Self-Healing Coatings for Steel-Reinforced Infrastructure

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Abstract

The maintenance of infrastructure costs billions of dollars annually and disrupts people’s travels plans every day. A significant source of deterioration in infrastructure is the corrosion of steel reinforcement in concrete. A typical option for the protection of steel reinforcement is an epoxy coating, but when damaged, this coating becomes ineffective. A previous project investigated developing an experimental self-healing epoxy coating containing microcapsules. These microcapsules contained tung oil as a healing agent. The resulting coating was applied to steel rebar that was incorporated in reinforced concrete samples and subjected to accelerated corrosion testing. The results were promising, with the experimental self-healing epoxy coating lasting at least 300% longer than that an unmodified epoxy coating. However, there were no differences between damaged and undamaged experimental samples. This report presents the results of experimentation using more severe damaging techniques to show differences in the service lives of damaged and undamaged experimental samples. The project resulted in a new protocol for consistent and sufficient damage to epoxy coatings, which will allow for systematic study of novel rebar coatings. The resulting data indicate a promising future for self-healing coatings in infrastructure applications.
Executive Summary

Steel bar placed in concrete, called rebar, is a central component in the construction of modern infrastructure. Over 7 billion cubic yards (6.4 billion cubic meters) are in place in the United States, with an additional 380 million cubic yards (348 million cubic meters) constructed each year. Corrosion of said rebar constitutes a large portion of infrastructure deterioration as a whole. Epoxy coatings are typically applied to rebar to protect it from deterioration and extend infrastructure service life. However, if any portion of this epoxy coating is damaged, water that diffuses through the concrete can rust the rebar quickly.

To address the growing need for more resilient coatings to prevent rebar corrosion and subsequent reinforced concrete deterioration, self-healing coatings for rebar were investigated by a previous MQP team. Initial testing proved promising and further interest in this particular type of coating has followed. One limitation of the initial work was the inability to sufficiently and consistently damage coatings prior to embedding rebar in concrete in order to test the self-healing capabilities of the coating. This project aimed to create a procedure in which these coatings could be damaged to show distinguishable differences in service life between damaged and undamaged samples through accelerated corrosion testing.

Coatings containing 10 wt.% and 20 wt.% microcapsules were formed by combining microcapsules with a two-part epoxy coating. The procedure used to encapsulate tung oil in a poly(urea-formaldehyde) shell was based on the work of Samadzadeh et al. and is described in greater detail in Chen et al. A graduate assistant synthesized and provided the microcapsules. The microcapsules and the epoxy resin were combined using a planetary centrifugal mixer. Upon time of application, the microcapsule resin was hand stirred into the curing agent and the samples were
dip-coated. A total of 18 rebar samples were dip-coated with the self-healing coatings. An additional nine rebar samples were dip-coated with a control epoxy coating.

Damaged rebar samples were made by making a cut or through impact. Rebar had a 30° diagonal cut made opposite the rebar’s groove starting at 4 in (10.16 cm) and ending 1 in (2.54 cm) from the bottom of the rebar. These cuts were made by hand using a utility knife. An impact force was applied to other samples using an impact tester in order to damage coatings. The impact head of the tester had a spherical nose. The tester held a drop weight weighing 11 lbm (5 kg). The height the weight dropped from was 3 in (7.62 cm). After being damaged, all coatings were allowed to heal for three days before the rebar was embedded in mortar.

Along with the rebar being embedded in mortar, cylindrical mortar test specimens were made for compression testing. Compression testing and sample preparation was performed in accordance with ASTM C39/C39M-15a. The compression test cylinders were tested after three, seven, and 28 days of curing. These data provide a representative graph for the development of the mix design strength. Samples for each cure period were tested to determine whether the strength of the mix showed adequate curing progress.

Accelerated corrosion testing is a useful way to measure relative service lives of a particular coating material compared to another. Accelerated corrosion testing was performed in the manner used by the previous project group and proposed by Ahmad. A total of 30 samples underwent accelerated corrosion testing. The rebar samples had the self-healing epoxy coating applied to them containing differing weight percentages of microcapsules. Uncoated samples as well as samples with an unmodified coating were used as controls.

