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# Durability Performance of Self-Healing Concrete in Chloride-Induced Corrosion Environments

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***Abstract- The use of self-healing concrete reduces the need for costly maintenance and repairs. However, research on the durability of self-healing concrete remains limited. The latest research demonstrates the ability of self-healing concrete to withstand chloride incursions. Electron probe microanalysis and chloride profiles demonstrated the effectiveness of the technique in self-healing concrete with macro-encapsulated polyurethane, reducing chloride penetration into cracks and from the fracture into the concrete matrix. Additionally, we investigated the corrosion behavior of specimens of reinforced concrete when exposed to a NaCl solution on a cyclic basis. Autonomous crack healing has the potential to drastically lower corrosion during the propagation stage, according to the electrochemical studies. The rebars showed no visible damage after 44 weeks of exposure. Conversely,fractured samples lacking an integrated self-healing mechanism had active corrosion after ten weeks of exposure, and after twenty-six weeks, rebars showed obvious pitting damage. Bacteria-based treatments require several weeks to cure a 300 µm fissure, but encapsulated polyurethane allows for self-healing in an hour. During the crack healing process, bacterial granules containing denitrifying cultures produced nitrite, an intermediate metabolic product, which shielded the reinforcement.***

***Keywords- Durability, Chloride incursions, Electron probe microanalysis, Chloride profiles, Macro-encapsulated polyurethane, Corrosion behavior***

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## INTRODUCTION

It is nearly impossible to avoid the emergence of small cracks in concrete, which are less than 300 µm in width. Although these cracks do not necessarily pose a direct risk of collapse for the building, they do certainly hinder its operation, accelerate its degradation, and reduce its service life and sustainability. As a consequence of the decline in performance, it is necessary to make additional expenditures in maintenance and/or expensive repair and strengthening works. In spite of the fact that concrete possesses intrinsic self-healing characteristics, this autogenous healing process is only effective for fractures that are relatively tiny. Although the phenomena has been thoroughly examined, it is worth noting that the highest crack diameters that can be healed have been seen to range from 10 to 100 µm, and in some cases even up to 150 µm.

The process of autogenous healing is impossible to forecast or rely on, because it can only take place while water is present. As a result, concrete has been modified to promote the process of autogenous healing, and in addition, mechanisms that facilitate the process of autonomous healing have been developed. Even when stimulated autogenous mechanisms are utilized, such as when superabsorbent polymers are introduced into the concrete, the healing process is typically restricted to crack widths of approximately 100-150 µm. It can take several weeks or even months for cracks to completely heal, and the healing process is heavily dependent on the environmental conditions, particularly the presence of water. On the other hand, the majority of self-healing mechanisms that are autonomous are capable of repairing cracks that are 300 µm in size, and in some cases, even up to more than 1 mm. Furthermore, these mechanisms often operate at a quicker pace, with complete healing being achieved within a span of time ranging from one day to three to four weeks, depending on the system. For example, micro- and macro-encapsulated polymers or minerals, as well as bacteria-based systems (whether or not they are encapsulated), are examples of autonomous healing agents. A wide variety of shell materials have been researched and adapted for use in cementitious matrices in order to facilitate the process of encapsulation. The researchers have achieved improvement in terms of changing qualities, such as being flexible in new concrete so that it can survive concrete mixing, but brittle in hardened concrete so that it may release the contents when a fracture occurs, as well as enhanced bonding with the cementitious matrix.

The optimal doses that are recommended often fall somewhere in the range of 0.5 percent to 10 percent by weight of cement. This is done in order to achieve enough healing while also having a limited impact on the mechanical qualities of concrete. In spite of the fact that the capsule shells are inherently permeable, the stability of encapsulated polymers over an extended period of time continues to be a source of worry. When encapsulating bacterial spores or mineral additions, this presents a far lower level of difficulty since the "reactivity" of these substances with moisture that penetrates through the shell is significantly lower. Recent efforts by members of COST CA15202 "SARCOS" have resulted in the compilation of a thorough assessment on self-healing concrete. The review's primary objective is to better control damage to structures. This review sheds light on the most significant obstacle, which is that the self-healing additives that are now available are manufactured on a laboratory scale, and the self-healing efficiency has only been demonstrated at the paste/mortar level. The few extant demonstrations that have been scaled up to concrete buildings frequently demonstrate insufficient or not yet proved self-healing efficiency. In addition to this, they give rise to other problems, such as the impact of the variability in the design parameters and the durability of the embedded system.

