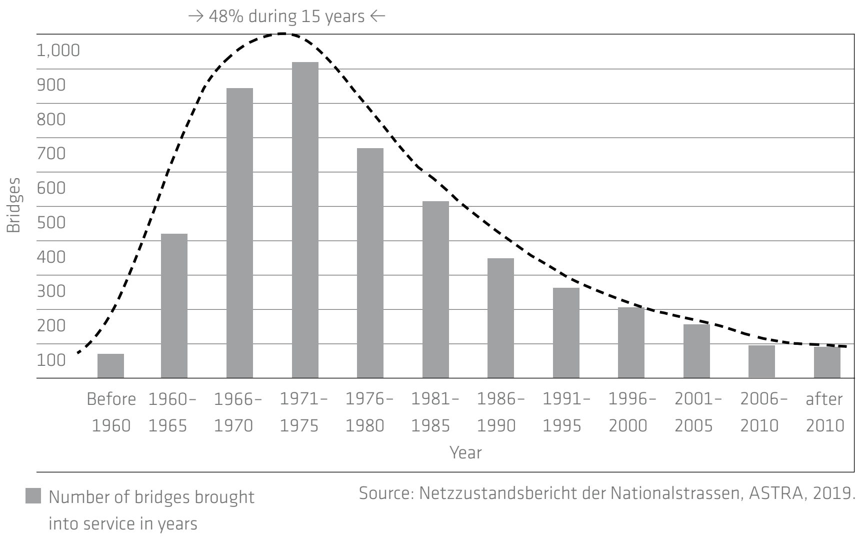
EFFICIENCY CHALLENGES IN INFRASTRUCTURE MANAGEMENT

DOES SOCIETY HAVE THE MEANS AND ENOUGH BUDGET TO PROPERLY MAINTAIN AND GUARANTEE THE SAFETY OF OUR INFRASTRUCTURE?

KEEPING STRUCTURES SAVE AND OPERATIONAL can be both difficult to achieve and expensive. The inherent lack of detailed information about the internal condition and integrity of structures, as well as the level and rate of the underlying damage mechanisms, or the long-term performance of effected repair measures, combine to make it difficult for owners to manage infrastructure maintenance efficiently.

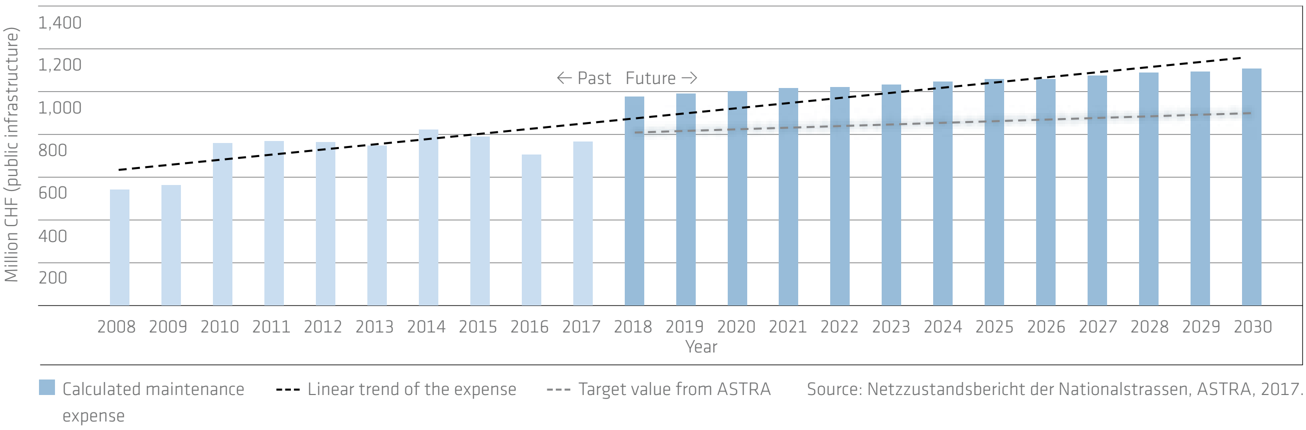
The number of structures reaching a critical age and operating beyond their designed service life is increasing markedly in industrialized countries. For example, the number of road bridges in Switzerland that are reaching their design service life of 50 years, will increase from 40 – 50% to 70 – 80% within the next 20 years [01]. Statistically and from experience, we know this means that the number of bridges in need of significant repair works, will also increase strongly in the coming decades. From the USA, we know that nationwide, road bridges found to be structurally deficient and in need of significant repairs, are 68 years old on average.[02]

YEAR OF CONSTRUCTION OF SWISS BRIDGES (Figure 1)



Source: Netzzustandsbericht der Nationalstrassen, ASTRA, 2019.

DEVELOPMENT OF THE REPAIR AND MAINTENANCE COSTS OF SWISS FEDERAL ROAD INFRASTRUCTURE (Figure 2)



Source: Netzzustandsbericht der Nationalstrassen, ASTRA, 2017.

Ageing reinforced concrete infrastructure leads to higher repair costs in the future, and with a rising tendency. The concrete infrastructure in Europe is markedly aged, and repairs already require more than 50% of the annual road construction budget today [0]. In Switzerland, these maintenance costs are expected to reach CHF 1.2 Billion in 2030 [0], and this is for the Swiss federal road infrastructure alone (i.e. excluding roads owned by the different cantons, cities, and private owners), which represents a 62% increase compared to the costs in 2016 (Figure 2).

