RECLAMATION

Managing Water in the West

Using Self-Healing Concrete for Concrete Repairs on Aging Concrete Structures

Research and Development Office
Science and Technology Program
(Final Report) ST-2016-7064-1

U.S. Department of the Interior
Bureau of Reclamation
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Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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Reclamation's aging infrastructure, along with the challenge of budget constraints, has created an opportunity to investigate concrete repair methods that will provide positive long lasting results. Currently, when repairs to critical infrastructure are performed we find that there are several challenges that affect the success of the repair activities. Specifically, those factors include the use of unskilled labor, unsatisfactory weather conditions, and limitations on sizes of repairs due to financial limitations. As a result of these factors and several others, concrete repairs can undergo a short life span due to the development of cracks. These cracks will eventually lead to the deterioration of the repair area as water or debris enter the cracks and increase it susceptibility to damage. In contrast to traditional concrete mixes, self-healing concrete can be comprised of polymer capsules within the batched concrete mix that activate when a crack opens the capsule. As water penetrates the crack it activates the polymer solution and fills the crack thereby protecting the repair area from the environment. The polymer solution contains a unique bacteria (Bacillus pasteurii) that is alkali-resistant and can live within the concrete for 200 years.

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Disclaimer

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Executive Summary

Need and Benefit

Reclamation's aging concrete infrastructure along with the challenge of budget constraints provides an opportunity to investigate concrete repair methods that will provide long lasting results. Currently, when repairs to critical infrastructure are performed, several challenges affect the success of the repair activities. Those factors include the use of unskilled labor, unsatisfactory weather conditions, and limitations on sizes of repairs due to financial limitations. As a result of these factors and others, unsuccessful concrete repairs can have a short life due to the development of cracks in the repair material. These cracks may eventually lead to deterioration of the repair area as water or debris enter the cracks and allow for various deterioration mechanism to damage the repair..

Concrete cracking and unsuccessful repair projects are not limited to the Bureau of Reclamation (Reclamation). This is a common problem for the entire repair industry. Experimentation and application of self-healing concrete technology has shown promise and the potential benefits include reduction in maintenance costs, increased durability, as well as the elimination of recurring repairs.

Self-healing concrete can be comprised of capsules within the batched concrete mix that activate when a crack opens. As water penetrates the crack it activates the capsules which reacts to fill the crack, which can protect the repair area from the environment. Another approach is self-healing concrete that relies on bacteria. When a crack forms and water penetrates the repair area the bacteria activate and produce a limestone that seals the crack. This unique bacteria (Bacillus pasteurii, Escherichia coli, etc.) is alkali-resistant and can live in the concrete for 200 years.

The result of this study would have a Reclamation wide benefit. The Nebraska-Kansas Area Office (NKAO) and Great Plains Region Construction Services Office would partner in this project by providing access to Dam Infrastructure where the self-healing concrete can be applied to concrete repair projects.

Current Research

During a literature search, several resources were found that describe self-healing concrete including the chemical composition, ingredients, applications, and current projects. For those studies, focus was placed on the size and dosage of the compressed powder spheres that contain the self-healing agents and how their existence impacts the compression strength of concrete. The self-healing agents housed in the spheres release the bacteria when ruptured, and activation occurs when water enters the crack resulting in the production of calcium carbonation. The studies showed that concrete crack healing is limited to cracks of widths up to 0.031-inch [1].

Several Reclamation engineers including partners from the Great Plains Regional Office Construction Office were consulted on current and previous Reclamation projects involving concrete repairs. The Great Plains Regional Office Construction Services Group provided data on previous concrete construction projects along with costs. The data was reviewed and further information was received pertaining to projects that had experienced concrete cracks shortly after repairs were made. The projects included Glen Elder Dam and Kirwin Dam. Investigation of these two projects (Glen Elder and Kirwin Dam) will also include discussion on the crack mitigation technology (Prevent-C) that was used on new placements.

Along with consultation from Reclamation engineers, publication reviews of existing and past research projects directly related to concrete crack mitigation by Reclamation's Concrete, Geotechnical, and Structural Laboratory (CGSL) are underway. Excerpts from these various projects are being compiled to support the application of self-healing concrete on concrete repair projects. Following this review more participation with CGSL will be required to support the future purchase of the self-healing concrete ingredients to examine in-house.

Following the conclusion of this Scoping Study (conducted in FY 16), further review of publications supporting the benefits of self-healing concrete on new construction, discussions with Bureau of Reclamation Engineers and Research specialists physical testing is planned to continue to investigate the use of this technology on Reclamation infrastructure. Self-healing concrete is a new technology and its ingredients and applications have been researched but there is no availability of the materials outside the patent holders. However, in 2016 the Delft University of Technology located in the Netherlands formed a commercial company that produces the self-healing materials making it available commercially. This has allowed this research project to continue to investigate the uses of self-healing concrete for concrete repair.

Future Research Questions

Laboratory work will be conducted to familiarize CGSL specialists with self-healing concrete ingredients and test for compressive and tension strength. Data will be collected and presented in a final paper available to Reclamation peers, government agencies, and participating partners. Under coordination with the Reclamation Nebraska/Kansas Area Office field testing will be conducted, if appropriate, at new projects or projects undergoing concrete repairs. Following application of the self-healing concrete, monitoring will be done to collect data on the performance of the product and cite any drawbacks. Findings of the field study will be presented in the final paper.

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Introduction

As Reclamation's infrastructures continue to age, many structures have surpassed their expected service life. The increased demands on these systems further strain their capacity to maintain normal operations. Limited resources for maintenance and repair at all levels also contribute to limiting repairs. Concrete cracks are an important indicator for determining the overall condition of a structure. While not all concrete cracking is detrimental to a structure, the size, location and severity can dictate the importance of repairs. Large cracks can indicate the existence of structural overloading or severer deterioration. Smaller cracks can also provide evidence of damage, including those related to poor substrate preparation, poor curing, deterioration from a number of causes, and use of poor quality materials.

Concrete cracks can be hard to control and prevent and can lead to durability-related issues with concrete. Reclamation and others have published numerous studies analyzing the factors that cause concrete cracks and mitigation strategies with the goal of extending the service life of concrete and concrete repairs. . Such publications have examined factors such as poor substrate preparation prior to new concrete placements, concrete shrinkage reducing additives (Prevent-C), effects of bond strength between existing and new concrete, and durability issues due to materials. These studies indicate that while some progress has been made by the concrete repair industry there are still durability problems with many repair projects. Obviously, performing repeat repairs after only a few years of service is very costly.

Increasing the performance of a concrete repair and extending the service life of the structure as long as possible by reducing cracking is the goal. An alternative to standard concrete has been developed with the ability to for cracks to self-heal. Bacteria-based self-healing concrete has proven to successfully heal cracks up to 0.031-inch in width, survive in high alkali environments, remain dormant within concrete placements for up to 200 years, and thrive in wet environments [1].

In the spring of 2016 the technology was made available for the first time through the Dutch company Basilisk Concrete. This technology was patented by Dr. Henk Jonkers from the Delft University of Technology. Through funding provided by the Dutch government there are several projects with the Netherlands and South America that have used the bacteria-based self-healing concrete. With the support of Reclamation's Science & Technology program and the participation of Reclamation partners it is our goal to perform laboratory testing, field testing, and application for future concrete projects to evaluate the effectiveness of this technology.