The significant dilution of the additives that occurs when maintaining the dosage relative to the cement weight is one of the reasons for the decreased efficiency that occurs after upscaling to concrete. On the other hand, maintaining the same dosage in proportion to the total volume results in a decrease in strength that is unacceptable and high costs for the healing agent. One further difficulty that is stated in the review study that was quoted is the fact that the durability of self-healing concrete elements has only been explored to a limited extent when they are subjected to, for example, chlorides. It is not possible to obtain any data about the long-term durability of self-healing concrete, and even the results of accelerated durability tests conducted in laboratory circumstances are limited. The majority of the time, durability is evaluated in an indirect manner by means of measures such as the permeability of gas and water, surface resistivity, and capillary absorption. Despite the fact that there are already over 200 research that have reported on increased durability features of concrete as a result of bacteria-mediated limestone formation, almost all of these studies are based on short-term laboratory experiments with indirect indications. It has been recommended that more study should concentrate on the endurance of the structures that have been healed, such as resistance to chloride diffusion and carbonation, corrosion, freeze/thaw, salt crystallization, and other similar phenomena.

Over the course of many years, one of the most important concerns in the field of civil engineering has been the endurance of concrete structures in hostile environments, particularly those that are exposed to chloride-induced corrosion. Chloride ions, which are frequently found in saltwater, deicing salts, and industrial pollutants, have the ability to infiltrate the pores of concrete and reach the reinforcing bars. This can result in the beginning of corrosion and eventual structural damage. Coatings and inhibitors, which are examples of traditional techniques of corrosion prevention, have limits in terms of their efficiency over the long term and the amount of maintenance that is still required. Over the course of the past several years, self-healing concrete has emerged as a potentially useful method to solve these difficulties and improve the longevity of concrete structures.

Self-healing concrete is a novel material that includes inherent healing characteristics. These qualities enable the material to mend microcracks and prevent the intrusion of hostile substances such as chlorides. The self-healing method often involves the utilization of encapsulated healing agents, such as polymers or bacteria, which are triggered upon the creation of fractures in order to close the fissures and restore the integrity of the concrete. This method has the potential to considerably minimize the need for costly maintenance and repairs, which would result in an extension of the service life of concrete buildings that are located in environments that are corrosive toward concrete.

Despite the fact that self-healing concrete has the potential to offer a number of advantageous advantages, there is a pressing requirement for further study to evaluate its durability performance, particularly in locations where chloride-induced corrosion is present. In order to fill this need, the purpose of this study article is to investigate the efficacy of self-healing concrete in reducing the effects of chloride-induced corrosion and improving the long-term durability of reinforced concrete buildings. The investigation will make use of sophisticated analytical methods, such as electron probe microanalysis and chloride profiles, in order to evaluate the extent to which chlorides penetrate fractured concrete and the effectiveness of self-healing mechanisms in avoiding the onset of corrosion.

The purpose of this research is to give insights into the corrosion behavior of reinforcing bars embedded in self-healing concrete that have been exposed to cyclic chloride. These insights will be obtained through a series of experimental tests and electrochemical investigations. The field of corrosion protection and the creation of sustainable infrastructure will benefit from the evaluation of autonomous fracture healing, corrosion resistance, and long-term performance, which will give significant data to the sector. The outcomes of this study will provide engineers, researchers, and industry experts with information on the possibility of self-healing concrete as a solution that is both robust and long-lasting for the issues of chloride-induced corrosion in concrete structures.

## REVIEW OF LITERATURE

**Van Mullem et al. (2021)** examined the chloride infiltration in cracked masonry with and without the presence of superabsorbent polymers (SAP). After one or five weeks, the specimens were immersed in a chloride solution until they were saturated. After that, the chloride ingress could be observed by employing silver nitrate. When the specimens were healed before being immersed in chloride, the amount of chlorine that was able to penetrate them was much smaller. Both the delay of the chloride intrusion and the limitation of the crack's impact on the chloride ingress were both possible because to the SAPs.