CAN DEVELOPED COUNTRIES ADEQUATELY MAINTAIN THEIR AGING INFRASTRUCTURE WITH CURRENT MAINTENANCE STRATEGIES?

The condition of reinforced concrete structures, and the full extent of any damage, is often not visible on the concrete surface. Corrosion damage and structural deterioration can occur internally and be propagated to a large extent, before this is evidenced on the surface, such as with chloride induced pitting corrosion. Condition surveys and structural assessment methods try to identify these hidden issues at the time of inspection, though there is always a great deal of uncertainty. As a result, **preventive maintenance** strategies are widely applied, or even used overall on structures to try to ensure safety. Due to there always being limited budgets and/or available capacities in the construction sector, it is often not possible to accelerate the rate of repair to the level required to ensure continuous operation and safety of our infrastructure. Simultaneously, whilst the safety of our infrastructure must be ensured at all times, sometimes, keeping infrastructure operational can become the more critical requirement.

It is also essential to optimize the number of structures for repair and maintenance, as well as optimizing the cost-effectiveness and extent of the repair works. Thus, alternative approaches are being embraced, such as **predictive maintenance**, to reduce both direct and indirect repair costs (such as downtimes) while ensuring safe operation. Optimized life cycle planning with so-called predictive maintenance of reinforced concrete infrastructure, requires a repair and maintenance strategy that allows the anticipation of potential damage. The goal is to catch potential asset malfunction as early as possible to avoid the need for bigger and more disruptive repair works in the future. However, to achieve this, detailed **information and reliable data is needed, to allow reliable prediction of structural condition and the level of deterioration. This is something that only continuous structural health corrosion monitoring can provide (industry 4.0 approach)**.

At the same time, the efficiency of concrete repair measures is also a global concern: as up to 20% of these repairs are unsatisfactory after only 5 years, with up to 55% after 10 years, and 90% of concrete repairs being unsatisfactory after 25 years [0, 0]. One of the key questions is how to avoid repeated repair of the repairs. Monitoring the effectiveness of repair works in-situ allows the rapid gain of experience about the effectiveness of these repair methods and materials over time. This means that the optimum extent of future repair needs can be more accurately determined, and the most appropriate repair and protection methods can be selected for each case.

SIKA AND DuraMon PROVIDE A COMBINED SOLUTION

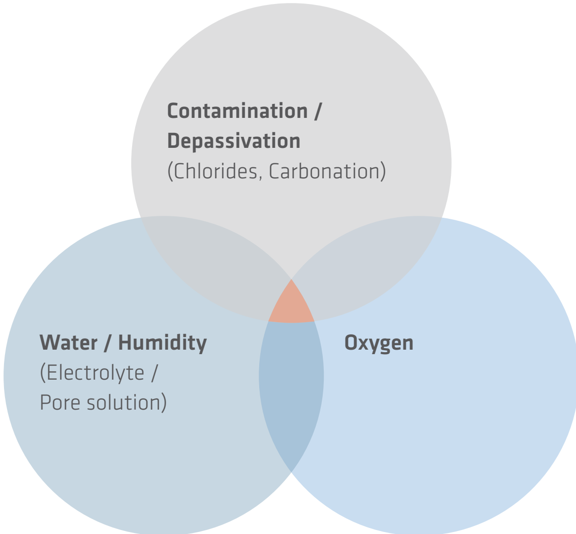
This solution allows a reliable condition assessment for the health of a structure, including root-cause diagnosis of damage with a prediction of future deterioration, enabling selection of the most appropriate repair and protection principle and methods for specific structures or elements. This allows downtimes to be minimized (e.g., optimized repair and maintenance schedules), using resources efficiently and sustainably, while extending the service life of the structure.

SIKA'S PORTFOLIO FOR CORROSION PROTECTION

To extend the service life of concrete structures

CORROSION OF THE STEEL REINFORCEMENT IS the most widespread degradation mechanism in reinforced concrete structures (>74%) [6]. This page shows how Sika approaches this problem and protects structures from further corrosion.

In the alkaline environment of a concrete matrix, the steel reinforcement is protected from corrosion by the formation of an oxide layer (passive film) on its surface. However, this passivity can be lost due to the presence of chlorides, or to a decrease in alkalinity of the pore liquid (e.g., pH lowered through carbonation). Once passivity is lost and in the presence of moisture and oxygen, corrosion processes can take place, leading to the loss of effective steel cross section, the loss of bond between steel and concrete, the development of expansive stresses promoting concrete cracking, and therefore to a decrease in structural safety.



To increase the service life of reinforced concrete structures suffering from corrosion, the simplest and most effective approach is act on at least one of the parameters mentioned above:

Reducing the moisture content at reinforcing steel level (Principle 2 & 8 of EN 1504-9):
Numerous studies have shown that, when moisture level is reduced significantly at the reinforcing steel level, the corrosion rate can be reduced to a negligible level. This overall reduction may even occur when active corrosion still takes place at a certain location due to the presence of chlorides. The reduction of moisture content may occur if liquid water ingress is prevented whilst the migration of water vapour is maintained [7]. The best system for this prevention approach, is usually the use of a hydrophobic impregnation/passive corrosion inhibitor, having an indirect effect on the corrosion by increasing the resistivity of the concrete. When applicable, this measure is highly attractive as it leads to a minimal invasive repair and increased sustainability (i.e., the removal and replacement of contaminated concrete is avoided).

