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Data-Driven Monitoring Solutions for Concrete Structures: Long-Term Insights with CorroDec2G Sensors

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ABSTRACT: Passive sensor technologies offer a robust solution for monitoring concrete structures. These technologies utilize advanced methods to measure critical parameters such as moisture, corrosion, and temperature within the concrete. By employing RFID technology, the sensors operate wirelessly and require no maintenance. With a lifespan exceeding 80 years, passive sensors enable comprehensive and efficient long-term structural monitoring.

This article provides insights into the installation methods, the benefits of the cloud-based data platform, and how this technology contributes to improved safety, durability, and the preservation of infrastructure.

KEY WORDS: SHMII-13; Full paper; Corrosion monitoring; Moisture monitoring; Passive RFID sensors; Bridge rehabilitation

1 INTRODUCTION

1.1 The importance of preventive monitoring of concrete structures

In modern structural monitoring, the early detection of damage plays a central role.
Concrete structures such as bridges are exposed to extreme loads and environmental influences on a daily basis. The increasing demands on the safety and durability of such structures make continuous monitoring indispensable [1]. Preventive monitoring helps to identify potential damage at an early stage and to initiate appropriate measures before costly repairs or even critical failures occur [2].

In this context, the passive sensor technology CorroDec2G by Infrasolute offers innovative solutions. This technology enables long-term monitoring of structural integrity by capturing key parameters such as moisture, corrosion progression, and temperature within the concrete. Since 2018, these sensors have been used in various reinforced concrete structures and have established themselves as a reliable early warning system. The robust design of the sensors and their easy integration into existing structural elements facilitate their use in both new constructions and retrofit applications.

The advantages of this technology lie particularly in its passive nature—meaning it does not require an external power supply, which reduces maintenance costs. In addition, the sensors deliver precise long-term data that can be processed using modern data analysis systems to identify trends and potential damage patterns at an early stage.

This article uses two practical examples (Figure 1) to explain how Infrasolute's sensor technology works, how installation is carried out, and what kind of data is collected. These case studies demonstrate how the use of CorroDec2G technology can extend the service life of structures and improve operational safety.

1.2 Moisture as a risk factor

In the case of durability-relevant bridge damage, moisture penetration is the most common cause, which can lead to corrosion-related damage to prestressing steel in older bridges [3]. Therefore, both the determination of the amount of moisture and the moisture condition are of great importance—on the one hand to monitor the long-term functionality of structures, and on the other to quantify the direction of moisture flow. This enables timely and effective decisions regarding necessary maintenance measures.

Moisture can be measured either directly or indirectly. Direct moisture measurement methods are usually based on extracting the amount of water from the material and determining it directly [4]. This approach allows for very accurate results; however, it is considered a destructive method and is therefore only suitable to a limited extent for use on bridges [5].

Alternatively, the moisture content can be determined indirectly by measuring certain material properties of the water that are functionally related to the moisture level. For example, by measuring the conductivity of the water, the actual moisture content can be inferred using specific calibration curves [5]. Indirect methods are well-suited for continuous measurements; however, the results can be influenced by various parameters such as temperature, density, material composition, and conductivity [4].

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Figure 1. A selected practical example: Elevated Road Oberwerth, B327, in Koblenz (Copyright: Christian Steffes, Infrasolute).

2 FUNCIONALITY AND MEASUREMENT PRINCIPLE

The CorroDec2G sensors from Infrasolute are based on the indirect measurement method. They are characterized by their passive mode of operation. In contrast to active sensors, they do not require any cables or batteries to collect measurement data. Developed in cooperation with the Fraunhofer Institute for Microelectronic Circuits and Systems (IMS) in Duisburg, the sensors are designed to remain fully enclosed and maintenance-free within the concrete for the entire service life of a structure—at least 80 years—while transmitting data (moisture, temperature, corrosion) from within the structure [6].

The energy required for passive operation is supplied externally via RFID (radio-frequency identification) technology. RFID is a technology also used in everyday applications such as contactless credit card payments and enables wireless, contactless data transmission. With a reading range of up to 30 cm through concrete, the sensors can be reliably interrogated [10]. A specially designed antenna setup can extend this range up to 100 meters. In such cases, the measuring unit is embedded in the concrete, for example in the center of the roadway, while the reading unit is positioned in a strategically advantageous location outside the flow of traffic, allowing data retrieval without disrupting traffic.