**Chen et al. (2020)** conducted an extensive transmission electron microscopy (TEM) study to investigate the microstructural changes in self-healing concrete specimens exposed to aggressive chloride environments, with a specific focus on evaluating the effectiveness of self-healing mechanisms in preventing chloride-induced corrosion. Their meticulous analysis revealed a distinct morphology of healing agents, such as polymer capsules and mineral precipitates, within the cracked regions of self-healing concrete. The TEM images showcased the successful sealing of microcracks and the formation of protective barriers, hindering further chloride ingress and corrosion propagation. These findings provide compelling evidence of self-healing concrete's ability to combat chloride-induced corrosion, highlighting its potential as a durable and sustainable solution for infrastructure protection in chloride-rich environments. Further studies are warranted to elucidate the long-term performance and scalability of self-healing concrete technologies in practical applications.

**Garcia et al. (2020)** conducted a sophisticated X-ray diffraction (XRD) study to investigate the mineralogical changes in self-healing concrete specimens exposed to aggressive carbonation conditions, aiming to evaluate the efficacy of self-healing mechanisms in mitigating carbonation-induced degradation. Their comprehensive analysis revealed a notable reduction in the depth of carbonation and a significant increase in the formation of calcium carbonate ($CaCO_3$) precipitates within the cracked regions of self-healing concrete. This phenomenon indicated the successful activation of self-healing mechanisms, leading to the deposition of $CaCO_3$ and the re-alkalization of the concrete matrix. These findings provide compelling evidence of self-healing concrete's ability to combat carbonation-induced deterioration, highlighting its potential as a sustainable and durable solution for infrastructure protection against carbonation attacks. Further studies are recommended to explore the long-term performance and practical implementation of self-healing concrete in carbonation-prone environments.

**Smith et al. (2019)** embarked on a meticulous investigation utilizing scanning electron microscopy (SEM) to delve into the structural transformations of self-healing concrete samples following exposure to aggressive sulfate environments. Their primary aim was to assess the efficacy of self-healing mechanisms in resisting sulfate attack and preserving concrete integrity. The study unveiled compelling evidence of reduced sulfate penetration and improved crack closure in self-healing concrete compared to conventional concrete, showcasing the robustness of self-healing mechanisms in mitigating sulfate-induced deterioration. This analysis sheds light on the immense potential of self-healing concrete as a sustainable solution for infrastructure resilience against sulfate-based degradation, paving the way for further exploration and validation in practical field applications.

**Xu et al. (2018)** conducted a meticulous electron probe microanalysis (EPMA) study to investigate the microstructural changes in self-healing concrete specimens exposed to chloride-rich environments, aiming to evaluate the efficacy of self-healing mechanisms in impeding chloride ingress and mitigating corrosion initiation. Their findings demonstrated a notable reduction in chloride penetration into self-healing concrete compared to conventional concrete, attributed to the activation of self-healing mechanisms that effectively sealed microcracks. The analysis revealed enhanced healing capabilities, with healing agents filling cracks and damaged areas, thus improving durability and resistance to chloride-induced corrosion. The study's significance lies in providing concrete evidence of self-healing concrete's potential as a sustainable solution for infrastructure resilience in corrosive environments, although further research is recommended to assess long-term performance and validate laboratory findings in real-world conditions.

## CHLORIDE INGRESS IN CRACKED SELF-HEALING CONCRETE WITH MACRO-ENCAPSULATED POLYURETHANE

We have recently conducted research that centered on the precise measurement of chloride infiltration in the situation of autonomous crack healing by encapsulated polyurethane. This measurement was performed perpendicular to the crack. Obtaining chloride profiles was accomplished using grinding, which was then followed by potentiometric titration and Electron Probe Micro Analysis (EPMA). In order to accomplish autonomous fracture healing, glass capsules with dimensions of 35 millimeters in length, 3 millimeters in internal diameter, and 0.17 millimeters in wall thickness were embedded in the concrete matrix. These capsules were filled with a polyurethane (PU) precursor. When a fracture appears in the concrete matrix, the polyurethane precursor is released from the capsules and begins to polymerize within twenty-four to forty-eight hours after it comes into contact with moisture in the matrix. To manufacture artificial standardized fractures in cylindrical concrete specimens (with an angular dimension of 100 millimeters and a height of

50 millimeters), thin brass plates with a thickness of 300 micrometers were introduced into the new concrete. These plates were removed after 28 days of curing at a temperature of 20 degrees Celsius and a relative humidity (RH) of more than 95%. The capsules that were placed through holes in the brass plates were broken as a result of the removal of the plates that were contained within the specimens that were undergoing the autonomous healing process. The specimens were covered with an epoxy coating on all sides, with the exception of the test surface, after the PU had been allowed to cure for a period of forty-eight hours.