The accelerated corrosion testing of the rebar samples proved to be an effective method for inducing corrosion within the rebar samples. One-way ANOVA was used to evaluate to statistical
significance of trends. With a confidence interval of 90%, it was concluded that the damaged coating samples had shorter service lives than those of the undamaged coatings. The modified damaged coatings were able to last longer than the undamaged unmodified coatings, showing that the modified coatings had a better overall service life in general. To attain a higher confidence interval, testing on a larger testing population is recommended as outliers in the data had an effect on statistical analysis.

When examining impact damaged rebar samples after testing, the impacted side showed greater signs of corrosion than that of the undamaged backside. This shows that the impact damaging had distinguishable effects on the rebar sample during the accelerated corrosion testing. Samples that were not impact damaged showed corrosion beginning in many locations. From this it can be determined that impact damaging does have an effect on the coatings ability to self-heal when under accelerated corrosion testing.

In summary, self-healing coatings for rebar were prepared by incorporating microcapsules containing tung oil into a conventional epoxy coating. The use of impact damaging was implemented in order to create distinguishable performance differences between damaged and undamaged epoxy coatings. This method proved to be successful with the impact damaged experimental coatings still lasting longer than that of the undamaged unmodified coatings. The impact damaged samples also showed distinguishable effects on coated rebar during accelerated corrosion testing and it is recommended that this damaging technique be used in the future. It can be concluded that the experimental coating is a more effective means of protecting steel reinforcement than that of an unmodified coating.
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Introduction

The American Society of Civil Engineers (ASCE) provides a quadrennial analysis of the nation’s infrastructure. Letter grades are assigned to infrastructure overall as well as to individual categories such as roads, bridges, and hazardous waste management. The most recent analysis, conducted in 2013, assigned a letter grade of D+ to infrastructure in the United States.\(^1\) This grade illustrates a growing problem, as repair and maintenance estimates total billions of dollars.\(^2\) These repairs will soon be necessary, as neglecting them will lead to transit delays and have an adverse effect on the environment.

Steel bar placed in concrete, called rebar, is a central component in the construction of modern infrastructure. Over 7 billion cubic yards (6.4 billion cubic meters) are in place in the United States, with an additional 380 million cubic yards (348 million cubic meters) constructed each year.\(^2\) Corrosion of said rebar constitutes a large portion of infrastructure deterioration as a whole. Epoxy coatings are typically applied to rebar to protect it from deterioration and extend infrastructure service life. However, if any portion of this epoxy coating is damaged, water that diffuses through the concrete can rust the rebar structure quickly. This rust has a larger volume than the original steel, producing internal stresses during corrosion that crack the concrete cover from within.\(^3\)

To address the growing need for more resilient coatings to prevent rebar corrosion and subsequent reinforced concrete deterioration, self-healing coatings for rebar were investigated by a previous MQP team.\(^4\) Initial testing proved promising and further interest in this particular type of coating has followed. One limitation of the initial work was the inability to sufficiently and consistently damage coatings prior to embedding rebar in concrete in order to test the self-healing capabilities of the coating. This project aims to create a procedure in which these coatings can be damaged to show distinguishable differences in service life between damaged and undamaged samples through accelerated corrosion testing.
Background

Design of Steel Rebar

Steel rebar is used in conjunction with concrete to take advantage of the various strengths that each material brings. Steel has a high tensile strength, while concrete provides a high compressive strength. In order to ensure that stress will transfer from loaded concrete to the reinforcing rebar, a strong interfacial bond must be created between the steel and concrete.

Rebar is grooved to promote bonding between the steel reinforcement and concrete. When coatings are added to the rebar, the shear bond strength may decrease. This can prove catastrophic in the event of natural disasters such as earthquakes, which produce large shear stresses. When a coating is too thick, the grooves in the rebar are less pronounced and pullout strength also decreases. Poor adhesion of the coating can cause it to delaminate from the rebar when placed under tensile stress and compromise the system if any interface were to fail.

Environments that Cause Corrosion

Environments that have extreme temperature changes, high rainfall, or require surface de-icing tend to see the effects of corrosion faster. Corrosion in these settings is due to the low pH of water and salt solutions. Chloride ions also diffuse through concrete, often leading to electrolytic corrosion. These factors provide a suitable environment in which steel can corrode and the structure can be put in jeopardy.