Preventing the ingress of chlorides, CO_2, and moisture (Principle 1 of EN 1504-9):
Even if the concrete is partially or fully carbonated, and/or a certain amount of chlorides are present, hindering the ingress of water and further water-borne aggressive agents may eventually lead to a redistribution of chlorides, moisture, and other deleterious soluble elements, thereby reducing the corrosion propagation to a non-critical level. This can be achieved by using an appropriate protective concrete coating. When applicable, this measure is highly attractive as it leads to a minimal invasive repair and increased sustainability (i.e., the removal and replacement of contaminated concrete is avoided).

Delaying and/or reducing the ingress of chlorides and moisture (Principle 2 of EN 1504-9):
Delaying and/or reducing the ingress of moisture and any dissolved aggressive elements such as chlorides, also delays the onset and/or reduces the rate of corrosion, thus extending the service life of the structure. For this approach, the use of a highly concentrated silane-based hydrophobic impregnation, acting as passive inhibitor has proven to be the most efficient method [8].

In areas where active corrosion takes place, or it is about to start, strategies acting on and/or at the level of the steel reinforcement to keep and/or restore its passivity may be highly efficient. The main approaches to achieve this are:

Forming a passive film around the reinforcing steel bars (Principle 11, method 11.2 of EN 1504-9):
In carbonated concrete where the concrete quality and cover are generally low, the use of active corrosion inhibitors that penetrate to the surface of the reinforcing steel, is a cost-effective alternative solution to arrest corrosion, provided that the active ingredients reach the reinforcing steel surfaces.

Restoring passivity / removing chloride-contaminated concrete – repair mortars (Principle 7 of EN 1504-9):
Typical approaches are based on increasing the concrete cover depth by applying a new cement mortar over the existing concrete, or by replacing the existing contaminated (i.e., chloride-contaminated and/or carbonated) concrete. Ensuring a good bond of the new mortar / concrete onto the existing underlying concrete, and its resistance to corrosion initiation (e.g., resistance to carbonation and slow chloride transport processes), will be key parameters to achieve satisfactory long-term performance.

Cathodic Protection (Principle 10 of EN 1504-9):

In some cases, when the conditions are not met for the application of the previously mentioned approaches, or when corrosion is already too advanced, then a cathodic protection system, using galvanic or hybrid anodes, can be used as the remedial solu-tion or preventive measures.

The above alternative options are presented in an exhaustive form in an article published at the ALCONPAT (Latin America Association of Quality Control, Pathology and Construction Renovation) Journal (https://doi.org/10.21041/ra.v13i2.690).

SIKA'S PORTFOLIO FOR CORROSION PROTECTION

EXAMPLES (NON-EXHAUSTIVE) OF SIKA PRODUCTS:

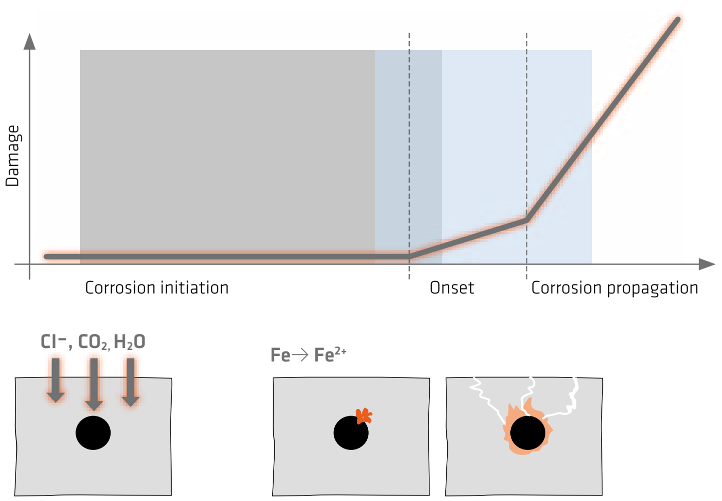
Sika products	Type of protective measure	Chemical basis / working principle	Advantages	Typical areas of use
Sikagard®-705 L/-706 Thixo	Reducing moisture and chloride ingress, – Hydrophobic impregnation/passive corrosion inhibitor	Concentrated silane	■ Deep penetration ■ Drying rate class I, allowing high transmission of vapour	Crown areas in tunnel portals, the splash & exposed areas of marine structures, etc.
Sikagard®-5500	Prevention of ingress of chlorides, CO_2, and moisture – Elastic, protective concrete coating	Acrylic resin based	■ Highly crack bridging ■ Maintains prevention of CO_2 ingress over long-term	Exposed concrete facades, parapets, & other surfaces, on reinforced concrete buildings & infrastructure, etc.
Sika® FerroGard®-903 Plus	Forming a continuous film around the reinforcing steel bars, – Active corrosion inhibitor	Amino-alcohol based	■ High active content ■ Deep penetrating ability	Carbonated concrete structures
Sika MonoTop®-4012	Restoring passivity – Increasing the concrete cover	Cement based mortar complying to EN 1504-3	■ High bond ■ High workability ■ Low carbon footprint	Increase of the cover depth needed as per principle 7 of EN 1504-10
Sika® FerroGard®-500's Patch	Cathodic protection – Range of galvanic anodes	Zinc anodes	■ Installed in the surrounding concrete, works independently of the repair mortar used to fill the patch	Mitigation of the incipient anode corrosion phenomenon in chloride contaminated structures by acting as sacrificial anodes instead of the surrounding rebars
Sika® FerroGard®-300's Duo	Cathodic protection – Hybrid anode (first phase with impressed current, followed by a second phase with galvanic current	Zinc anodes	■ Repassivation of the reinforcing steel during the impresased current phase. ■ Maintains the passivation by galvanic current	Cathodic Protection of sound but contaminated concrete structures with active corrosion.