Main Report

Alkaliphilic Spore-Forming Bacteria

2.1 Development of Self-Healing Concrete

Previous research on autogenous (self) healing in concrete shows that healing can occur in cracks of widths up to 0.004 – 0.008-inch this healing is dependent on several factors including the composition of the concrete mixture and its service environment. Portland cement used in concrete has potential for autogenous crack-healing. Healing can occur from several mechanisms, including hydration of non-hydrated or partially hydrated cement particles [2]. Another beneficial characteristic of concrete mixes is the ability to develop strength via a process called carbonation. The existence of carbon dioxide in water will react with the non-hydrated cement particles resulting in secondary hydration. The portlandite (calcium hydroxide) particles react with the carbon dioxide to produce calcium carbonate-based mineral precipitates [1]. As self-healing takes place within cracks the permeability of concrete reduces, and as a result the risk of water or chemicals reaching the steel reinforcement is limited.

Cement production accounts for nearly 10% of anthropogenic CO_2 emissions worldwide. However, adjusting cement content to improve autogenous healing is not a practical solution. Increasing cement content too high results in increased costs, higher shrinkage, and more problems with thermal cracking. On the other hand, using a high water/cement ratio to reduce lower greenhouse gas emissions results in poor durability concrete. Other engineered cement composites such as those optimized with PVA (polyvinyl alcohol) fibers result in the presence of high fiber content in the material matrix which suppresses localized brittle fractures. Additionally, it favors the formation of evenly distributed micro cracks of 0.0019-inch which in combination with tight crack widths and high cement content result in high self-healing efficiency [1].

With this challenge in mind, Dr. Henk Jonkers of the Delft University of Technology investigated the potential of mineral producing bacteria to improve the durability of concrete. Natural soils, alkali lakes, natural stones and mineral harbor groups were examined for the presence of a variety of non-pathogenic bacteria that have the ability to produce bio-minerals [3]. These specialized bacteria included alkaliphilic and endolithic as well as calcite-producing bacteria. The endolithic bacteria of genus Bacillus are particularly adaptive to high-alkaline environments. Due to their ability to survive in an environment similar to the concrete matrix and high alkaline pH, the alkaliphilic- and endolithic bacteria groups were chosen as self-healing agents (Figure 1).

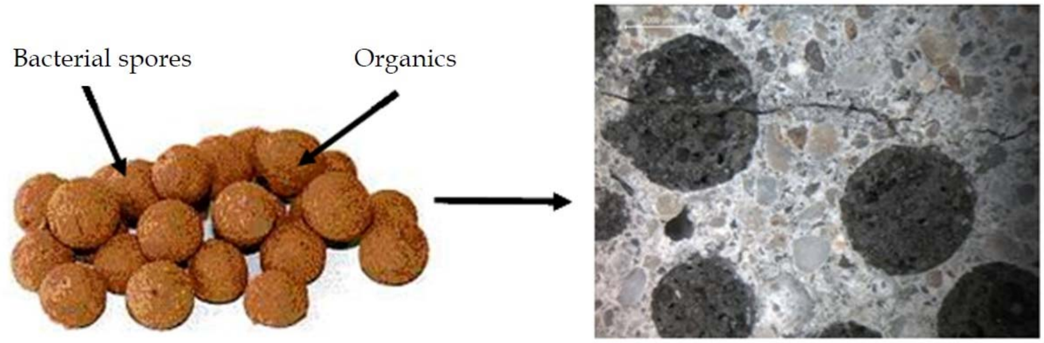


Figure 1. Self-healing bacterial clay particles (left) containing bacterial spores and organic bio-mineral precursor compounds (calcium lactate). Bacterial clay particles imbedded into the concrete matrix (right).

Early applications of bacteria-based mixtures to surface cracks resulted in effective sealing when applied to surface damage and inserted into cracks. Due to this early success, follow up studies focused on application of an alkali-resistant bacteria of the genus Bacillus within a concrete mixture. Results from this experiment showed that the bacteria spores germinated with the introduction of water. The product of the reaction produced crack-filling calcium carbonate as a byproduct of the bacteria feeding on a specified organic compound. Further investigations found that the self-healing potential of the bacteria was limited to concrete within 7-days of casting [1].

Due to these limitations, further studies focused on placing bacterial spores and their food source composed of organic compounds into porous clay particles. The clay particles with the bacteria and organic compounds were then introduced into the concrete mixture. Introduction of the bacteria and its food source within clay particles had the ability of protecting the spores and embedding the bacteria within the concrete matrix. The results of this study indicated that the calcium carbonate mineral precipitate successfully sealed cracks [1].

2.2 Bacterial Concrete Testing

Following the successful introduction of the clay particles into the concrete matrix further research focused on the impacts of the particles on the overall concrete characteristics. Analysis discovered that various organic compounds including, yeast extract, peptone, and calcium acetate influenced the compressive strength dramatically. However, it was discovered that choosing calcium lactate as the food source increased the compressive strength by 10%. Specimen testing followed which consisted of replacing a portion of the aggregate material (0.078 – 0.157-inch size class) with similar sized clay particles containing the self-healing bacteria (bacterial spores $5.99X10^{103}$ oz^{-1} expanded clay particles, corresponding to $3.1X10^{9}$ spores $inch^{-3}$ concrete, plus 5% w/w fraction calcium lactate, corresponding to 0.53 oz $inch^{-3}$ concrete) [1]. Bacterial dosage shows no influence on flexural and compressive strength characteristics for concentrations of bacteria up to $6.10 \text{ X } 10^{8}$ $inch^{-3}$ [4]. Prior to experimentation, the bacterial clay particles were oven dried to eliminate weight loss due to evaporation (one week at 40^{o}C). Several control specimens with similar aggregate composition using non-bacterial clay particles were also prepared. Table 1 reflects the concrete specimens for this experiment [1].

Table 1. Composition of concrete specimens. LWA refers to Liapor Sand R ¼ expanded clay particles

Compounds	Volume (in^3)	Weight (oz)
0.078 – 0.157 in. LWA	11.92	5.89
0.039 – 0.078 in. LWA	8.98	4.41
0.019 – 0.039 in. Sand	8.98	14
0.009 – 0.019 in. Sand	7.78	12.20
0.005 – 0.009 in. Sand	4.15	6.56
Cement CEMI 42.5N	6.91	13.55
Water	12.10	6.77
Total	**60.82**	**63.38**

During this trial the light weight aggregate made up 50% of the entire aggregate volume. Researchers theorized that the replacement of the sand and gravel with the clay particles would affect the overall strength of the concrete. Results of the test indicated that the compressive strength of concrete was reduced by 50% compared to specimens without the clay particles [1].

However, the tests on pre-cracked concrete slabs that were sawed from 56 day (2 months) water cured concrete cylinders found that the bacterial clay particles had a higher capacity for healing cracks. Evidence was provided from light microscopic images before and after permeability quantification. For the test, the pre-cracked concrete slabs (3.9 inch diameter, 0.6 inch thickness) were glued in an aluminum ring and mounted in a custom made permeability setup. The development of the cracks was achieved by controlled application of compressive-tensile stress at the 2 months cured specimens. The resultant cracks were of 3.1-inches in length running from top to bottom and a crack width of 0.006-inch running through the 0.6- inch specimen. After the cracks were formed each of the sets (6 of each) of control (clay particles without bacterial agents) and bacterial concrete specimens (clay particles with bacterial spores and organic compounds) were then submerged in tap water at room temperature for two weeks. During this time the permeability of the cracked specimens was quantified by automated recording of tap water percolation in time during a 24 hours period (Fig 2) [1].