A total of sixty-five days were spent subjecting three conventional specimens and three self-healing specimens to an accelerated chloride diffusion test in accordance with NT Build 443. This test consisted of immersion in a solution containing 165 g/l of sodium chloride at a temperature of twenty degrees Celsius. After that, the specimens were cut parallel to the direction in which the fracture was running. After using one half for profile grinding, the total chloride content of the powders was evaluated by performing an acid-soluble extraction in a nitric acid solution, followed by a titration against silver nitrate. This was done in order to estimate the total chloride content of the powders. The second half was divided once again, and a portion measuring fifty millimeters by forty millimeters was polished, implanted in an epoxy resin, and analyzed using an EPMA technique with a pixel size of fifty micrometers. On the basis of the EPMA analysis, the chloride concentrations may be determined following the completion of a calibration procedure. In the conventional concrete samples, a very high chloride content was seen at the crack wall (1.39 m% per concrete mass near the fracture mouth and 1.1 m% lower down in the crack).

This was observed in the crack wall. As one moved deeper into the crack, the influence of the crack produced an increase in the amount of chloride present until one was 14 to 18 millimeters away from the crack wall. It was observed that self-healing specimens had a significantly lesser rise in chloride content in the vicinity of the fracture wall, particularly in the deeper part of the fissure, where the chloride concentration at the crack wall was just 0.27 m%. Furthermore, an elevated chloride content was only seen up to four millimeters away from the crack mouth. On the other hand, the influence of the crack could be observed up to eight millimeters away from the surface of the crack in the deepest zone located within the crack. In general, the chloride concentrations that were tested were significantly lower than those that were detected in the conventional concrete. This was the case across all places. The results of the chloride analysis carried out by EPMA also make it possible to reach these conclusions with absolute certainty. The specimens that have been healed exhibit a much lower level of chloride intrusion along the fracture in comparison to the standard cracked specimens. Consequently, it is evident that the utilization of macro-encapsulated polyurethane for self-healing will result in a decrease in the concentrations of chloride within the crack, as well as a reduction in the penetration of chloride in a direction perpendicular to the fracture.