The system's special design ensures that no component extends beyond the concrete surface, thereby eliminating potential weak points in the structure. This concept not only protects the structural integrity but also significantly extends the service life of the sensors by shielding them from environmental influences such as moisture, temperature fluctuations, and mechanical stress [5]. Such innovative RFID-based systems represent an important step toward sustainable structural monitoring, as they are cost-efficient in the long term and do not interfere with the structure's operation.

3 INSTALLATION METHODS

3.1 New construction and rehabilitation

The installation of the sensors can be carried out both in new construction and during rehabilitation works. In new construction projects, as illustrated in Figure 2, the sensors are directly attached to the reinforcement using binding wires to ensure stable anchoring and to maintain their position during concreting—preventing, for example, floating within the fresh concrete. During rehabilitation works, such as after hydrodemolition (high-pressure water jet removal), the sensors can likewise be installed by affixing them to the exposed reinforcement. This allows for effective integration of the monitoring system even in existing structures without major modifications.

Figure 2. Attachment of moisture sensors in a new construction project using binding wires directly on the reinforcement (Copyright: Christian Steffes, Infrasolute).

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Such precise installation procedures are particularly important to ensure accurate measurement data, which are crucial for condition assessment and maintenance planning [5].

3.2 Retrofitting installation

The sensors can be retrofitted into existing structures using core drilling. As shown in Figure 3, a core hole with a diameter of 100 mm allows the sensors to be embedded into the concrete without significantly affecting the structural integrity of the building. The sensor is placed in a thin layer of a special mineral-based, open-pored coupling mortar. This layer ensures optimal bonding with the existing concrete.

After installation, the coupling process begins. During this phase, moisture measurements can be used to monitor the drying of the surrounding coupling mortar. Once equilibrium moisture content is reached, the sensor can deliver precise data about the surrounding environment. The design of the coupling mortar ensures effective moisture migration from the existing concrete to the sensor.

To avoid creating a structural weak point, a sealing mortar is applied above the sensor after installation. This ensures a durable and secure integration into the structure while maintaining the mechanical and protective properties of the original concrete.

Figure 3. Core drilling with a diameter of 100 mm and installation of the sensor using coupling mortar (Copyright: Eugen Kronhardt, Infrasolute).

4 SENSORS AND DATA TRANSMISSION

4.1 Sensor variants

The **corrosion sensor** developed by Infrasolute can be identified by its characteristic red housing and the four surrounding wire layers (Figure 4).
The measurement method is based on the principle of proxy corrosion, in which the properties of the wires are specifically designed to closely replicate the corrosion behavior of reinforcement steel. Over time, the wires corrode in response to the surrounding environmental conditions [7].

The wire layers arranged around the sensor provide information about the presence and progression of corrosion, acting as indicators for the location of the passivation front. By analyzing the depth-wise arrangement of the wires, it is possible to determine at what depth the passivation has broken down and how quickly the passivation front is advancing toward the reinforcement.

This data is critical for assessing the condition of the structure, planning further structural investigations, and initiating timely countermeasures to prevent the progression of corrosion [7].

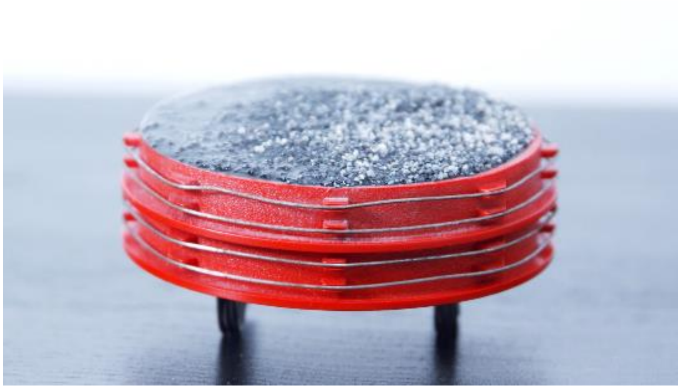

Figure 4. Corrosion sensor with two measurement wire layers (Copyright: Christian Steffes, Infrasolute).