DuraMon's UNIQUE MONITORING SOLUTION

A key element for more efficient infrastructure management

THE USE OF EMBEDDED SENSORS combined with data acquisition and transmission technologies offers new possibilities to reliably monitor the condition of concrete structures. By monitoring all corrosion-relevant parameters and evaluating the sensor's data, a complete picture of the structure's condition can be obtained, the risk of steel corrosion can be continuously monitored, and any onset can be detected at an early stage with its future prognosis. This allows for a better understanding and prediction of the underlying degradation mechanisms and optimization of repair strategies.

Commercially available sensors allow the measurement of a few parameters (e.g., temperature, steel potential, electrical resistivity, etc.). However, these parameters only provide information once corrosion has started, or it is about to start. To make reliable corrosion damage predictions long before any damage takes place, requires the additional measurement of the parameters that determine corrosion initiation (i.e., free chloride concentration, and pH). In addition, accurate corrosion diagnosis and prognosis (e.g., information on which parameters control the corrosion rate), requires the simultaneous measurement of all relevant parameters associated with corrosion (i.e., the pH, free chloride concentration, temperature, steel electrical potential, electrical resistivity of the concrete, and the corrosion current).



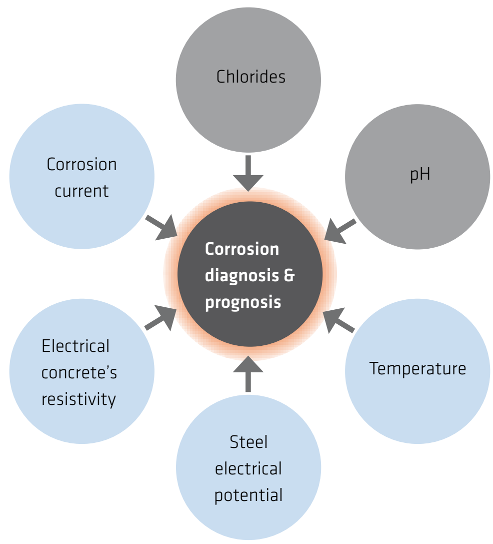


Figure 3. Reliable corrosion diagnosis and prognosis requires simultaneous monitoring of free chloride concentration, pH, temperature, steel electrical potential, concrete electrical resistivity, corrosion current.

DuraMon multisensors can be used in both new and existing structures, and thus allows monitoring of the existing (contaminated) concrete condition and performance, as well as the new repair mortars.

DuraMon IS CONTINUOUSLY DEVELOPING NOVEL SENSOR ARRANGEMENTS AND INSTALLATION METHODS FOR DIFFERENT TYPES OF STRUCTURES AND APPLICATIONS, TO ENSURE THAT CONSISTENT AND REPRESENTATIVE DATA IS OBTAINED FOR EACH STRUCTURE.