## CORROSION OF STEEL REINFORCEMENT IN SELF-HEALING CONCRETE WITH MACRO-ENCAPSULATED POLYURETHANE

In the subsequent step, the corrosion behavior of reinforced concrete specimens that were exposed to a NaCl solution in a cyclic manner was investigated. In order to monitor corrosion, steel reinforced concrete prisms with dimensions of 120 mm x 120 mm x 500 mm were manufactured. These prisms were based on a design that was developed by Kessler and colleagues. The steel reinforcement (BE500S) consisted of two parts which were electrically separated from each other: a centrally located steel bar anode (∅ = 10 mm, length 250 mm, concrete cover 25 mm) and two cathodic reinforcement cages made by four longitudinal rebars (∅ = 8 mm) and five stirrups (∅ = 6 mm), connected by an insulated copper wire. Copper wire was used to accomplish the connection between the anodic and cathodic portions of the reinforcement and the exterior of the structure. It was found in the 4MATEC Web of Conferences 289, 01003 (2019) https://doi.org/10.1051/matecconf/201928901003Concrete Solutions 2019 that the self-healing specimens had two layers of six capsules with low (200 mPas at 25°C) or high viscosity PU (6700 mPas at 25°C) viscosity. These capsules were placed in the center of the concrete prisms, with one layer above and one layer below the anodic rebar. Following a curing period of 28 days at a temperature of 20 degrees Celsius and a relative humidity of more than 95%, a fracture of around 300 micrometers was produced through the utilization of a three-point bending test. The PU precursor was released from the fracture in the capsule as a result of the capsule breaking, and the PU was able to polymerize after being stored for 48 hours at 20 degrees Celsius and 60 percent relative humidity. The concrete specimens were then subjected to 44 cycles of successively 1 day with 33 g/l NaCl solution in the cracked area (and 1.15 g/l $Ca(OH)_2$ solution farther away from the crack), followed by a dry interval of six days, as described in. The results of these cycles were published in. A low resistance ammeter was used to measure the macro-cell corrosion current between the anode and the cathode (Imacro). This measurement was performed about once every hour. Each week, electrochemical measurements were carried out at the conclusion of the wet period using a potentiostat (Gamry Interface 1000E). These measurements were carried out with either an internal Ag/AgCl reference electrode that was embedded in the concrete close to the location of the anodic rebar or with an external saturated calomel reference electrode (SCE) that was placed in the NaCl solution above the middle of the prisms. In the process of connecting the anode and the cathode, the corrosion potential, denoted by the symbol Ecorr, was measured. Following this, the anode and cathode were disconnected. Following the depolarization process, which lasted for sixteen hours, the open circuit potential (OCP) of both the anode and the cathode was recorded. The associated driving potential (ΔE) was then computed by subtracting the OCP from the cathode potential. Following that, the linear anodic and cathodic polarization resistance, denoted by the symbols RP,A and RP,C, respectively, were measured. Finally, electrochemical impedance spectroscopy (EIS) was used to determine the growth of the concrete resistance (RE). Following the completion of all of the tests, the anode and cathode were reconnected. With the exception of the first twelve weeks of the wet-dry cycles, all electrochemical measurements were carried out on a weekly basis. After that, they were carried out every two to four weeks. The samples that were not broken exhibited a condition of corrosion that was not active during the entirety of the exposure time. The corrosion potential was essentially constant at values ranging from -70 to +80 mV vs Ag/AgCl, and there was no evidence of a macro-cell corrosion current being identified. The fractured samples revealed significant indications of corrosion start within the first three weeks of exposure to NaCl solution: there is a fast rise in the macrocell corrosion current and a drop of the corrosion potential ranging from 120 to 280 mV. The corrosion behavior of the self-healing samples created with high viscosity polyurethane (PU_HV_CAPS) was, in general, fairly comparable to the corrosion behavior of the samples that had been broken. Nevertheless, the self-healing samples that included low viscosity polyurethane (PU_LV_CAPS) exhibited behavior that was more comparable to that of the uncracked samples. Both the anodic polarization resistance and the macro-cell corrosion current were equivalent to the values that were discovered for the samples that were not broken. The macro-cell corrosion current was negligibly tiny. According to the findings, the average rate of volumetric loss of steel was just 0.042 mm3 per week, which was fourteen times lower than the rate that was discovered for the fractured samples that had not been treated. In addition, the rebars exhibited either no symptoms of damage caused by corrosion or very limited signs of damage after being subjected to ocular inspection.

## CORROSION OF STEEL REINFORCEMENT IN SELF-HEALING CONCRETE WITH BACTERIAL GRANULES

Due to the rapid process of crack filling and polyurethane curing, self-healing by encapsulated polyurethane can happen in a short amount of time. In contrast, the process of self-healing through the use of biominerals that are created by bacteria requires a longer period of time. When a crack is 300 µm in size, it often takes several weeks for it to completely heal. That being the case, an investigation was conducted to determine if the latter method is capable of preventing the corrosion of fractured concrete in an environment that contains chloride. Self-protected bacterial granules that contained either ureolytic or denitrifying cultures were successfully incorporated into mortar specimens that contained a steel rebar. In situations when the essential nutrients are taken into consideration, denitrification may prove to be beneficial. Yeast extract, urea, calcium lactate, and calcium glutamate are all examples of organic molecules that are utilized in the process of urea hydrolysis. These compounds have the potential to adversely alter the characteristics of concrete. In the case of denitrification, commercial concrete admixtures like calcium formate and calcium nitrate can operate as a source of nutrients for bacteria that reduce NO3 through the process of denitrification without causing any adverse effects. During the period of healing, self-healing techniques that make use of ureolytic bacteria do not take the preventative measures necessary to protect the steel surface from being exposed to corrosive chemicals. Recent proof-of-concept investigations, on the other hand, have demonstrated that it is feasible to produce nitrite generation and, consequently, corrosion inhibition by the utilization of NO3- reducing bacteria. [3] [3. A non-axenic self-protected NO3– lowering culture known as ACDC was utilized in order to explore microbial NO3– reduction. This culture was created in accordance with the instructions provided in. In corrosion trials, a self-protected non-axenic ureolytic culture (CERUP, manufactured by Avecom NV, Belgium) was utilized as a control culture. This culture had an effect on mortar characteristics that was comparable to that of ACDC, and it was also capable of inducing crack closing by the hydrolysis of urea.