Geographically, the United States experiences moderate to severe levels of corrosion in the coastal regions. Northern areas also experience a high level of corrosion due to modern de-icing methods. Bridges with a normally estimated service life of 50 to 100 years have exhibited signs of distress up to 15 years earlier than average in areas such as Wisconsin and New England. Repairing structures adds to transit delays and can contribute to fuel costs. Maintenance for these
repairs are also directly correlated to the taxation of the average driver. Combined, these costs can be substantial. Figure 1 shows a map of corrosion throughout the world.

Figure 1: Distribution of national corrosion data worldwide (NACE).
Methods of Corrosion Prevention

A number of methods have been developed to prevent infrastructure corrosion. Epoxy resin coatings are commonly used because they demonstrate better anti-corrosion performance than non-coated rebar. These coatings are thermosetting, meaning they form a permanent network that cannot be removed except through degradation. Once applied, these coatings work to slow down chloride access to the rebar surface, thus delaying corrosion. Factors that must be taken into account when applying these coatings include the bonding qualities between the coating and the rebar as well as the thickness of the applied coating.

Another method by which corrosion of steel rebar has been prevented is the use of stainless steel rebar, which gained popularity in the mid-1990s as an alternative to typical carbon steel rebar. Research has regularly concluded that stainless steel has a higher corrosion resistance than carbon steel and that deterioration would require high chloride and hydroxide exposure that is not expected in normal concrete systems. Use of stainless steel is not always the most cost effective solution, however, as it is substantially more expensive than epoxy-coated steel.

Methods of Steel-Reinforced Concrete Testing

Accelerated corrosion testing is a useful way to measure relative service lives of a particular coating material compared to another. Compression testing is also implemented to ensure that the compressive strength matches standard industry values, meaning that concrete used in the rebar structure has cured properly. Pullout testing measures tensile strength of the concrete and can be related to the compressive strength in that it helps determine if the concrete has cured properly and bonded with the rebar. Through these standard measurements, comparisons can be made between various materials and coatings and conclusions can be drawn as to their effectiveness. The American Society for Testing and Materials (ASTM) is an internationally recognized standards
organization that publishes consensus technical standards. These standards provide methods with which to determine certain properties of specimens.
Literature Review

Epoxy Coatings

Epoxy coatings are widely used to prevent corrosive agents such as water and salts from coming in contact with rebar. A study conducted in 2010 by the Florida Department of Transportation investigated the level of corrosion of bridges with epoxy-coated rebar. Factors contributing to the corrosion of the structures included the permeability of the concrete as well as preexisting cracks in the structure. Although the majority of bridges tested were in poor condition, bridges with epoxy-coated rebar generally required less repair and replacement than non-coated bridges.

Self-Healing Concrete

All concrete contains the potential for natural self-healing from non-hydrated residual cement. Concrete that utilizes this self-healing is a newer area of research that could prove to be beneficial to the repair and service life of steel-reinforced concrete structures. These concretes aim to repair cracks that can increase the diffusion of water and salts through concrete structures. Two processes often take place in self-healing concrete when a complete through-crack is developed. The first is the physical phenomenon of swelling and continued hydration of the non-hydrated cement in the crack surface that promotes the eventual repair. The second is the formation of calcium carbonate and the growth of crystals on the crack faces. This occurs when the calcium ions within the pore water of the concrete react with carbonate ions in the crack. The combined calcium carbonate then precipitates in the crack. These reactions depend on temperature, pH, and the concentrations of reactants. When in conditions that promote these developments, self-healing can take place and the concrete surrounding the rebar can be repaired without human interaction.
The use of biochemical agents containing bacterial spores and calcium lactate has also been investigated by Jonkers et al.\textsuperscript{17-19} This two-component self-healing system allows for the production of calcium carbonate through the catalyzed metabolic conversion of calcium lactate. Bacterial spores and calcium lactate are mixed into the concrete and have been shown to have no negative effects on the compressive properties of the concrete.\textsuperscript{17,19} This healing method has promoted and enhanced the self-healing capacity of concrete, doubling the healable crack width as compared to that of the control specimens. Oxygen measurements also provided evidence that the bacteria remained viable and functional several months after concrete casting.\textsuperscript{17-19}