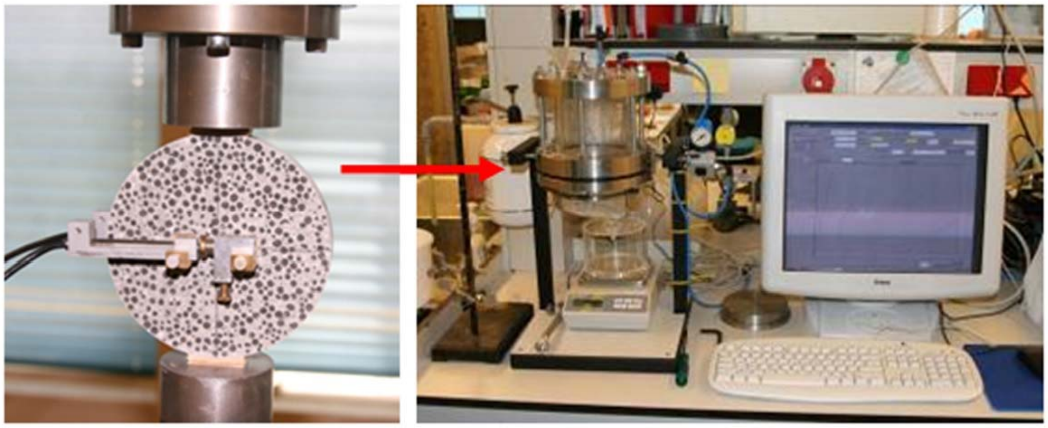


Figure 2. Pre-cracking of concrete slab and subsequent permeability testing

Results from this study were as follows:

- All six of the bacterial specimens were completely sealed with no resulting permeability (percolation of 0 fl oz. water/hr), in contrast
- Only two of the control specimens (clay particles with no bacterial elements) were visually healed. The remaining four control specimens recorded permeability (water percolation) values between 0 to 0.06 fl oz./hr.

Further microscopic examination of the cracks (on the side of the slab that was exposed to the water column) showed precipitation of calcium carbonate-based mineral precipitates for all specimens. Each set of specimens displayed unique mineral precipitation, the control specimens maintained precipitation near the crack whereas the bacterial specimens displayed mineral precipitation within the crack (Fig 3) [1].

Further observations on the cracked specimens and locations of the mineral precipitation indicate that additional chemical reactions take place during healing. The existence of carbon dioxide in the water would have reacted with the non-hydrated cement particles in the controlled specimens resulting in secondary hydration. The portlandite (calcium hydroxide) particles in the controlled specimens reacted with the carbon dioxide to produce calcium carbonate-based mineral precipitates. For the controlled specimens, the location of the precipitation near the crack rim would be due to the high concentration of calcium hydroxide and carbon dioxide due to the opposing diffusion gradients of the respective reactants. As calcium hydroxide diffuses away from the crack interior to the bulk water the carbon dioxide diffuses from the bulk water to the crack interior where it reacts with high concentrations of calcium hydroxide as evident from the following reaction [2]:

$$CO_2 + Ca(OH)_2 \rightarrow CaCO_3 + H_2O$$

The resulting calcium carbonate production (insoluble limestone) inside the crack in the control specimens was a product of the low amount of CO_2 already present in the water that existed inside the crack interior.

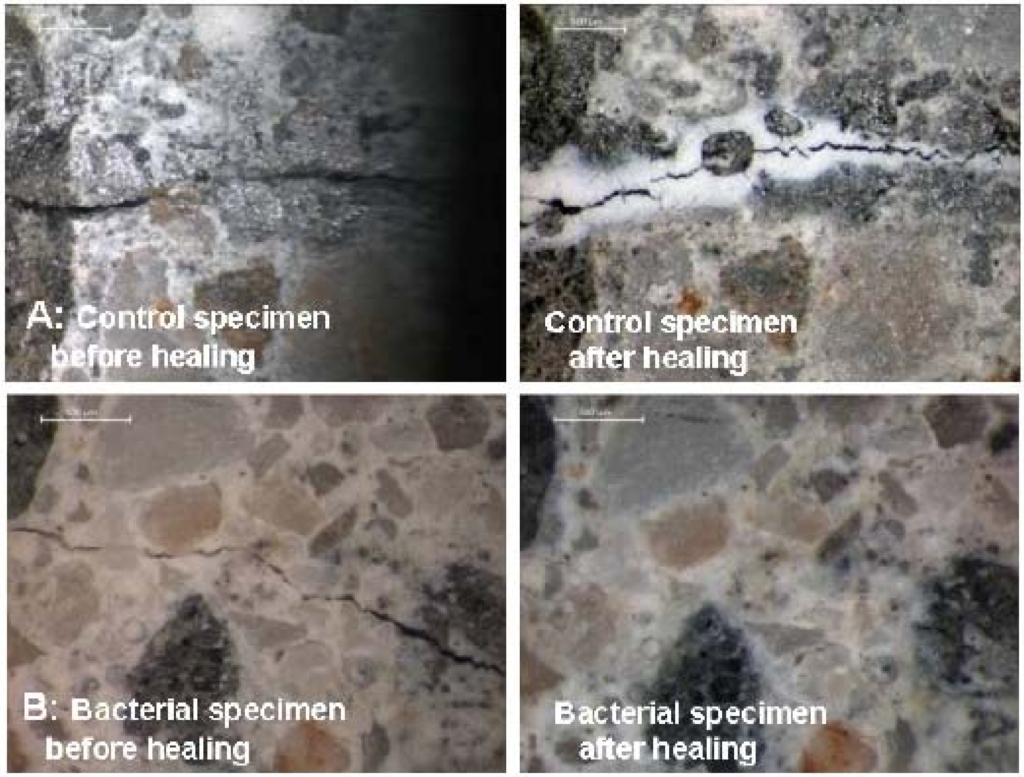


Figure 3. Light microscopic images (40 times magnification) of pre-cracked control (A) and bacterial (B) concrete specimen before (left) and after (right) healing (2 weeks submersion in water). Mineral precipitation occurred near the crack rim in control and inside the crack in bacterial specimens. Efficient crack healing occurred in all six bacterial and two out of six control specimens.

In contrast, the self-healing evident by the bacterial concrete was more efficient due to the metabolic conversion of calcium lactate by the bacteria [2]:

$$Ca(C3H5O2)2 + 7O2 \rightarrow CaCO3 + 5CO2 + 5H2O$$

Due to this process, the precipitation inside the crack contains a higher amount of calcium carbonate. The crack also benefits from the Portlandite remaining on the crack surface, as it reacts with the CO_2 present in the water resulting in additional calcium carbonate. Overall, test results for the bacterial calcium lactate conversion produced crack sealing as shown in (Fig 3) [1].

During testing all specimens used tap water for curing, self-healing, and permeability experiments. It is speculated that the presence of bacteria in the tap water could have assisted with the metabolic conversion of the calcium lactate to calcium carbonate-based materials [1].

With the success of this study, further attention was placed on reducing the amount of bacterial clay particles in the concrete mix from 50% of the volume of concrete to 20% of the total volume of the concrete. This resulted in a reduction of the compressive strength of concrete by 25%. Presently, a third generation of testing eliminated the need for the clay particles as carriers for the bacteria and calcium lactate. Using a compressed powder, the self-healing agents are housed securely and make up less than 1% of the volume of concrete. No negative effects to the compressive strength of concrete were discovered as a result of this change [5].

According to Basilisk Concrete use of the bacterial concrete can extended the service life of a structure by an additional 30% [6]. The self-healing capacity and overall cost of bacterial concrete is directly related to the quantity of product used in a conventional mix. The price structure of the bacterial concrete is between \$38/yd^3 to \$200/yd^3. A higher distribution throughout the concrete matrix would have the ability to heal cracks extending through the entire depth of the concrete panel. Limitations of this technology are directly related to the width of the crack, as the largest recorded crack width is 0.031-inch [7].