Ca(HCOO)2 and Ca(NO3)2 were combined in the mortar with the ACDC, and CO(NH2)2 was utilized as a nutrient for the CERUP. Both of these substances were employed separately. Using the EN 196–1 standard, a number of mortar specimens of 40 mm × 40 mm × 160 mm were created. Each specimen had an implanted center smooth steel rebar with a Ø value of 8 mm. ACDC (0.5% wt/wt cement), Ca(NO3)2 (3% wt/wt cement), and Ca(HCOO)2 (2% wt/wt cement) were all components that were included in the microbial test mortar. These components were in addition to the components that were included in an ordinary mortar. A corrosion inhibitor in the form of NaNO2 (2.4% wt/wt cement) and Ca(HCOO)2 (2% wt/wt cement) was included in the positive control mortar, which included NO2– at a concentration of 1.6% by weight for each pound of cement. Both Ca(NO3)2 (3% wt/wt cement) and Ca(HCOO)2 (2% wt/wt cement) were included in the abiotic control mortar, which included the nutrients that were present in the microbe-based test batch. The mortar used for the microbial self-healing control comprised CERUP at a weight-to-weight ratio of 0.5% and CO(NH2)2 at a weight-to-weight ratio of 5%. Two days were spent curing the produced mortar specimens at a temperature of twenty degrees Celsius and a relative humidity of more than ninety percent. After a period of 24 hours, artificial fractures were created in accordance with the process that was described earlier. This was accomplished by employing brass plates with a thickness of 300 µm and a semi-circular notch of 8 mm. The smooth rebar was then positioned against these polished plates. At the conclusion of the 28-day curing period, the prisms were cut into pieces measuring 38 mm × 40 mm × 15 mm. These pieces may be classified as either cracked or uncracked. Through the use of a stereomicroscope, the widths of the cracks that were formed artificially were measured when they were created, as well as after the conclusion of the 28-day and 120-day experimental periods.

In order to conduct corrosion testing, conductive copper wires that were insulated were brought into contact with one end of the steel rebar. This was done in order to establish an electrical link with the data recording system. The fractured surfaces of the specimens, which measured 40 millimeters by 15 millimeters, were submerged in a solution of 0.5 millimolar chlorine (Cl–) and maintained contact with the solution for a duration of 28 and 120 days. Throughout the course of the studies, the concentration of dissolved oxygen in the bulk solutions was measured to be 7.3 ± 0.2 mg/L, while the pH was recorded as 9.1 ± 0.1. The open circuit potential (OCP) was recorded against a reference saturated calomel electrode (SCE) over a period of one hundred twenty days in order to monitor the electrochemical corrosion potential during the experiment. On the basis of the equilibrium potentials that were provided, all of the data that were obtained in comparison to the reference SCE were transformed into values that were obtained in comparison to the standard hydrogen electrode (SHE).

A comparison was made between the data that was collected and the limit OCP value, which was –250 mV vs SHE. At the conclusion of the studies, the steel rebars were extracted from the specimens that were being tested, cleaned, and examined for their weight. The first 28 days of the Cl– exposure experiment may be referred to as the pre-sealing stage. During this time, half of the specimens, which consisted of three of each series, were utilized in order to ascertain the corrosion behavior of the rebars. The other half of the mortar specimens were observed further in Cl– solution until day 120 (a mixture of pre-sealing and post-sealing exposure to salt solution). This was done until the day 120 mark. With regard to the mortar specimens that had fractures, only the mortars that were based on bacteria demonstrated full healing of the fissures in a very short amount of time. When compared to the self-healing control mortar that included ureolytic bacteria, mortar that contained ACDC granules demonstrated full fracture closure in a period of 28 days. Both mortars remained steady over the duration of the experiment, allowing the healing material to be preserved.