An alternative method to creating self-healing concrete is the use of polymeric capsules that release healing agents containing polyurethane to seal cracks upon rupture.\textsuperscript{20-22} These capsules are able to resist breaking during the mixing process while still being able to release healing agents when a crack occurs in the concrete at room temperature. Testing through three point bending has produced favorable results with a healable crack width of up to 0.3 mm in individual studies.\textsuperscript{20,21} The mechanical properties of concrete with microcapsules were not statistically different from those of conventional concrete.\textsuperscript{21,22} Although initial reports are promising, the compatibility between polymeric capsules and two-component polyurethane-based healing agents needs to be improved for future use.\textsuperscript{20,22}

**Self-Healing Coatings**

Self-healing coatings are a recent avenue of research that could provide a way to fight the deterioration of modern infrastructure. Conventional anti-corrosive coatings have limited effectiveness if even a small portion of the coating is damaged.\textsuperscript{11} Self-healing coatings, however, can continue to function due to their ability to heal after fracture.\textsuperscript{23} In effect, this self-repair is anticipated to be able to greatly prolong the life of steel rebar structures. Initial investigation into
application on steel rebar was conducted by Chen et al.\textsuperscript{4} This technology could be applied to rebar structures that are typically coated with epoxy coatings in the highly corrosive areas of the Northeast to combat rapid corrosion rates.

Self-healing coatings that initiate self-healing through external cracking or damaging has seen substantial research. These coatings often have microcontainers mixed in that can rupture easily when acted upon. The containers hold healing agents that then seal the crack and prolong the functionality of the coating. Containers that hold these healing agents can vary from polyurethane microcapsules to microfilament tubes and often have little effect on the mechanical properties of the coating. Research in this area has provided good results and application in real world environments can be further investigated.\textsuperscript{23-25}

The development of polymer coatings that react to environmental stimuli such as heat or pH changes to initiate crack healing has also been investigated.\textsuperscript{26-28} Coatings that react to heat have achieved success, with some retaining all of their mechanical properties after multiple healing cycles.\textsuperscript{27,28} As polyelectrolyte nanocontainer coatings, changes in the pH of the solution have been able to set a response within seconds.\textsuperscript{29} Full recovery of the mechanical properties of the coatings were also achieved, making it a promising option for research in the future.\textsuperscript{29}

Drying oils such as tung oil and linseed oil have received significant investigation regarding their healing properties and encapsulation.\textsuperscript{30-32} When exposed to air, tung oil will polymerize into a tough, glossy, waterproof coating. These characteristics have made drying oils a valuable component in paints, varnishes, and printing inks. Tung oil encapsulation was first achieved by Samadzadeh et al.\textsuperscript{33} These urea-formaldehyde microcapsules displayed good adhesion to the epoxy matrix, compared to industry standards, by testing the microcapsules pull-off strength following ASTM D4541-09.\textsuperscript{34} Testing of damaged samples to measure service life through
immersion in sodium chloride solutions was conducted. Results were promising, as the tung oil microcapsules extended service life up to nine times that of epoxy coatings after damage.

Preliminary research on the use of microencapsulated self-healing coatings in steel-reinforced concrete structures was conducted by Chen et al.⁴ Two epoxy coatings were synthesized with 10 wt.% and 20 wt.% tung oil microcapsules. Standard compression and pullout tests were performed as a preliminary precaution to determine if transportation industry standards were met. While compression results were within acceptable limits, the pullout strength of rebar with the 10 wt.% microcapsule coating was weaker than both the unmodified and 20 wt.% coatings. Further testing and a review of the precision of encapsulation synthesis was recommended.

Some samples were then damaged using a utility knife in order to compare the effectiveness of the coating once damaged to an undamaged sample. A control group using a conventional epoxy as well as uncoated samples was also prepared for comparison. Accelerated corrosion testing was then performed based on the procedure proposed by Ahmad.³⁵ Upon accelerated corrosion testing, the samples coated with self-healing coatings took at least 300% longer to fail than the conventional epoxy coating.⁴ This showed potential for extension in service life for steel rebar placed in real world settings. However, a need for further testing was also recommended in this area, as the level of damage made to the self-healing epoxy was not sufficient to cause differences in accelerated corrosion testing performance. This need for further testing has motivated the following project.
Methodology

The purpose of this project was to develop a protocol for damaging rebar coatings in such a way that significant differences in service lives could be observed between undamaged and damaged samples. Various damaging techniques were used to give a basis for the damage required to show significant results in the corrosion testing. This project also aimed to determine what level of damage is required to render the epoxy coating ineffective. Having a better understanding of self-healing coatings’ responses to various damage will allow for a more reliable procedure to be created for replicable testing.