The sensor operates using a redundant system, in which two circumferential wires form a single measurement layer. This design enhances the reliability of the measurement results and reduces potential sources of error. In addition, the corrosion sensor also measures temperature within the concrete, as temperature fluctuations can significantly influence corrosion dynamics [8]. The combination of corrosion monitoring and temperature measurement makes the corrosion sensor a vital tool for long-term monitoring and for implementing preventive maintenance strategies in reinforced concrete structures.

The **moisture sensor** (Figure 5) measures both moisture and temperature within the concrete. The moisture condition is a critical parameter in the formation of corrosion, as it affects the electrophysical environment required to initiate corrosion processes. By combining moisture and temperature data, it is possible to gain detailed insights into moisture development within the concrete. Early detection of moisture fluctuations allows for minimization of potential damage and contributes significantly to extending the service life of the structure.

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Figure 5. Moisture sensor (Copyright: Christian Steffes, Infrasolute).

By combining a corrosion sensor and a moisture sensor placed approximately 15 cm apart, early information on corrosive processes and anomalies can be obtained. This spatial proximity enables detailed observation of the correlation between changes in moisture levels and the dynamics of corrosion processes, providing a deeper understanding of the environmental conditions that influence structural degradation.

4.2 Data acquisition and transmission

There are two methods for retrieving data from the sensors embedded in the concrete. One option is to enable continuous data transmission, allowing the data to be accessed remotely at any time. For this purpose, a gateway, as shown in Figure 6, is installed near the sensor. This gateway both powers the sensor and transmits the collected data directly to the Infrasolute cloud platform.

Data transmission is carried out via NB-IoT (Narrowband Internet of Things), a communication standard specifically designed for reliable, energy-efficient data transfer in monitoring applications [7].

Figure 6. Solar-powered gateway (Copyright: Christian Steffes, Infrasolute).

As a low-bandwidth radio technology, NB-IoT (Narrowband Internet of Things) enables highly energy-efficient data transmission, allowing sensors and gateways to operate with minimal power consumption [10]. The technology also provides excellent building penetration, ensuring reliable signal transmission even through thick concrete structures (e.g., the new IT center in Koblenz, ground floor, wall thickness approx. 80 cm).

Thanks to support from existing mobile networks, NB-IoT is widely available, making it ideal for use in remote or hard-to-reach structures. Additionally, the low data transmission rate results in reduced operating costs, making NB-IoT a cost-effective solution for long-term monitoring applications.

The gateway is flexible in terms of power supply and can be operated via mains power, a long-life battery, or solar energy, depending on the construction site and local infrastructure. This flexibility enables deployment even in locations with limited access to conventional power sources. The combination of NB-IoT and energy-autonomous gateways represents a significant advancement in structural monitoring, as it not only improves data quality but also reduces maintenance efforts.

Alternatively, there is the option of using a handheld reading device to manually retrieve sensor data on-site. The device shown in Figure 7 has been specially developed for this application. The process of collecting a sensor's measurement takes only a few seconds and is often carried out during routine bridge inspections by simply bringing the handheld device close to the sensor, enabling contactless and wireless data acquisition [7].

Figure 7. IoT handheld reader for manual sensor data acquisition (Copyright: Christian Steffes, Infrasolute).

The data collected by the handheld reader is transmitted directly to the cloud-based data platform via NB-IoT technology. This enables immediate verification and visualization of the measurement values on-site at the structure [8]. Both the gateway and the handheld reader transmit their data wirelessly via NB-IoT after sensor readout.

The sensor data is stored, referenced, visualized, and analyzed in the cloud platform by comparing it with previous measurements to enable precise trend analyses. Users can define threshold values, which—when exceeded—trigger automatic alerts, allowing potential issues to be identified at an early stage.

The platform also allows the integration of collected data into existing monitoring systems and can proactively send reports via email to all relevant project stakeholders. The data generated on the platform is presented in a user-friendly and easily understandable format, enabling all involved parties—regardless of their technical background—to effectively interpret the information.