Self-healing Concrete Field Application

3.1 Irrigation Canal in Ecuador

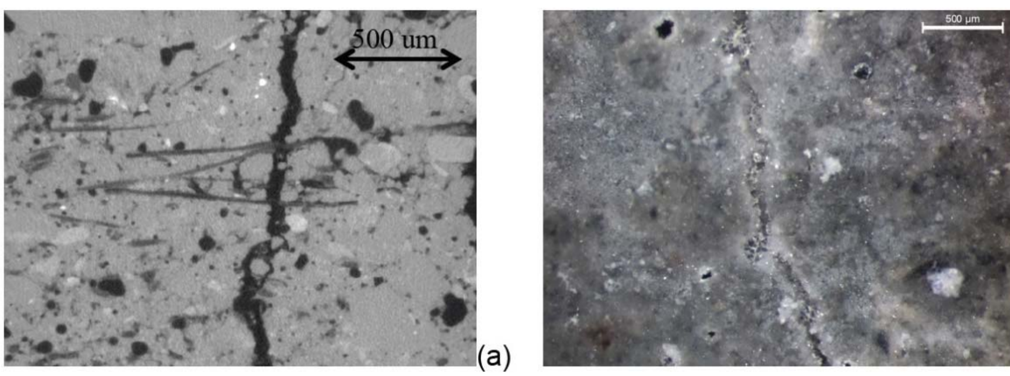
Field application using the 2nd generation bacterial clay particles took place in the highlands of Ecuador in July 2014. The goal of this project was to increase the yield of an irrigation canal that was losing 70% of its water via evaporation and infiltration. The canal was of approximately 15 miles and located in a region where the air temperature varied between 5^{o}C and 20^{o}C with the occasional temperatures dropping to zero. The canal was at an altitude of 1.7 to 2 miles above sea level. Typical conditions of the canal included walls and bottoms made out of compressed soil without concrete [8].

Prior improvements included lining the canal with conventional concrete without steel reinforcement. During the first year of operation the concrete began to crack with resultant water losses. In collaboration with the Delft University of Technology, the Foundation Imagine (NL) and the Catholic University of Santiago de Guayaquil (Ecuador) an alternative to conventional concrete was proposed consisting of self-healing concrete with the use of Abaca fiber for reinforcement.

To increase the tensile strength of the concrete an indigenous fiber called Abaca was chosen due to its availability and mechanical properties. The Abaca fibers would also contribute by controlling the crack widths developed during concrete replacement. Many structures in Ecuador had already been using the Abaca fibers as reinforcement for mortar to withstand seismic loads [8].

Prior to field application the concrete mix design was evaluated to validate flexural and compressive strength. The evaluation included testing two separate specimens, one specimen with the self-healing agents and the other a control specimen with no self-healing agents. The self-healing agent selected for this project contained bacteria with the ability to heal cracks by direct and indirect calcium carbonate ($CaCO_3$). The concrete mix included gravel with maximum size of 0.394-inch, sand, cement, lightweight aggregates (LWA) containing the self-healing agent and the Abaca fibers. The control specimen was comprised of the same elements without the self-healing agent. The self-healing agent was composed of a mixture of alkali-resistant bacteria spores with a food source composed of Calcium lactate – (0.09 oz/fl oz.) and yeast extract- (0.001 oz/fl oz.). The healing agent was then placed within expanded clay particles (Liapor R 0.079 – 0.157-inch, Liapor GmbH Germany) [8].

Compression testing revealed that the mix with the self-healing agent had a compressive strength of 4,351 psi, and the mix without the healing agent had a strength of 3,770 psi. To further test the self-healing capabilities of both mixes a crack of 0.0055-inch was produced in the concrete samples via the three-point bending test. The specimens were then allowed to heal with the cracked surface in contact with water to simulate field conditions. Observations of the specimens after 6 weeks indicated crack sealing (Figure 4) [8].



(a) (b)

Figure 4. (a) CT image showing Abaca fibers bridging the crack, (b) Crack sealing.

Concrete placements took place at approximately 1.80 miles above sea level with a temperature reading of 5°C. The canal dimensions included a square cross section of 39.4 X 39.4-inch and a wall and bottom thickness of 3.9-inch. Three linear meters of concrete linings with self-healing agents were placed and three linear meters of control concrete without agents. Materials such as sand and gravel were provided by the local farmers and water for mixing the concrete was provided by the local water in the canal. The concrete mix sequences remained consistent with the building practices of Ecuador. The Abaca fibers used for tensile strength were cut to a length of 0.8-inch. During concrete mixing operations a superplasticizer was used to evenly distribute the Abaca fibers and for proper workability of the mix. The placement consisted of 3,300 fl oz. of concrete [8].

No signs of segregation were evident when the formwork was removed after 3 days. Five months after resuming normal operations an inspection of the area revealed no signs of cracking or deterioration. In the laboratory, six months later the bacterial concrete test specimens that were cracked and allowed to cure showed crack healing [8].

3.2 Concrete Wastewater Treatment Tank

In partnership with the Dutch company Verdygo a wastewater treatment tank in Limburg, the Netherlands will be constructed using self-healing concrete [9]. The tank is composed of steel reinforcement with prefabricated concrete elements with dimensions of 23 ft. X 5 ft. X 1 ft., (Figure 5). Full operation of the treatment tank will begin in the fall of 2016 [10].

Figure 5. Concrete Wastewater Treatment Tank in Limburg, the Netherlands

3.3 Groninger Forum

Planned for completion in 2017 the Groninger Forum will be a cultural center housing a library, cinema, and portions of the Groninger Museum. The structure will have a 5-level basement housing a 390-space parking garage along with a 1500-space bicycle lot [11] and have 10-storys above ground, (Figure 6). Located in Groninger, the Netherlands the complex structure was designed to withstand increased seismic activity related to gas extraction from the Groninger gas field [12].

Currently, the substructure excavation has been completed and it is comprised of exposed diaphragm walls. Following completion, it was discovered that several areas had evidence of sweat stains and small leaks due to micro cracks [13]. It was speculated that high groundwater pressures may have contributed to the micro cracks. In collaboration with Basilisk Concrete the leaks would receive application of a self-healing repair mortar.

Prior to application, the cracks were cut to approximately 1.96-inch deep to provide a good bonding surface. A fast setting cement was then applied to the cracks to mitigate the water flow coming from the cracks. After the fast setting cement cured, the self-healing repair mortar was applied to the areas, (Figure 7). Due to the low-shrinkage properties of the mortar there was good adhesion with the underlying concrete. Fibers were also added to the mortar to provide added tensile stress to the repair areas and reduce micro-cracking. After ten weeks of application the areas were assessed and the existing cracks appeared to be watertight [13].

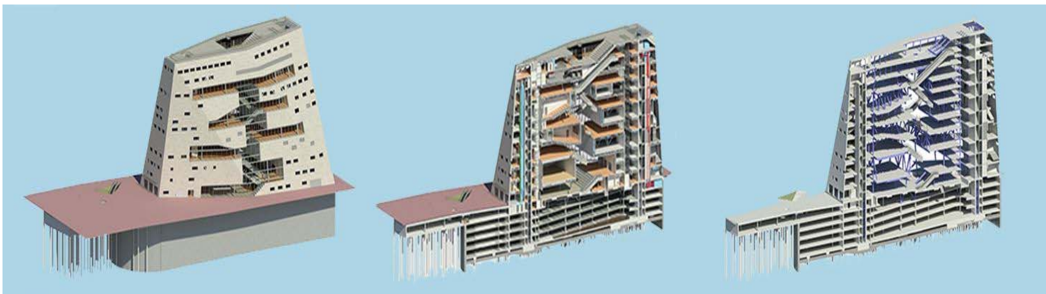


Figure 6. Groninger Forum structural model

Figure 7. Groninger Forum Diaphragm wall repair with bacterial mortar

3.4 Parking Garage Apeldoorn

Following the success of a small pilot study performed on a garage in Vissingen, the Netherlands the use of a self-healing liquid repair system was applied in two phases to an intermediate floor in the Parking Garage Apeldoorn [14]. The goal of this project was to eliminate leakage from the intermediate floor and prevent damage to vehicles and reinforcement. The project would consist of using a bacterial liquid repair system that would cover a total of 129,167 ft^2. The first phase took place in October of 2014 and the second phase in March of 2015. Both floor areas consisted of an equal surface area of 64,584 ft^2 [15]. The liquid repair system was chosen for its ability to be applied externally with low-pressure in contrast to conventional injections that could cause damage to the existing polymer topcoat [14]. Each phase received a different application, for the first 64,584 ft^2 the bacterial liquid solution was applied through the use of scrubbing machines (Figure 8). For the second phase the bacterial liquid solution was distributed using hand-carried high pressure spraying devices (Figure 9) [14].