Mortar Mix Design

Standard mortar was prepared using portland cement mix and fine aggregate. Ingredient specifications of 45 vol.% cement paste and 55 vol.% fine aggregate were followed. A 0.3 water-to-cement ratio was used. A mixer was used to combine dry aggregate and portland cement for two minutes. Water was added and mixing continued until the mortar was moist and well-mixed. The mix was left to set for one minute before being placed in cylindrical molds.

Prior to filling, the molds had a release agent applied to them to ease the removal of the mortar specimens. The cylindrical molds were filled and rodded following ASTM C192/192M. Once filled, the entire mold was placed inside a sealed plastic bag and put in a curing room. The bag acted to keep the relative moisture content of the system stable for the initial 24 hour curing period. After the initial curing period, the cylinders were de-molded and placed back into the curing room until they had cured for their specified time.

Tung Oil Microencapsulation

The procedure used to encapsulate tung oil in a poly(urea-formaldehyde) shell was based on the work of Samadzadeh et al. and is described in greater detail in Chen et al. A graduate
assistant synthesized and provided the microcapsules. The microcapsule batch was then imaged using Scanning Electron Microscopy (SEM) to find the size distribution of the microcapsules.

**Preparation of Self-healing Coating**

Two different self-healing coatings were created. Coatings containing 10 wt.% and 20 wt.% microcapsules were formed by combining microcapsules with a two-part epoxy coating (Super Glaze, Rust-Oleum Parks). The microcapsules and the epoxy resin were combined using a planetary centrifugal mixer (Thinky Mixer ARE-310). The mixing was performed at 200 rpm for two minutes, followed by degassing at 400 rpm for 30 seconds. This degassing step helps remove air pockets within the coating. Upon time of application, the microcapsule resin was hand stirred into the curing agent and the samples were dip-coated. A total of 18 rebar samples were dip-coated with the self-healing coatings. An additional nine rebar samples were dip-coated with conventional epoxy coating.
Preparation of Damaged Rebar Samples

Table 1: Types of coatings and damaging methods.

<table>
<thead>
<tr>
<th>Type of Coating</th>
<th>No Damage</th>
<th>Cutting</th>
<th>Impact Damaging</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncoated</td>
<td>3 Samples</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unmodified</td>
<td>3 Samples</td>
<td>3 Samples</td>
<td>3 Samples</td>
</tr>
<tr>
<td>10 wt.% Microcapsule</td>
<td>3 Samples</td>
<td>3 Samples</td>
<td>3 Samples</td>
</tr>
<tr>
<td>20 wt.% Microcapsule</td>
<td>3 Samples</td>
<td>3 Samples</td>
<td>3 Samples</td>
</tr>
<tr>
<td></td>
<td>Total Number of Samples: 30</td>
<td></td>
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</tr>
</tbody>
</table>

Table 1 shows the number of samples and the damaging methods performed. Damaged rebar samples were made by making a cut or through impact. Rebar had a 30° diagonal cut made opposite the rebar’s groove starting at 4 in (10.16 cm) and ending 1 in (2.54 cm) from the bottom of the rebar. These cuts were made by hand using a utility knife. A three day period was taken in between damaging and embedding in mortar to allow for the coatings’ repair. Figure 2 shows the resulting damage from the spiral cut.

![Image of rebar with damage marks](image)

Figure 2: Damage from a spiral cut on rebar.
An impacting force was applied to samples using an Instron Dynatup 8250 impact tester in order to damage coatings. The impact head of the tester had a spherical nose. The tester held a drop weight weighing 11 lbm (5 kg). The height from which the weight dropped was 3 in (7.62 cm). After being damaged, the coatings were allowed to heal for three days before the rebar was embedded in mortar. Samples were marked 2.5 in (6.35 cm) above the bottom of the rebar. Alignment of the samples underneath the tester was done by hand using the markings as guide points. Masking tape was used to hold samples in place. Figure 3 shows the impact tester with a rebar sample ready for damage.