5 SENSORS AND DATA TRANSMISSION

5.1 Südtangente in Koblenz – sensor variants

The Südtangente in Koblenz (Figure 8), constructed between 1972 and 1975, is a major traffic artery located just before the South Bridge crossing the Rhine River. It plays a key role in reducing urban traffic congestion. With a daily traffic volume of approximately 45,500 vehicles, including around 3% heavy goods traffic, it is considered part of the region's critical infrastructure [9]. The bridge connects important

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transportation routes and is essential for both regional and long-distance traffic.

Figure 8. Südtangente in Koblenz (Copyright: Martin Lichtl, Infrasolute).

To meet the demands of increasing traffic volumes and to ensure the long-term durability of the bridge, the Südtangente in Koblenz has been undergoing comprehensive rehabilitation since 2020. As part of these measures, the roadway surface, structural waterproofing, guardrails, edge beams, and drainage systems have been renewed. In addition, all concrete surfaces have been repaired to enhance the load-bearing capacity and improve protection against environmental influences.

5.2 *Sensor installation*

As part of the rehabilitation, a comprehensive monitoring system was installed. The foundation for this was the execution of a potential field measurement, which enabled the precise localization of corrosion hotspots within the concrete. The results served as the basis for the targeted placement of sensors.

During the first two construction phases of the rehabilitation of the South Bridge in Koblenz, a total of 22 corrosion sensors and 62 moisture sensors were installed. The sensors were placed at critical and representative locations such as low points, expansion joints, waterproofing areas, structurally sensitive points, reference zones, and the corrosion hotspots identified by the potential field measurement. The final sensor placement was defined in coordination with the planning team. The installation layout is shown in Figure 9.

The sensors were installed into the existing concrete using core drilling (Figure 10). To optimize data retrieval, they were equipped with remote antennas. This allowed the readout units to be placed within the box girder of the bridge, providing protection from mechanical stress and weather conditions.

The gateways, which are connected to the existing power supply within the box girder, handle the data transmission. Each gateway collects the measurement data from four sensors and transmits the data wirelessly via NB-IoT to the Infrasolute cloud platform.

Figure 10. Installed sensors with remote antennas (Copyright: Benedikt Seuss, Infrasolute).

5.3 *Measurement data and analyses*

The continuous monitoring of the Südtangente in Koblenz, which has been carried out since the installation of the first sensors in the initial construction phase at the end of 2020, has so far shown no signs of corrosive activity.

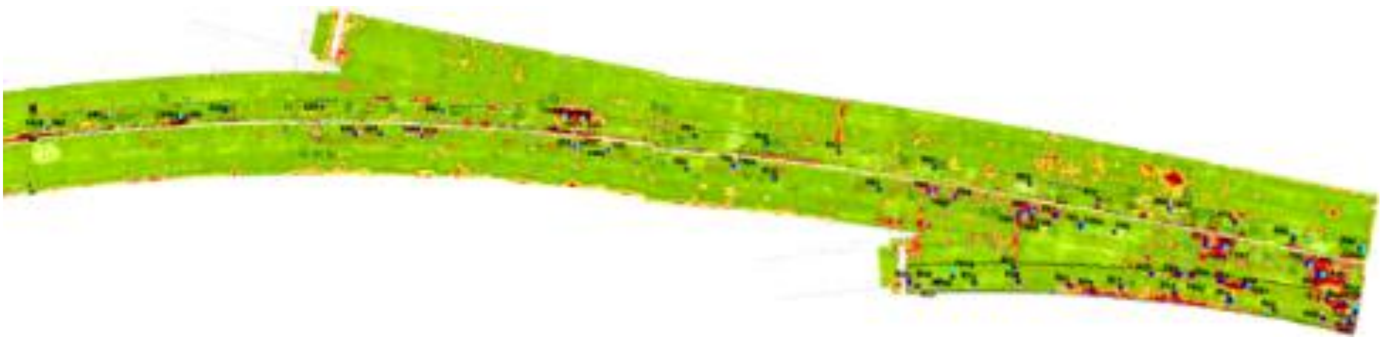

Figure 9. Potential field measurement and sensor positioning (Copyright: Christian Steffes, Infrasolute).

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An exception was one measurement point that reported corrosion on the first wire level three months after installation (Figure 11). The cause was identified as a construction-related weakness in the waterproofing, which was subsequently corrected during post-processing. Following this measure, the sensors detected no further corrosion progression.