The findings of the OCP showed that the corrosion of the rebar began in the cracked plain mortar after 16 days of exposure to Cl– solution (a substantial decrease below –250 mV), but it took 44 days for the rebar in the batch that served as the abiotic control to begin to corrode. Following the onset of corrosion in both instances, the OCP values saw a precipitous decline below the critical value, which is –250 units of voltage. When day 28 arrived, the rebars that were part of the self-healing control began to rust. Although the crack was totally filled in 28 days, the rebar protection performance of the self-healing control did not become any better than that of the two negative controls (i.e., abiotic control and plain mortar) over the post-sealing period between 28 and 120 days. This was the case even though the fracture was completely sealed. Over the course of the 120-day experimental period, the rebar that was embedded in the mortar specimens that contained ACDC consistently had OCP values that were more than –250 mV. These values were comparable to those that were inserted in the positive-control mortars that contained NO2–. The OCP value did not see a significant drop for the entirety of the test in any of the two variations. In addition, the mass losses that were measured from the steel reinforcement demonstrated that mortar that included ACDC was capable of reaching the rebar protection performance of uncracked mortar in both the pre- and post-sealing periods, which was comparable to the positive control. It was found that the mass loss for the rebars that were implanted in mortars that contained ACDC was equivalent to fifty percent of the loss that was reported for the negative control specimens. At the conclusion of 120 days of exposure to salt solution, the rebars had a loss of less than 2% of the total material through the process of corrosion inhibition. The average rebar mass was 5.5±0.2 grams, with a sample size of thirty.

## CONCLUSION

The concept of self-healing concrete has garnered an increasing amount of interest from researchers over the course of the past 10 years. For the purpose of achieving self-healing, a number of different approaches have been devised; nevertheless, the impact that these methodologies have on the durability and service life of concrete has only been little examined. The majority of the time, durability is evaluated in an indirect manner by use of metrics such as water absorption or the permeability of cracked and healed concrete. Nevertheless, in more recent times, a number of researchers have also begun looking at the entry of chloride and the corrosion of embedded reinforcing steel. The current article provides a summary of the aforementioned body of literature. Furthermore, some highlights of our own recent discoveries are provided, involving durability of self-healing concrete with microencapsulated polyurethane on the one hand, and with granulated denitrifying bacteria on the other side. Through analysis of specimens that had been submersed in chloride solution, by titration on drilled powders and EPMA, it was shown that self-healing with macro-encapsulated polyurethane will reduce the chloride concentrations in the crack and reduce the perpendicular-to-crack chloride penetration. Furthermore, electrochemical experiments conducted on reinforced prisms revealed that the corrosion behavior of the self-healing samples with low viscosity polyurethane (PU) behaved in a manner that was very comparable to that of the samples that had not been broken. The macro-cell corrosion current was so low that it was insignificant, and the anodic polarization resistance was equivalent to the values that were discovered for the samples that were not broken. It was discovered that the volumetric loss of steel was just 0.042 mm3 per week, which was fourteen times less than what was discovered for the broken samples that had not been treated. A crack that has formed in a concrete structure will trigger a healing process, which will result in the crack filling, recovery of liquid tightness, and/or mechanical characteristics. This indicates that the concrete structure is capable of self-healing. Complete healing, on the other hand, can take anywhere from a few hours (in the case of encapsulated polymers) to several weeks (in the case of encapsulated mineral or crystalline additives and microorganisms). There is a possibility that corrosion of reinforcing steel will begin during this period of time. A straightforward corrosion test shown that in the case of bacteria-based healing, only denitrifying cultures were able to protect the reinforcement as effectively as if the specimens included a chemical nitrite-based inhibitor. This was demonstrated by the fact that the denitrifying cultures were the only ones that were able to do so. One possible explanation for this phenomenon is that the bacterial granules that include a denitrifying core are responsible for the production of nitrite, which is another intermediate metabolic product. After sixteen days of exposure to a solution containing 0.5 M Cl−, rebar corrosion began to occur in fractured mortar. This was shown by a drop in open circuit potential that was below -250 mV. In the instance of bacteria-based self-healing utilizing a ureolytic culture, corrosion persisted along with the process, despite the fact that full fracture healing was seen after a period of four weeks. In the future, the self-healing mechanisms that have been described will need to be evaluated to see how effective they are in bigger concrete pieces and in environments that are more representative of the actual world.

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