Figure 3: Impact damaging setup.
A typical direct blow generated approximately 7,000 lb (31,137 N) upon impact. Shifting of the test sample may have occurred upon a direct blow, but no differences in damage were observed. Of the nine samples that were damaged, only sample number one received a glancing blow. A glancing blow has the potential to create damage over a larger area, which could expose rebar to the point that the coating could not self-heal. To reduce this occurrence in the future, it is recommended that a more reliable clamping apparatus be used to reduce shifting. Some damage was also present on the backside of the rebar samples from the force of the impact. Figure 4 provides images of the damage.

Figure 4: Resulting impact damage to the rebar front (left) and damage to the back (right).
Compressive Strength

Compression testing and sample preparation was performed in accordance with ASTM C39/C39M-15a. Cylindrical molds 4 in (10.16 cm) in height by 2 in (5.08 cm) in diameter were prepared. The compression test cylinders were tested after three, seven, and 28 days of curing. These data provide a representative graph for the development of the mix design strength. Testing was performed using a Tinius Olson Universal Testing Machine. Before testing, each sample was measured and weighed. These dimensions were put into the testing software to calculate the stresses that each cylinder underwent. Samples for each cure period were tested to determine whether the strength of the mix showed adequate curing progress. Figure 5 shows a sample in the compression tester at an age of three days.

Figure 5: Compression testing of a cylinder sample.
Accelerated Corrosion

Accelerated corrosion testing was performed in the manner used by the previous project group and proposed by Ahmad. Briefly, cylindrical mortar samples with diameters of 2 in (5.08 cm) and heights of 4 in (10.16 cm) were prepared with damaged and undamaged rebar. Samples with diameters of 2 in (5.08 cm) and heights of 4 in (10.16 cm) were prepared with damaged and undamaged rebar 12 in (30.48 cm) in length partially encased in them. A total of 30 samples underwent accelerated corrosion testing, the conditions of which are specified in Table 1. The rebar was held 0.75 in (1.91 cm) from the bottom of the mold. The rebar samples had the self-healing epoxy coating applied to them containing differing weight percentages of microcapsules. Uncoated samples as well as samples with an unmodified coating were used as controls. The samples were submerged in a 5 wt.% sodium chloride solution with the waterline just below the top of the mortar. Two stainless steel plates were attached to negative leads and submerged in the solution. A positive lead was then attached to the rebar suspended above the surface. A 30 volt potential was applied to the system. A data logging program tracked the current in regular intervals. This current was used to help determine when a sample was damaged, as this corresponded to a significant loss in electrical resistance. Figure 6 shows the set-up of an accelerated corrosion tester.

Figure 6: Accelerated corrosion tester.
Results and Discussion

Curing of Microencapsulated Epoxy

Upon mixing of the experimental coatings, it was observed that the pot life of both the 10 wt.% and 20 wt.% coatings was shorter than that of the unmodified coatings. One explanation involves the mixing properties under which the experimental coatings were prepared. When the components were mixed, heat was generated as a result of the frictional forces between microcapsules. This added heat accelerates the reaction rate of the coating, causing it to cure more quickly. To overcome this short pot life, the epoxy resin and microcapsules were first mixed in the centrifugal mixer. The curing agent was then hand-stirred into the resin immediately before application.
Size Distribution of Microcapsules

The microcapsule samples received were imaged to find the batch size distribution using Scanning Electron Microscopy (SEM). The resulting diameter distribution can be seen in Figure 7. The diameters, based on 114 microcapsules measured, were spread over a relatively wide range. The largest number of microcapsules was in the 0.2-0.25 mm and 0.25-0.3 mm ranges, with 44 total microcapsules within the two categories. The mean and median diameters of all the microcapsules were found to be 0.343 mm and 0.308 mm, respectively. A total standard deviation of the average diameter was calculated to be 0.093 mm. Figure 8 shows a representative SEM image of the microcapsules.

Figure 7: Microcapsule diameter distribution

Figure 8: SEM image of microcapsules containing tung oil.
Coating Thickness

Differences in coating thicknesses may prolong the time before corrosive damage occurs unrelated to the self-healing abilities of the coatings. Typically, it can be expected that a thicker epoxy would provide added protection from corrosion. Before the rebar samples were embedded in mortar, diameter measurements were taken using calipers. These results, shown in Figure 9, demonstrate that the experimental coatings were similar in diameter to the regular coatings and coating thickness is therefore unlikely to affect the results of the accelerated corrosion test.