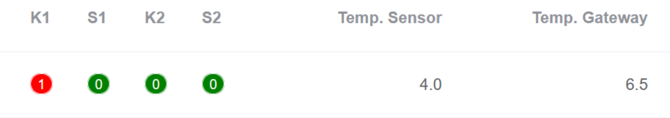

Figure 11. Data analysis in the software – display of a corrosion sensor showing corrosive activity at the first measurement wire level (Copyright: Christian Steffes, Infrasolute).

When corrosion is detected at the first wire level, the indicator K1 is no longer displayed within a green circle with a “0”, but instead within a red circle with a “1”. This provides a clear and unambiguous indication that corrosion has occurred at the first measurement wire level. The K2 value represents the status of the underlying wire level, allowing the progression of corrosion into deeper areas to be monitored and enabling a multi-layered condition analysis [7]. The values S1 and S2 serve the system’s internal self-referencing. These reference mechanisms ensure the accuracy and validity of the measurement data by automatically detecting any internal deviations or errors. This significantly enhances the reliability of the monitoring system and minimizes the risk of false diagnostics [8]. In addition, the sensor temperature within the concrete is shown under the indicator “Temp. Sensor”, providing essential information on the thermal conditions that may influence corrosion dynamics. The temperature of the gateway, located at the surface of the concrete inside the bridge’s box girder, is displayed separately as “Temp. Gateway”. In all other areas of the bridge, the moisture sensors showed a normalization to equilibrium moisture levels within the first six months after installation, without any notable irregularities or significant fluctuations. These results confirm both the effectiveness of the rehabilitation measures and the stability of the moisture conditions within the structure.

5.4 Conclusion

By implementing sensor technology, the operator of the South Bridge gains the ability to monitor the success of rehabilitation measures in the short term. At the same time, the 24/7 online monitoring allows for the long-term observation of the internal condition of the structure, enabling the early detection of damage and the proactive initiation of maintenance actions. This minimizes the risk of unexpected damage and supports a preventive maintenance strategy that significantly enhances operational safety [7].

5.5 Structure overview: Dieblich Bridge

The bridge along federal road B 411 near Dieblich serves as an important connection to the motorway network and functions as a regional access route. Compared to the heavily trafficked South Bridge in Koblenz, the traffic volume on this structure is significantly lower. The two-lane bridge spans a length of 92 meters and is used by both passenger vehicles and agricultural traffic.
In 2023, a comprehensive concrete rehabilitation was carried out after elevated chloride levels were detected in the concrete. As part of the refurbishment, it was also necessary to partially replace the reinforcement to ensure the continued structural integrity and durability of the bridge.

5.6 Sensor positions and installation

With a budget of under €10,000, an efficient moisture monitoring system was implemented to continuously provide data on the structural moisture content. This monitoring serves to track moisture levels following the rehabilitation measures and to draw conclusions about the success of the repair works and the containment of corrosive processes.

In the first step, the most critical areas of the structure were identified. This was achieved through a combination of a previously conducted potential field measurement and a detailed analysis of the structural topology. This comprehensive assessment allowed for the precise localization of potentially vulnerable zones.

Based on this analysis, it was jointly decided to install the moisture sensors at the lowest points of the structure, as these areas are particularly susceptible to moisture accumulation due to their proximity to the drainage system, as illustrated in Figure 12. The sensors were equipped with remote antenna configurations, allowing the actual measurement point to be positioned directly in the drainage area, while the readout unit was installed at a central, traffic-independent location behind the safety barrier near the expansion joint. This strategic positioning ensures easy maintenance and data retrieval without interfering with traffic.

For secure placement, the sensors were directly attached to the exposed reinforcement, as depicted in Figure 13.

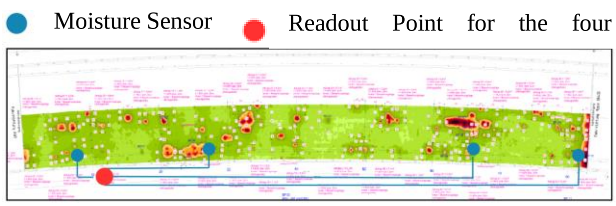

Figure 12. Potential field measurement and positioning of sensors and the readout point (Copyright: Christian Steffes, Infrasolute).