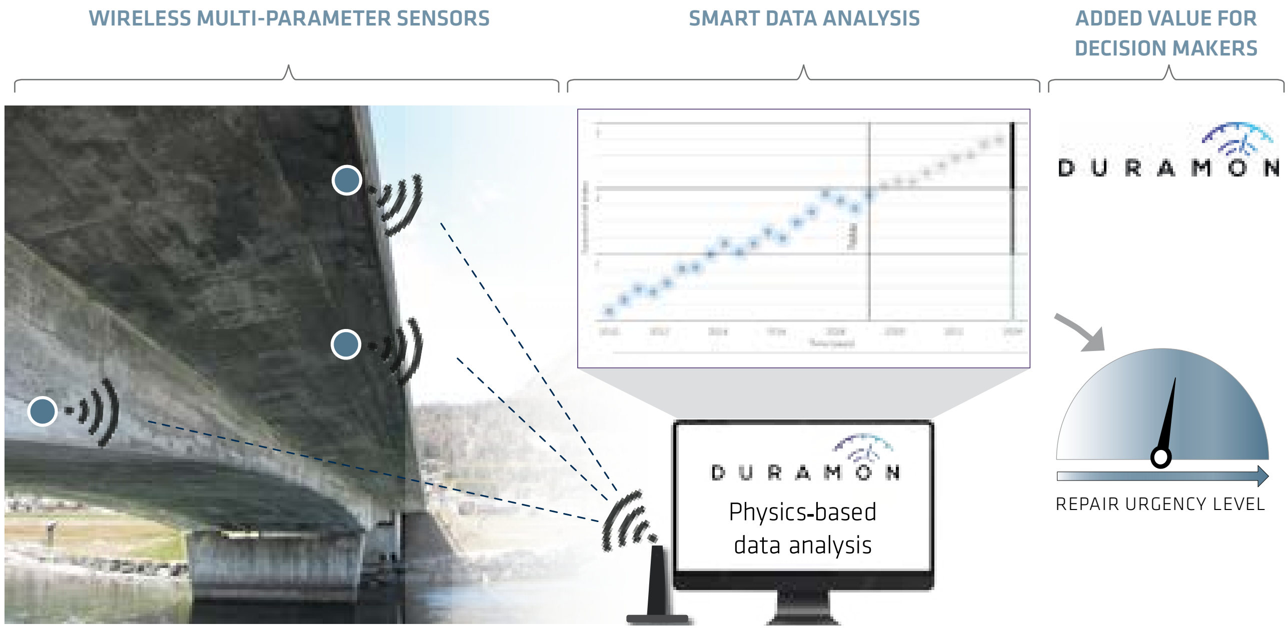


Figure 4. DuraMon's complete structural health corrosion monitoring solution

DuraMon provides embeddable, wireless, multi-parameter sensor nodes (multisensors) for use on concrete structures, which for the first time, can non-destructively monitor all relevant parameters associated with reinforcement corrosion in concrete, and at different depths, including: pH value, free chloride content, electrical resistance of the concrete, steel potential, corrosion current, temperature. DuraMon's sensor node includes several (i.e., typically between 10 and 20) individual miniature sensors (diameter <1.5 mm, length <20 mm) and a measuring unit, i.e., a data logger that measures the data from the individual sensors and transmits them wirelessly via Long Range (LoRa) technology.

The transmitted data is evaluated using "state-of-the-art" physical-chemical models that consider the interaction of all measured parameters, providing a structure's corrosion health indicators. On this basis, DuraMon provides a prognosis, which is an interpretation of the sensor measurements based on the latest scientific understanding, that allows prediction of the evolution of the potential deterioration. This includes a recommendation for further in-depth inspections and/or future repair requirements for the structure. Altogether, DuraMon provides the first standalone solution, combining novel sensors, data logger, data analysis services, and data interpretation services.

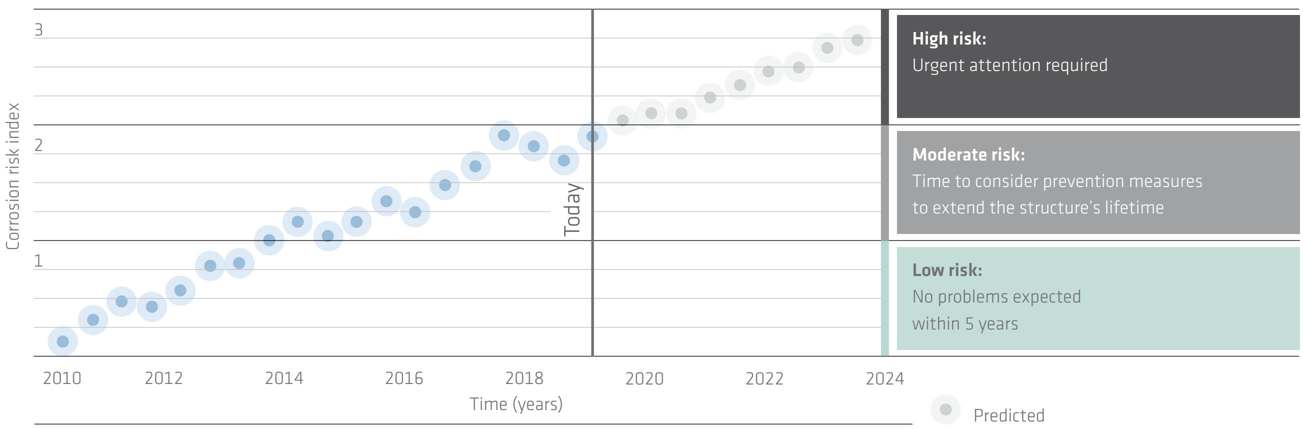
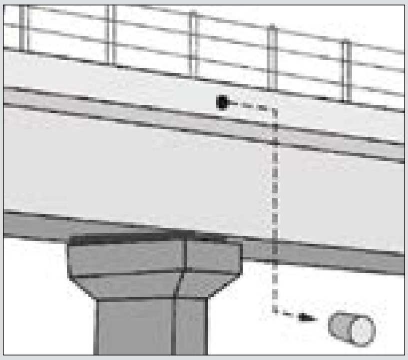


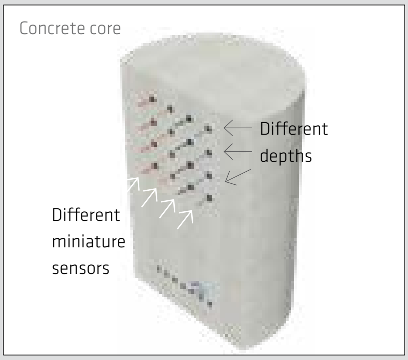
Figure 5. The risks from steel corrosion can be monitored constantly and predicted into the future thanks to DuraMon structural health corrosion monitoring solutions