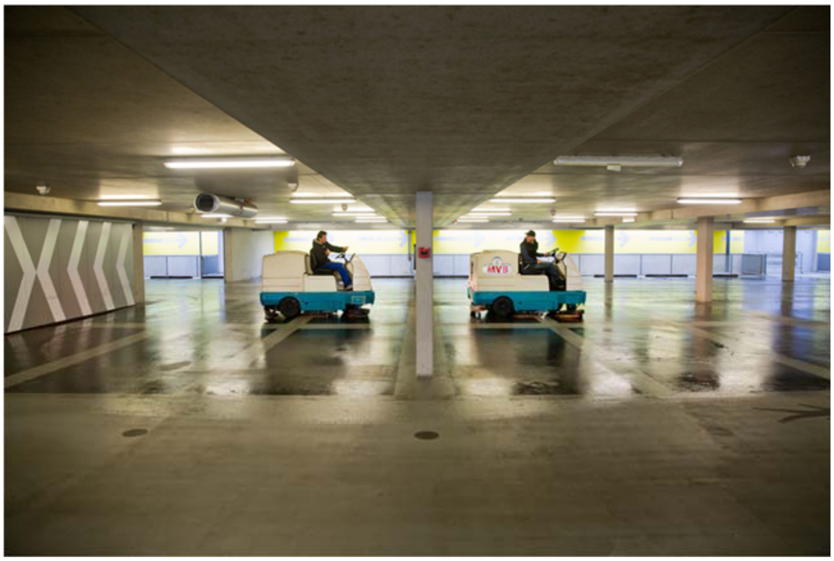


Figure 8. Application of bacterial liquid with scrubbing machines

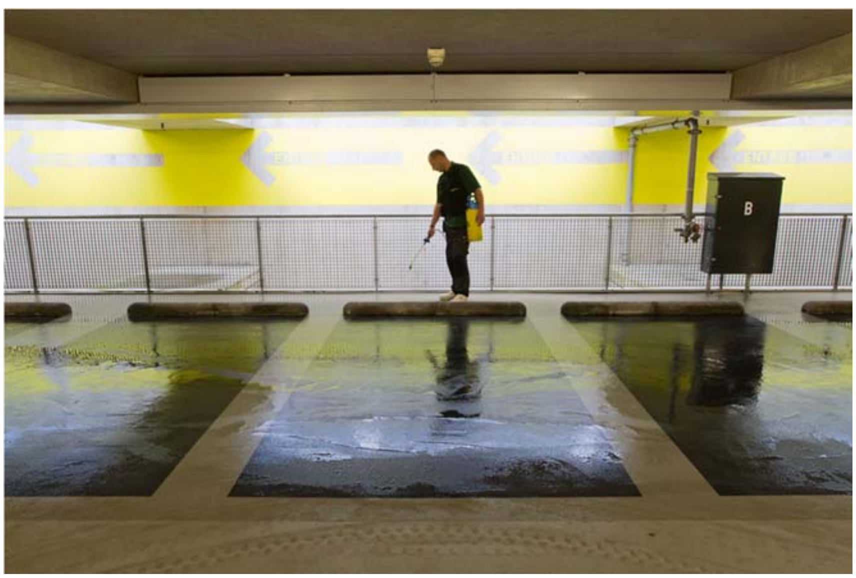


Figure 9. Application of bacterial liquid with hand-carried spraying device

According to the supplier Basilisk concrete, the low viscosity of the bacterial liquid would allow penetration through the small pores in the polymer topcoat and hairlines cracks [14]. However, some underlying cracks of larger width did not allow the liquid to produce the necessary formation of the calcium carbonate. Therefore, successive applications on the topcoat were necessary to produce even application of the bacterial liquid.

Basilisk concrete reported that results were evident after 6 weeks, as formation of limestone was present in drilled cores, with the majority of the limestone occurring deeper in the cracks. Further studies revealed a reduction in water penetration. After a period of up to six months the surfaces did not show any evidence of wet spots even after a rainy period [14].

During the course of application several tests were performed to measure the effectiveness of the bacterial liquid. The repair system was tested at regular intervals by analyzing the level of water penetration at the position of the crack. The procedure was performed by placing wooden frameworks at specific locations on the floor. Frames were filled with 300 fl oz. of water, the water penetration rate was tested in accordance with a protocol defined by the registration of the number of continuous drops per minute. Prior to treating the cracks a measurement of 45 drops per minute per crack (0.008-inch to 0.0118-inch wide) was recorded. After a period of four months following the treatment the number of drops was reduced to a single drop per minute [14].

Nebraska/Kansas Area Office Concrete Cracking Case Studies

Over the course of the last five years the Nebraska/Kansas Area Office has faced challenges with concrete cracks as a result of damage from freeze-thaw and alkali-silica reaction at several dams. During that time concrete spillway projects included over $2 million in concrete repairs for Glen Elder Dam Spillway structure and over $2.5 million in concrete repairs for Kirwin Dam Spillway and Stilling Basin. Due to the extensive nature of the deterioration at Kirwin Dam and Glen Elder Dam concrete repairs exceeded their original projected costs by almost 20% at Kirwin and 60% at Glen Elder. During concrete removal the deterioration boundaries often expanded and depths of repair varied including up to full depth removal (18-inches). Completed concrete replacement projects at both dams have also produced concrete that has exhibited minor flaws due to factors such as quality of local aggregate, overlay surface preparation, and extensive shrinkage cracking.

4.1 Glen Elder Dam

Glen Elder Dam is a zoned earthfill embankment located across the Solomon River in northcentral Kansas. The spillway is located at the right abutment of the dam and consists of an excavated earthen inlet channel, a concrete inlet apron (approach slab), a concrete radial gate structure, a downstream chute, a hydraulic jump stilling basin, and an excavated outlet channel.

The gate structure contains twelve 50-foot-wide by 21.76-foot-high radial gates (seated on top of a concrete ogee crest) and eleven 4-foot-wide separating piers. The gate bays between piers are numbered from the left abutment (Bay 1) to the right abutment (Bay 12). Longitudinal joints are located at the center of each bay. The inlet apron extends across the spillway from the left abutment to the right abutment, directly upstream of the gate structure for a distance of 50 feet. Longitudinal joints divide the inlet apron into a series of 18-inch-thick reinforced concrete slabs which are numbered from the left abutment (Slab 1) to the right abutment (Slab 16). Each slab has a 6-foot-deep, 18-inch-thick buried cutoff at the upstream end and is anchored with #11 bars placed on a 6-foot, 3-inch pattern around the perimeter. These anchors are angled upstream at 30 degrees from vertical with the top of the anchor located downstream of the base and extend vertically 12-feet from the base of the inlet slab into the foundation bedrock. The slabs are typically 40 feet wide so the longitudinal joints between the adjacent panels do not align with the longitudinal gate structure joints except at the spillway centerline [16].