Figure 9: Thickness of coated and uncoated rebar. Error bars represent standard deviation.
Compression Testing

Figure 10: Compressive strength of mortar samples after different curing times. Error bars represent standard deviation.

Compression testing was performed on several groups of samples to ensure proper curing of the mortar. The compressive strengths of the samples exceed the physical property minimums of mortar following ASTM C-270-86a. Figure 10 shows that curing of the mortar samples took place, with a 28 day average compressive strength of 4,389 ± 540 psi (30.3 ± 3.7 MPa). Although the gradual increase in compressive strength shows curing of the specimens, the final compressive strength is lower than that of the concrete industry standard compressive strength of 5,000 psi (35 MPa). An explanation for this is the samples are made of mortar and thus have a weaker compressive strength than that of concrete which contains large aggregates that contribute to the strength of the concrete. From these results it was determined that the samples made were of acceptable quality and testing continued. Use of concrete samples in a scaled up environment could yield compressive results closer to industry practices and standards in the future.
Accelerated Corrosion Testing

Figure 11 shows the current averages of cracking age for the coating samples. The accelerated corrosion testing of the rebar samples proved to be an effective method for inducing corrosion within the rebar samples. The uncoated samples lasted an average of 1.5 ± 0.5 days, providing a baseline. The undamaged unmodified epoxy coating lasted an average of 12.5 ± 1 days. The undamaged modified epoxies exhibited service lives substantially longer than that of the uncoated and unmodified samples. The 20 wt.% coated samples lasted 44.5 ± 19 days while the 10 wt.% coated samples have had only one failure and continue to test.

The damaged unmodified and modified samples through cutting have shown results that support the claim that the modified samples exhibit a longer test life when undergoing accelerated corrosion testing. The unmodified cut samples averaged a lifespan of 12.5 ± 1.5 days. The 20 wt.% cut samples lasted longer than the unmodified with a service life of 29.5 ± 11 days. The 10 wt.% cut samples lasted the longest of the grouping with a testing average of 42 ± 26 days. These results
from cut damaging show a difference from the undamaged samples above, specifically in the case of the modified coatings.

The impact damaged unmodified epoxy coatings lasted 8 ± 1 days. The impact damaged experimental epoxy coatings have shown to possess significantly longer service lives than the unmodified damaged coatings. The impact damaged 20 wt.% coated samples lasted an average of 28.5 ± 7.5 days. The 10 wt.% damaged coating still has one sample yet to fail. It should be noted that this particular coating group had an outlier that failed three days into testing. Accelerated corrosion testing will continue to obtain additional data for the undamaged experimental coatings and the impact damaged 10 wt.% sample. One-way analysis of variance (ANOVA) was applied to the results shown in Figure 11. With a confidence interval of 90%, it was concluded that the damaged coating samples had shorter service lives than those of the undamaged coatings. To attain a higher confidence interval, testing on a larger testing population is recommended, as outliers in the data had an effect on statistical analysis.

When examining impact damaged rebar samples after testing, the impacted side showed greater signs of corrosion than that of the undamaged backside. This shows that the impact damaging had distinguishable effects on the rebar sample during the accelerated corrosion testing. Samples that were not impact damaged showed corrosion beginning in many locations. Impact damaged samples, in comparison, typically had greater signs of corrosion on the impact damaged side. From this it can be determined that impact damaging does have an effect on the coating’s ability to self-heal when under accelerated corrosion testing. Figure 12 shows an impact damaged rebar sample removed from its mortar shell.
Figure 12: Impact damaged sample showing the impacted side (left) and back (right) post testing.
Conclusions

Self-healing coatings for rebar were prepared by incorporating microcapsules containing tung oil into a conventional epoxy coating. The use of impact damaging was implemented in order to create distinguishable performance differences between damaged and undamaged epoxy coatings. This method proved to be successful, with the impact damaged self-healing coatings lasting longer than the undamaged unmodified coatings. The impact damaged samples also showed distinguishable effects on coated rebar during accelerated corrosion testing and it is recommended that this damaging technique be used in the future. It can be concluded that the self-healing coating is a more effective means of protecting steel reinforcement than an unmodified coating.