INSTALLATION OF DuraMon MONITORING SOLUTION

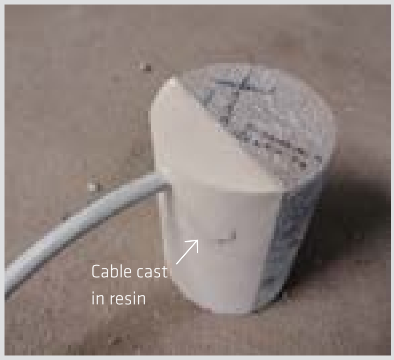
1 | **Concrete cores are taken and removed from the structure**



2 | **The concrete cores are fitted with DuraMon's Miniature sensors**



3 | **Cables are cast in epoxy resin**

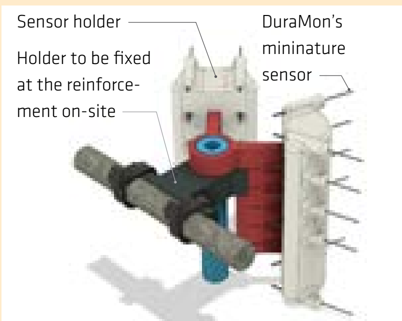


4 | **Concrete cores are replaced in their original locations in the structure and connected to the surrounding concrete with a filling mortar that ensures a good bond and rapid equilibrium with the existing concrete**

5 | **DuraMon's sensors are connected to DuraMon's data logger**

Figure 6. DuraMon multisensor installation in existing concrete using concrete cores fitted with DuraMon sensor system

Schematic representation of DuraMon's sensor system



1 | **DuraMon's Sensor System is fixed onto the steel reinforce-ment of the structure**

2 | **Concrete is poured and dis-tributed around DuraMon's sensor system**

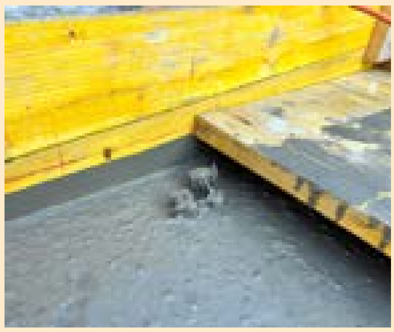


Figure 7. DuraMon multisensor installation for new concrete (also used in repair mortars and replacement concrete)

STRUCTURAL HEALTH CORROSION PROTECTION MONITORING

Sika-DuraMon's combined solution

SIKA AND DuraMon COMBINE TO PROVIDE REINFORCED CONCRETE STRUCTURES WITH A HEALTH MONITORING SYSTEM TO SAFELY AND EFFICIENTLY EXTEND THE SERVICE LIFE

EXPERIENCE SUGGESTS THAT CONCRETE REPAIR AND PROTECTION APPROACHES are not always fully effective, and/or structures can continue to deteriorate over time [3, 5]. The selection of appropriate repair strategies and materials, plus quality control during the application on-site, as well as inspection and monitoring during their anticipated service life, are all very important. However, it is not help-ful having to wait 10 years for example, to find out whether the repairs were successful and of good quality.

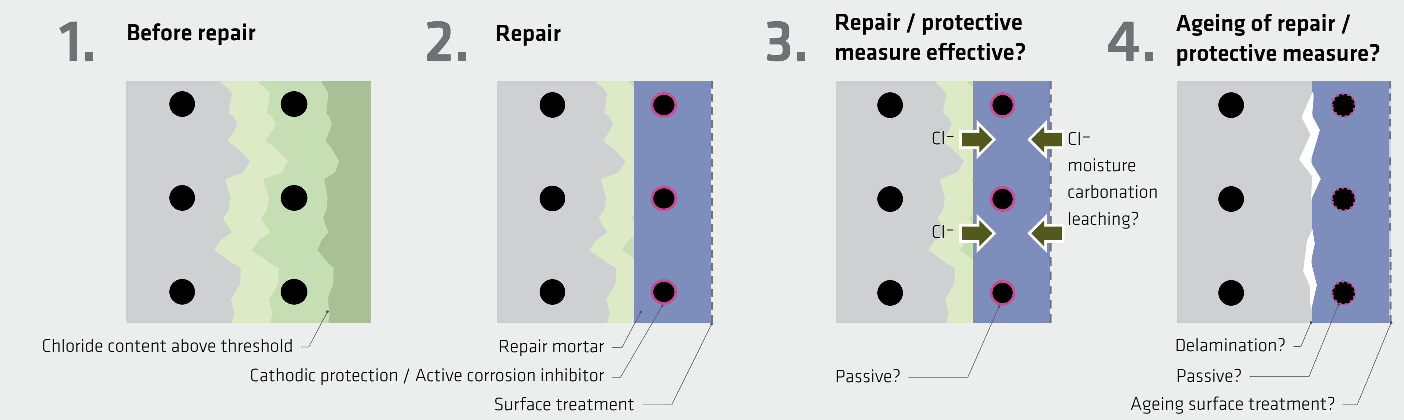
According to literature, the durability of correctly applied hydrophobic protective treatments have proven to be effective for at least 10 years and up to 20 years [9, 10, 11, 12].

Thus, information that allows refining the durability of such protective measures on-site, and in different locations, would help to significantly improve and optimize infrastructure management. For example, depending on the condition and exposure, in some areas of a structure, or on some structures, the hydrophobic treatment may need to be re-applied after 10 years, whilst in others, the maintenance interval might be extended, so that they only need to be carried out after 20 years, or even later.