The invert of the excavated inlet channel upstream of the inlet apron is approximately 1 foot higher than the inlet apron invert which creates a grassy berm upstream of the spillway. As a result, water which is located on top of the inlet apron (either from receding reservoir levels or precipitation) becomes trapped and remains ponded in this area (Figure 10) [16].

Figure 10. View of approach area of spillway. The soil berm trapped water on the apron, leading to deterioration of the concrete.

The concrete in both the inlet apron and the pier noses/gate structure were exhibiting areas of extensive deterioration. Results of a concrete core testing program [17] showed that the structure was suffering from freeze-thaw damage largely caused by absorptive aggregate. Cracking from freezing and thawing was then promoting alkali-silica reaction. There was also evidence of carbonation which could lead to susceptibility to reinforcement corrosion. Early evaluation of the approach apron of the structure indicated that about 43 percent of the inlet slab area was in need of repair with deterioration measured as deep as 14-inches during the concrete coring program [18]. A plan view (Figure 11) shows which areas were originally thought to be sound concrete and rough estimates of the depth of deterioration in the areas of damaged concrete. However, once repairs were started, the amount of damaged concrete was discovered to be much larger (Figure 12) [16].

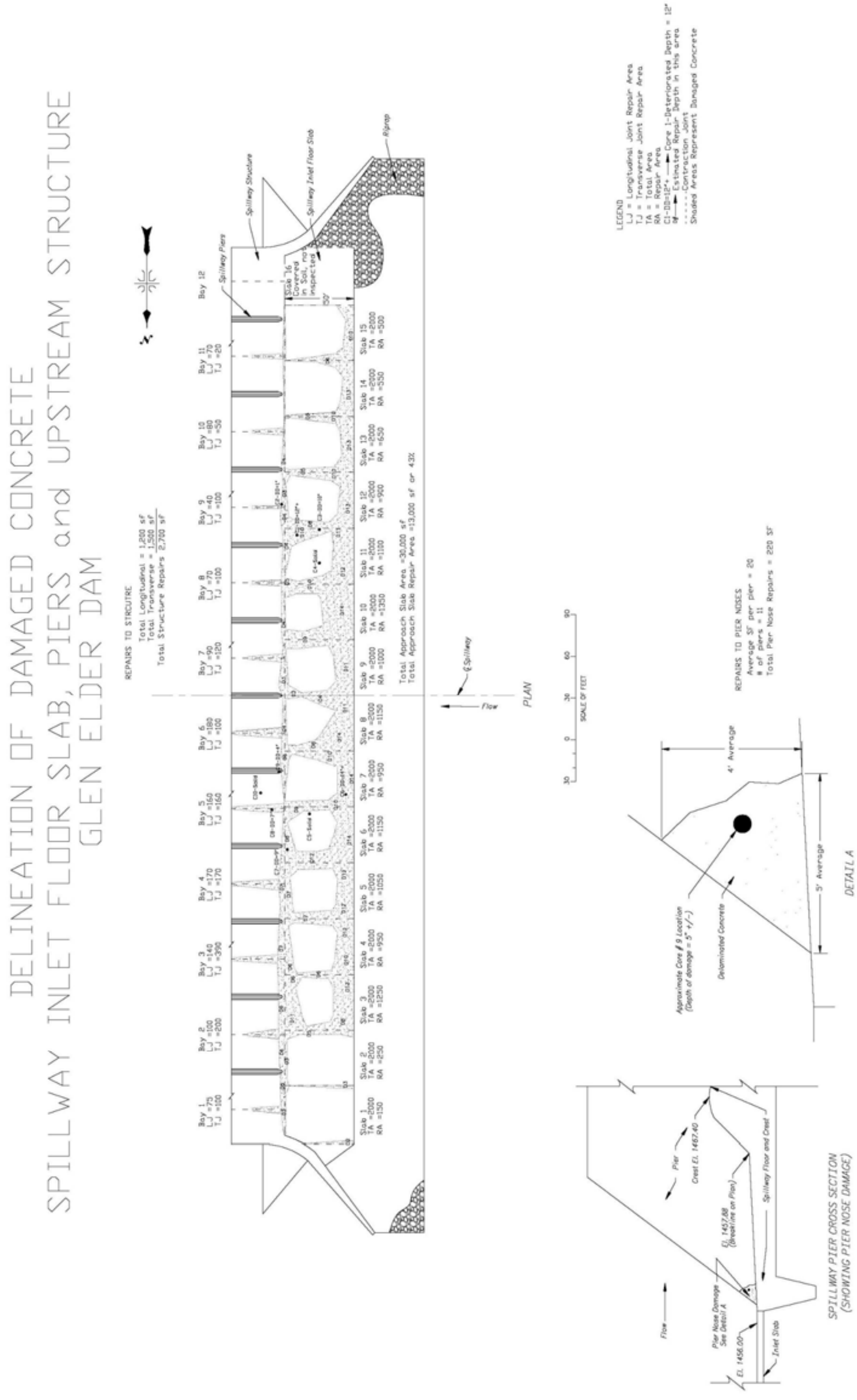


Figure 11. Early estimate of damaged concrete

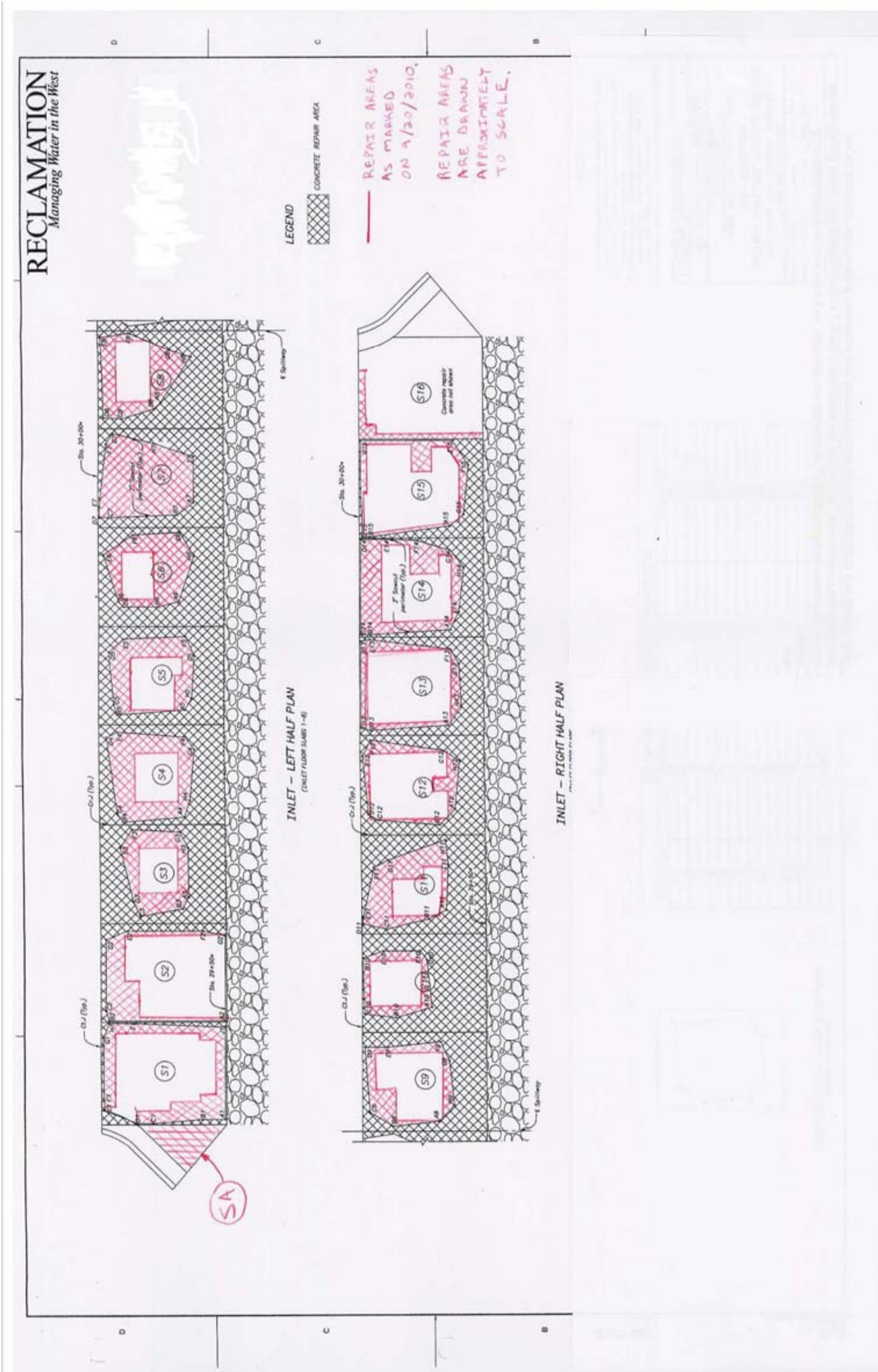


Figure 12. Revised area of concrete damage

The repair consisted of removing deteriorated concrete using hydro demolition methods and then placing new concrete back to the existing lines and grades. In most areas, damaged concrete was removed to a depth of about 6-inches, leaving about 12-inches of the original concrete. In some areas, due to the poor quality of the concrete, it was excavated down to the foundation. In addition, for some areas, no concrete was removed, so full depth areas of existing concrete were left in place (Figure 13) [16].

Figure 13. Example of concrete removal with some original concrete remaining

The replacement concrete mixture is shown in Table 2. The nominal maximum size for the course aggregate was ½-inch, and it contained sand sized particles. Because of that, the asmixed concrete aggregates contained about 50% sand [16].

Table 2 – Concrete Mixture Proportions

Cement Lbs./yd^3	Water Lbs./yd^3	Course Aggregate Lbs./yd^3	Fine Aggregate Lbs./yd^3	Air Content %	Other Admixtures
588	265	1240	1736	6	Water Reducing High Range Water Reducing

Using smaller aggregate usually increases the paste content of the concrete, which can exacerbate shrinkage problems. The smaller aggregate size used by batch plants in this area of Kansas is typical, since sources with larger aggregate are not readily available. Obtaining larger aggregate to use for the replacement concrete was deemed too costly and restrictive [16].

After initial placements were performed in the late summer and fall of 2010, restrained shrinkage cracking was observed in the new concrete (Figure 14). The occurrence of this cracking was not unanticipated, but the number and size was disconcerting [16].

Figure 14. View of shrinkage cracking first observed within one to two weeks of concrete placement.

4.2 Kirwin Dam

Kirwin Dam is a rolled earthfill structure, with a structural height of 169 feet and a crest length of 12,646 feet. About 9,537,000 cubic yards of earth and rock and 44,000 cubic yards of concrete were used in constructing the dam, spillway, and outlet works. The spillway is located on the right abutment of the dam and consists of a concrete inlet apron (approach slab), a mass concrete ogee crest, fifteen sluiceways, a hydraulic jump stilling basin, and an outlet works through the dam that acts as a canal and river outlet.

The fifteen gated sluiceways are 5- by 5-foot and provide flood control releases. The spillway, located in the right abutment about 4,000 feet southeast of the old river channel, is an ungated, overflow structure. It consists of a 1,200-foot long, unlined, shallow approach channel with approximate bottom elevation of 1720 and width of 90 feet. The spillway crest at elevation 1757.3 is 400 feet wide.

The ogee crest is separated into seven sections, and the longitudinal joints create 13 panels from the top of the spillway to the stilling basin. Transverse joints create 7 panels that extend from each abutment. Each panel is comprised of 18-inch-thick reinforced concrete slabs.