There are numerous avenues for future research concerning this experimental coating. The microcapsule size can be varied by adjusting synthesis conditions. Finding the most effective size and distribution to maximize the service life of the rebar specimens could be explored. This change in microcapsule size may affect pullout strength of the steel encased specimens, this relationship should also be further researched. Scale-up using larger test samples may be another viable option to test the epoxy in a real world corrosive environment.
Appendix
Compression Tests

Figure 13: Compression tests of day 3 peak strengths.

Figure 14: Compression tests of day 7 peak strengths.
Figure 15: Compression tests of day 28 peak strengths.

Thickness Test

Table 2: Data for coating thickness measurements.

<table>
<thead>
<tr>
<th>Diameter of Rebar (in.)</th>
<th>Coating Type</th>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
<th>Sample 4</th>
<th>Sample 5</th>
<th>Sample 6</th>
<th>Sample 7</th>
<th>Sample 8</th>
<th>Sample 9</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Uncoated</td>
<td>0.38</td>
<td>0.379</td>
<td>0.379</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>Unmodified</td>
<td>0.381</td>
<td>0.378</td>
<td>0.381</td>
<td>0.379</td>
<td>0.38</td>
<td>0.38</td>
<td>0.379</td>
<td>0.381</td>
<td>0.379</td>
</tr>
<tr>
<td></td>
<td>10%</td>
<td>0.382</td>
<td>0.379</td>
<td>0.381</td>
<td>0.382</td>
<td>0.381</td>
<td>0.378</td>
<td>0.38</td>
<td>0.382</td>
<td>0.381</td>
</tr>
<tr>
<td></td>
<td>20%</td>
<td>0.381</td>
<td>0.383</td>
<td>0.382</td>
<td>0.382</td>
<td>0.38</td>
<td>0.378</td>
<td>0.381</td>
<td>0.382</td>
<td>0.383</td>
</tr>
</tbody>
</table>

Table 3: Average coating thickness.

<table>
<thead>
<tr>
<th>Coating Type</th>
<th>Average (in.)</th>
<th>Avg. Coating Thickness (in.)</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncoated</td>
<td>0.379333</td>
<td>0.0000</td>
<td>0.0005</td>
</tr>
<tr>
<td>Unmodified</td>
<td>0.379778</td>
<td>0.0004</td>
<td>0.0010</td>
</tr>
<tr>
<td>10%</td>
<td>0.380667</td>
<td>0.0013</td>
<td>0.0013</td>
</tr>
<tr>
<td>20%</td>
<td>0.381333</td>
<td>0.0020</td>
<td>0.0015</td>
</tr>
</tbody>
</table>
Figure 16: Measure of force from impact damaging.

Microcapsule Imaging

Figure 17: SEM image of microcapsules used for sizing.
Figure 18: Additional SEM image of the microcapsules.
Civil Engineering Design Statement

The design problem for this project was to develop a way to damage the existing microcapsule epoxy to help test its self-healing properties when coating rebar. The microcapsule epoxy is working to help solve current infrastructure maintenance problems. Two types of damage were used, an impact force applied to the cured epoxy as well as a spiral cut. Both damages were applied to several different kinds of epoxy, an industry standard epoxy, 10% wt. of the microcapsule epoxy as well as a 20% wt. To determine the lifespan of the samples an accelerated corrosion test was used this will allow the testing of a control as well as test samples. The final data will show if test epoxy can recover from the damage as well as if it can out last the industry standard epoxy even when damaged.
Professional Licensure Statement

The professional licensure for civil engineering has a process of two steps. The first is to pass the (FE) Fundamentals of Engineering exam, once the exam is passed the individual becomes an Engineer in-Training for four years in their field of engineering under a professional engineer. After the four years the individual can then take the (PE) Professional Engineers exam once the exam is passed the individual can apply for the license from the state they reside in.

A PE license offers a sense of security to the engineer and the community that they are working in. The license is only awarded to an engineer who had the proper education and passed both of the exams. The PE license helps insure that the engineer is skilled enough in their field to safely perform their job as an engineer. The way the license is obtained is beneficial to the profession as well as the individual. For an individual to acquire the PE license it shows that they were dedicated to the profession and they invested the time to learn the profession. The PE license will help boost the career of the individual and will help the industry grow.
References