In addition, the performance of any concrete repair or protection product, is only as good as its application on site. It is therefore also important to verify whether passivity has been restored, or that the further ingress of aggressive agents has been prevented in areas after the protective treatments have been applied.

Additionally, in concrete repair works, it is often difficult to be sure that the repair strategy select-ed and the protective treatments applied are the right solution for the requirements. To have information regarding the root cause(s) and underlying failure mechanism(s) is also a key for success, although this is currently missing for some structures.

STRUCTURAL HEALTH CORROSION PROTECTION MONITORING



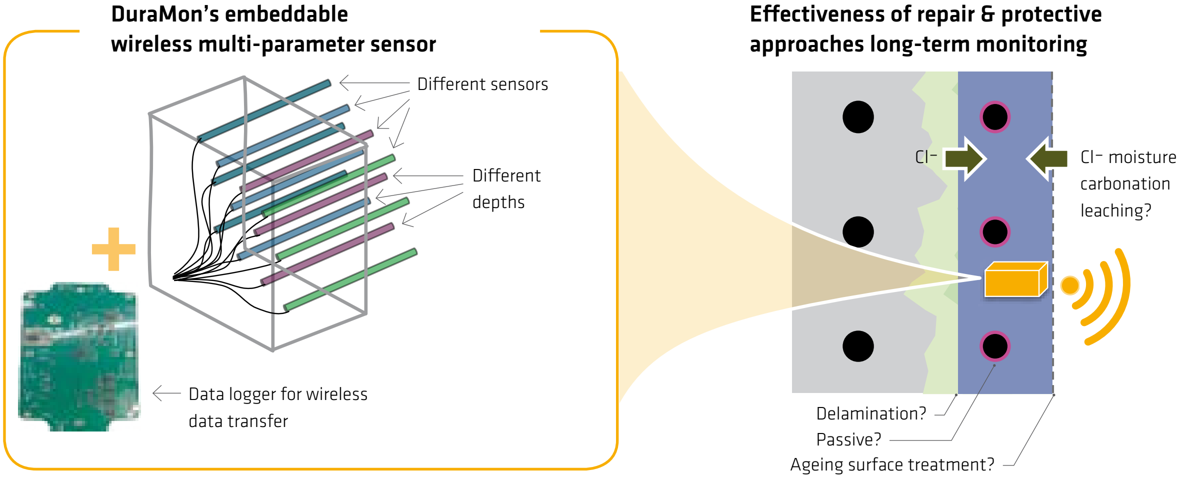
Combining the DuraMon concrete monitoring system with proven repair and protection measures, allows continual monitoring and tracking of protective efficiency at all times. This includes verification of effective application, correct design and long-term performance. In addition, the measured data can be used to better understand the underlying degradation mechanisms in each structure, providing a foundation for more efficient infrastructure management. Lessons learned can rapidly be applied to other structures. Finally, experience shows that the mere ability to monitor performance has an appreciable effect on the quality and workmanship of the works execution.

To be specific, the DuraMon system can measure:

- Chloride ingress, either from the old concrete, or from the exposed surface into the repair mortar
- pH changes in the repair mortar (carbonation, leaching)
- Potential of steel reinforcement in the repair mortar, which together with other DuraMon measurements (free chloride concentration, pH, electrical resistance of the concrete), which combine to determine whether the steel is in the active or passive state
- Electrical resistance measurements between sensors in the repair mortar and steel in the old concrete, can be used to indicate possible delamination, or a poor bond between the substrate and the repair mortar, or one developing over time.
- A combined evaluation of different sensors responses can give insight into time-dependent moisture distribution in the repair mortar and the underlying old concrete substrate.
- Changes in the corrosion rate at the reinforcement level

DuraMon's embeddable wireless multi-parameter sensor

Effectiveness of repair & protective approaches long-term monitoring



Finally, the information gained from the sensors placed in the repair area is always compared to a non-repaired / treated reference concrete spot. To gain information about the performance of the protective measures over the whole area / structure, a thorough review and evaluation must be made to determine the best positions for the sensors, as their location is very important.

HOW CAN THE COMBINATION OF DuraMon AND SIKA PROVIDE VALUE FOR EFFICIENT INFRASTRUCTURE MANAGEMENT?

Sika Products	Type of protective measure	Questions answered with DuraMon monitoring systems
Sikagard®-705 L/-706 Thixo	Reducing moisture and chloride ingress – Hydrophobic impregnation / passive corrosion inhibitor	Is the moisture ingress prevention still effective? How long will it last?
		Is the chloride ingress prevention still effective? How long will it last?
		Does the steel reinforcement remain in a passive corrosion state the whole time?
		Is the corrosion rate still at an acceptable level?
		When is it time to refresh the protective surface treatment?
Sikagard®-5500	Prevention of ingress of chlorides, CO_2, and moisture – Elastic protective concrete coating	Is the corrosion rate still at an acceptable level? In each location?
		In which areas will this protective measure lose its efficiency first?
		At what time and location(s) did / will chloride, CO_2 and moisture ingress resume?
		When and where should this protective measure be replaced?
Sika® FerroGard®-903 Plus	Forming a continuous film around the reinforcing steel bars – Active corrosion inhibitor	Are the surrounding rebars still in passive condition?
		In which areas did / will this protective measure lose its efficiency first?
		When and where should this protective measure be replaced?
Sika MonoTop®-4012	Restoring passivity – Increasing concrete cover	When did / will the mortar start to be carbonated?
		What is the level of chloride and moisture transport through the additional cover?
		When will the conditions allow corrosion initiation?
		Qualitative information on the corrosion rate
Sika® FerroGard®-500's Patch	Cathodic protection – Range of galvanic anodes	Is the corrosion rate still at an acceptable level? In each locations
		Are the surrounding rebars in passive condition?
		In which areas did / will this protective measure lose its efficiency first?
		When and where should this protective measure be replaced?
Sika® FerroGard®-300's Duo	Cathodic protection – Hybrid anodes	Is the corrosion rate still at an acceptable level? In each of the locations?
		Are the surrounding rebars still in passive condition?
		In which areas did / will this protective measure lose its efficiency first?
		When and where should this protective measure be replaced?