Concrete deterioration throughout the spillway was localized at the longitudinal and transverse joints. Similar to Glen Elder Dam, the concrete core tests revealed freeze-thaw damage due to absorptive aggregate and carbonation which could lead to reinforcement corrosion. Investigations on the spillway indicated that the concrete panels exhibited sound concrete further away from the joints. The repair consisted of removing deteriorated concrete using hydro demolition methods and then placing new concrete back to the existing lines and grades. In some areas, damaged concrete was removed to a depth of about 6-inches, leaving about 12-inches of the original concrete. In a larger portion of the areas, due to the poor quality of the concrete, excavations extended down to the foundation. As a result, the original estimated concrete removal and replacement quantities increased by almost 20%. Additionally, during original construction the reinforcement mesh was not placed appropriately thereby fluctuating between 6 to 2-inches below the concrete surface (3-inches required) [19].

The contractor used several replacement concrete mixtures but predominately used a mixture with a nominal maximum size of ¾ inch for the course aggregate. The mixture also contained sand sized particles and the final as mixed concrete aggregates volume contained about 50% sand.

Using smaller aggregate usually increases the paste content of the concrete, which can exacerbate shrinkage problems. The smaller aggregate size used by batch plants in this area of Kansas is typical, since sources with larger aggregate are not readily available. Obtaining larger aggregate to use for the replacement concrete was deemed too costly and restrictive.

After initial placements were performed in the summer, restrained shrinkage cracking was observed in the new concrete. The occurrence of this cracking was not unanticipated, but the number and size was disconcerting. Reclamation and contractor representatives concluded that other factors for hairline cracks were due to the fluctuating reinforced mesh, and inadequate preparation of the repair areas prior to placing concrete. Due to the successful performance of the shrinkage reducing additive at Glen Elder Dam in 2010, application of Prevent-C was also successfully used at Kirwin Dam.

Application of Prevent-C Additive

During the spring of 2010, Reclamation was introduced to Premier Magnesia, LLC's concrete shrinkage reducing additive called Prevent-C. The additive's shrinkage reduction properties help to prevent cracking or curling, and as a result would minimize water and salt infiltration, reduce required maintenance and repairs, and improve overall concrete durability. The product was characterized as being more effective and less costly than currently available technologies.

During a trial placement, the Premier product was used on two placements at Glen Elder Dam. The results of the trial would be compared to similar placements made the previous year for concrete placed without the additive. The trial placements occurred in early May. Two areas were approved for the trials including one bay area placement (B7, Figure 15) and one approach slab placement (S10, Figure 16) [16].

Figure 15. Bay 7 ready for trial concrete placement using concrete containing the Premier Magnesia additive.

Figure 16. Slab 10 ready for trial concrete placement using concrete containing the Premier Magnesia additive.

For comparison crack mapping, two similar areas with about the same shape were selected to map cracks (B3, Figure 17 and S3 Figure 18). One bay area placement (B8 and 9, Figures 19, shown after concrete placement) was added to the trial since material was available and the contractor had time to place additional concrete. A total of approximately 100 cubic yards of concrete were placed in three separate placements. The first placement was about 70 cubic yards, and the second and third were about 15 yards each [16].

Figure 17. Slab 3 placement made with concrete without the Premier Magnesia additive.

Figure 18. Bay 7 placement made with concrete without Premier Magnesia additive.

Results of the trial indicated that the Premier Magnesia product had significantly less cracking. One large test placement saw cracking reduced about 90% over the comparable placement made the previous fall. Overall, about 110 cubic yards of concrete were placed with the Premier Magnesia product. The first placement was about 70 cubic yards, and the second and third were about 15 yards each [16].

Figure 19. Placement B8/9 made with concrete containing the Premier Magnesia additive.