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Figure 13. Installation of a moisture sensor on the reinforcement (Copyright: Eugen Kronhardt, Infrasolute).

5.7 Data acquisition and transmission

Data acquisition is performed using an IoT handheld reader. The readout process takes less than 5 seconds and can be carried out at any time on-site from a centralized location. In this project, the readout point was placed at the beginning of the bridge, behind the guardrail, at the height of the bridge cap.

By surveying and documenting the sensor installation positions on the structural plan, and marking them on-site with reference markers, the sensors and their readout points can be easily relocated during follow-up inspections.

Furthermore, the selected location allows for the optional retrofitting of a gateway to enable automated and remote data acquisition in the future. This ensures that the system remains flexible and scalable for long-term monitoring needs.

5.8 Measurement data and analyses

Since their installation, the moisture sensors have shown a continuous drying trend without any irregularities. The moisture levels are visualized on the data platform and can be correlated with precipitation data from the nearest weather station.

This type of analysis enables a deeper understanding of moisture changes within the structure and helps determine whether these changes are caused by temperature variations or external influences, such as heavy rainfall events.

6 SUMMARY

The CorroDec2G monitoring system developed by Infrasolute offers a durable and forward-thinking solution for the structural health monitoring of concrete. With a lifespan exceeding 80 years, the system operates entirely without batteries, cables, or external power sources, making it uniquely suited for both new construction and retrofit applications. It enables the measurement of moisture, actual temperature, and corrosion activity—without compromising the structural integrity of the concrete. The wireless and battery-free technology, based on RFID, enables long-term and maintenance-free monitoring of structural conditions. Particularly noteworthy are the system's high reliability and energy efficiency, which are specifically tailored to meet the demanding requirements of structural diagnostics.

Thanks to its simple data retrieval process, the system is especially user-friendly. Measurement data can be collected within seconds, without the need for specialized expertise, and analyzed immediately. This significantly lowers the entry barrier for application and facilitates the integration into existing maintenance and monitoring workflows. Moreover, the data is presented in a clear and understandable format, enabling well-founded decisions regarding maintenance and repair actions to be made efficiently. This transparency benefits not only structure operators but also engineers and planners in ensuring the long-term safety and durability of concrete structures.

The primary advantages of CorroDec2G include its extremely long service life, energy independence, user-friendliness, and cost-efficiency. It supports condition-based maintenance strategies, contributes to the extension of structural service life, and helps optimize life-cycle costs by enabling the early detection of degradation mechanisms. Its rugged design and wireless operation allow for reliable performance in harsh environments such as underground garages or bridge structures. Moreover, its modular setup allows for flexible configurations and scalable integration into both small-scale and complex monitoring scenarios. Another key advantage of the CorroDec2G system is its cost-effectiveness. Continuous monitoring allows for the early detection of damage, minimizing expensive repairs and unforeseen failures. This not only contributes to the extension of the structure's service life but also supports sustainable resource use and optimizes maintenance costs.

Sensor data is accessible anytime and from anywhere, enabling efficient monitoring of multiple structures simultaneously. This is especially beneficial for critical infrastructure, where it supports effective prioritization of maintenance tasks and optimal use of resources [8].

Despite its strengths, CorroDec2G has inherent limitations. As a point-based early warning system, it provides localized data and does not offer full-surface or high-resolution spatial coverage. Strategic sensor placement - especially in critical zones identified by structural engineers - is therefore essential to obtain meaningful results. Furthermore, the system is not designed for high-frequency dynamic measurements but rather for long-term trends and early anomaly detection. Its value lies in its simplicity, reliability, and practical applicability in real-world construction environments

In an increasingly data-driven world, precise and reliable data collection plays a pivotal role. Advanced technologies such as Artificial Intelligence (AI), which are becoming more significant in the field of structural health monitoring, are also built upon such high-quality data. As a result, CorroDec2G serves as a bridge between traditional engineering and modern data science.

In summary, the CorroDec2G system provides an effective, forward-looking solution that actively promotes the safety,

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functionality, and preservation of concrete structures over the long term.

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