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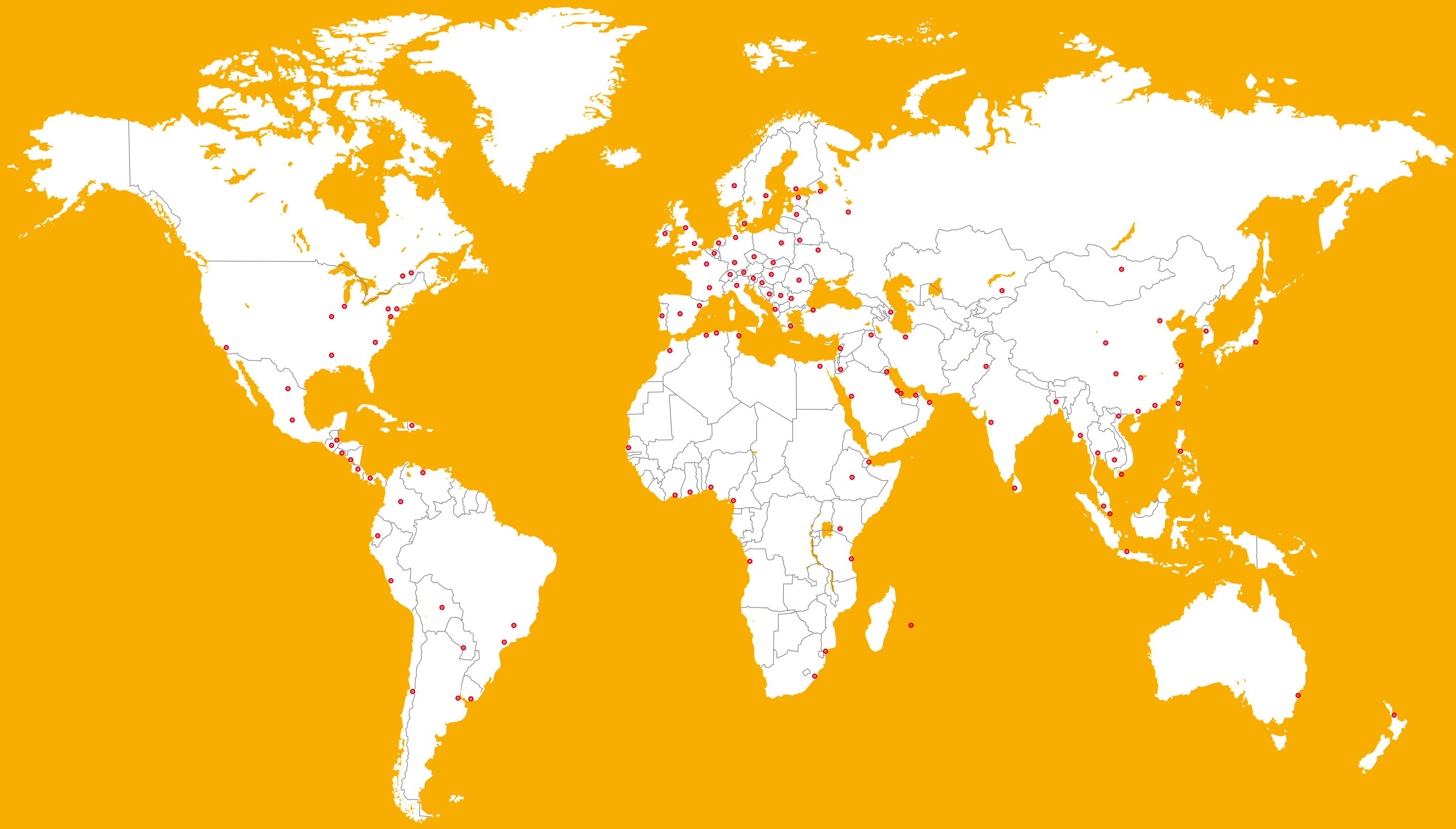
GLOBAL BUT LOCAL PARTNERSHIP



WE ARE SIKA

Sika is a specialty chemicals company with a leading position in the development and production of systems and products for bonding, sealing, damping, reinforcing and protecting in the building sector and the motor vehicle industry. Sika's product lines feature concrete admixtures, mortars, sealants and adhesives, structural strengthening systems, industrial flooring as well as roofing and waterproofing systems.

since 1986

since 1997

USGBC MEMBER

SIKA SERVICES AG
Tueffenwies 16
CH-8048 Zurich
Switzerland

Contact
Phone +41 58 436 40 40
www.sika.com

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