Materials Engineering Research Laboratory personnel traveled to the site just prior to the placements to map cracks from comparable placements made the fall before (Figures 20 and 21). The following day MERL personnel observed the concrete placements of concrete containing the Premier additive. In addition, executives from Premier and personnel from their laboratory were on site during the trial placements. Their lab ensured that the Premier additives were added properly and that concrete met the specified fresh properties before it was placed [16].

Typical shrinkage cracking mapping and measurement

Figure 20. Typical shrinkage cracking mapping and measurement.

Figure 21. Measuring crack openings.

The Premier product was manually added to the mixture by personnel from their lab. Each truck was loaded with about half the concrete batch, then the Premier products, comprised of a liquid component and a dry powder, were added by hand. The rest of the concrete ingredients were added to the truck, it was brought to mixing speed for the appropriate time, and fresh properties were measured. After that, trucks drove to the site, fresh properties were measured again, any adjustments were made as appropriate, and then the concrete was placed using a conveyor system.

The trial placements were completed by early afternoon. In general, difficulties were noted in achieving the specified air content and mixtures free of clumps and balls of poorly mixed material. However, these were likely issues related to batching and mixing and not the Premier additive, since these problems were noted for several other placements.

Three weeks later, personnel from MERL and executives from Premier returned to the site to examine the trial concrete placements. Only the placement for slab 10 (S10) showed any cracking (Figure 22), and that was significantly less than cracking observed in the comparison slab.

Figure 22. Slab 10 repair made with the trial concrete

The cracking in S10 was measured and documented in a drawing. The next day, construction activities at the site were halted due to flooding (Figure 23), and were resumed several months later [16].

Figure 23. Approach apron under water after flooding

Figures 24 and 25 are drawings showing the approximate crack locations and widths of the observed cracks. Since the placement for Bay 8/9 was not in the original plan, a comparable placement form last year was not evaluated. However, there was no cracking observed in that placement. Results show that cracking was either greatly reduced or completely eliminated when cracking was compared between concrete with and without additive. In addition, surface areas of open cracks were estimated from crack length and opening data. Table 3 shows those comparisons [16].

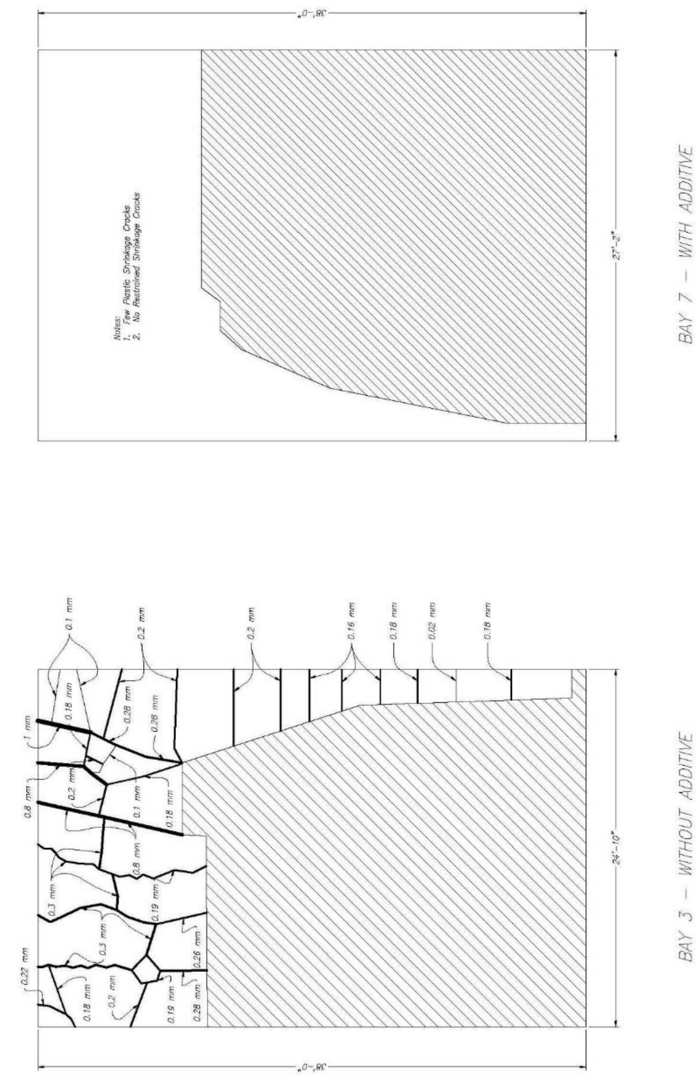


Figure 24. Comparison of bay placements made with and without the shrinkage reducing additive.

Figure 25. Comparison of slab placements for concrete placements made with and without the shrinkage reducing additive.

During the Kirwin Dam Spillway and Stilling Basin concrete repair and replacement project several new concrete placements began to exhibit hairline cracking. Investigations by Reclamation and contractor representatives did not produce a resolution as no determination of one specific factor could be pinpointed. It was determined that several factors could be at play such as the fluctuating reinforcement mesh, preparation of surfaces prior to placements, and ambient temperature changes. Under the advice of MERL representatives the Reclamation project managers advised the contractor of the successful trials with the use of Premier products at Glen Elder Dam. Following negotiations to share the cost of the additive with Reclamation the contractor began using the Premier products after September 2014. Due to this relatively new technology the contractor requested representatives from Premier Magnesia, LLC to assist the B&B Redi-Mix, Inc. plant operators with mix proportions, monitoring new placements, and provide technical guidance. Placements were performed by utilizing a forklift and concrete hopper to transport the concrete to each panel form. The concrete was then consolidated using concrete vibrators and screeding was performed using an electrical powered aluminum rolled screed filled with rocks for weight. The concrete was then cured with SpecChem Pavecure white curing compound and pre-wetted water curing fabric. Immediately following the first placements the hairline cracks were no longer evident. The successful use of the Premier products at Kirwin Dam continued and all placements after September began using the Premier products to combat the hairline cracking issues [16].

Table 3. - Comparison for Crack Data

Placement	Crack Area Opening, in^2	Ratio Crack Area to Concrete Area, $(ft.^2/ft.^2) \times 10^{-5}$
B3 (without additive)	20.4	39
S3 (without additive)	58.7	26
S10(with additive)	6.5	2.6
B7 (with additive)	0	N/A
B8/9 (with additive)	0	N/A

Conclusions

Bacterial based self-healing concrete and repair products has been successfully used in several different structures, including irrigation canals, parking structures, and retaining walls.

This product has proven to consistently heal micro-cracks up to 0.031-inch when used in conventional concrete mixes and also by gravity-feed methods (ponding) when applied in liquid form. Additionally, the bacteria is non-pathogenic and does not produce health risks to users. According to the supplier Basilisk concrete there is a potential for extending the service life of a structure by an additional 30%. Currently, the cost of the bacteria concrete ranges from $38/yd^3 to $200/yd^3 based on the desired distribution throughout the concrete matrix.

In investigating the cause of cracking for the original concrete placements at Glen Elder Dam and Kirwin Dam it was discovered that cracks were produced by freezing and thawing of absorptive aggregate. As water infiltrated the concrete it resulted in freeze-thaw damage and created a risk for reinforcement corrosion. The introduction of Premier Magnesia LLC's product to new concrete placements at both projects resulted in reducing shrinkage cracking up to 90% compared to control placements without the use of the product. This success has translated to full use at Echo Dam which is located in Summit County, Utah. Additionally, use of the Premier product is being considered for the Webster Dam Spillway Replacement project.

Recommendations

Field trials of the bacterial self-healing concrete have been discussed with the Nebraska/Kansas Area Office and additional laboratory testing would be necessary to acquaint CGSL staff and Reclamation engineers with the use of the product. Discussions with the supplier are ongoing including travel to Denver by representatives from the company or a supplier in the U.S. to oversee laboratory and field testing.

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