Innovative Techniques for the Repair and Strengthening of Concrete Structures

by

Alexander Otenti

__Abstract__

Concrete repair is a very complex process. There are a variety of different site conditions and concrete properties that cause deterioration. Wetting-drying cycles, the presence of chloride ions, concrete creep, and shrinkage, which caused the initial deterioration, are potential problems for repair materials. Understanding the causes of the initial deterioration is the fundamental, first step of concrete repair.

The next step, site preparation, can be universally applied to all site conditions. Site preparation involves cleaning the site to remove all loose concrete from the site and rust from the reinforcement. Studies have shown that rusted reinforcement actually has some advantages over clean reinforcement. However, it has one major drawback. Concrete with corroded steel rebar is much weaker in flexure than clean concrete.

Currently, polymer concrete is the most commonly used repair material due to its high strength, low permeability, and rapid setting time among other characteristics. Magnesia-phosphate concrete is also used for repair due to the fact that it achieves its final strength within only a few hours of setting.

In conclusion, there is no research that attempts to select the perfect repair material for different conditions. Most research is extremely focused on minute properties of a repair material. Studies on drying rate or water-cement ratios are useful when a repair material has already been selected but they are not helpful when determining which material to use.

Introduction

There are two categories of concrete repair: local repair and global/system repair. The most common local repair materials are epoxy resins, polyester resins, polymer latex, polyvinyl acetate, and magnesia-phosphate cement composites. The effectiveness of these materials will be investigated in this paper. This paper will not examine global/system repair schemes.

The service life of concrete is limited by severe cracking, spalling of the concrete cover, and rebar corrosion. Often repairing these problems can be as complex as designing a new structure. This is because concrete is a non-homogeneous material and each repair is different. Another major issue with repair materials is that they must be compatible with the original concrete. The repair material and the concrete must work as a single unit in order to carry the applied stresses and to protect the reinforcing steel. However, finding a compatible repair material is not an easy task. Compatibility is determined by a number of criteria. The material must have a similar modulus of elasticity, similar compressive strength, be chemically compatible, and have similar volumetric change properties. The repair materials must also provide strong bonding strength with the existing concrete, low permeability of water and chloride, and cure rapidly to limit disruption of service.

Background

Considerations Caused by Concrete Behavior

The Environment

Structures that are exposed to weather are subjected to drastic seasonal temperature changes as well wetting and drying cycles. These conditions cause strain to accumulate in the concrete. However, the effects of weather are less severe in core of the section than at the surface. This implies that there is some critical depth measured from the surface that feels the greatest strain from temperature and humidity changes. The depth of this layer is not constant for all specimens, even ones in the same climate. Some surfaces are exposed to direct sunlight for long portions of the day while others are shaded for a few hours or all day. Similarly, some surfaces are protected from rain while others are not [1]. Concrete made in hot-dry environments such as the Middle East also have water related problems. In this case lack of moisture causes extreme shrinkage leading to cracking of the concrete [6]. Modeling the hygral changes due to weather effects has been researched in a few studies.

Environmental exposure also leads to corrosion of rebars in reinforced concrete structures. Corrosion is an electrochemical process caused by three major instigators: chloride attack, carbonization, and microcell formation [4].

When reinforced concrete is first cast there is an alkaline cementitious matrix formed around the rebars, which protects them from corrosion [4]. This protective

barrier is broken down when chloride gains entrance through the concrete and reaches the reinforcement. Chloride either diffuses through uncracked cement or travels through micro or macro-cracks to the reinforcement. The conditions present during curing have a major influence on future chloride content in concrete. If the concrete is too dry hydration is limited at the surface, which leads to higher porosity and permeability and therefore higher diffusion [4]. On the other hand, if the concrete is moist during curing, but then rapidly dried cracking occurs allowing chloride ions to flow into the concrete through capillaries, through voids in the matrix, along cracks in the aggregates, and along the interface between aggregates and the cement [20]. Chloride is not able to travel through cracks less than 0.2mm in diameter, but cracks greater than 0.5mm leads to extensive chloride infusion [4]. Because repair materials generally develop strength within a few days or hours curing is not as important as in concrete [4].

The second corrosion inducer is carbonization. Carbon dioxide travels through cracks in the concrete or by diffusion. Cracks are a greater concern because diffusion is an extremely slow process. Only a single millimeter of concrete cover carbonizes each year [4]. When carbon comes in contact with the alkaline layer protecting the steel it begins to reduce the pH level. Once the level drops below 10 the protective layer is no longer functional [4].

Microcell formation is the final corrosion inducing process. This happens because of the interaction between the anode and cathode charges, which form microscopic distances from each other. This same effect happens on a greater scale when a deteriorated zone is cleaned and repaired. The new clean reinforcement becomes a cathode causing the rusted rebar on either side to rapidly corrode [4].

Shrinkage

It is extremely important to study the causes and process of shrinkage when selecting repair materials. Shrinkage is caused by the loss of water in drying and it is mostly reversed when the specimen is wetted. It is independent of the level of stress being applied to the specimen. Therefore, it is possible to calculate the shrinkage independently of the mechanical properties of the concrete. This is an important effect to consider for local concrete repair because once the repair mix is applied to the concrete it will begin to shrink, causing stresses to build between the concrete and the repair mix. If the stress reaches the ultimate stress level of the bond they repair material will spall. Rapid shrinkage also causes cracks, which give carbon dioxide and chloride ions an easy route to reinforcement.

As already stated, proper curing can limit shrinkage [4]. In fact, laboratory tests show that moist curing for three months or greater significantly reduces the shrinkage of concrete [1].

Creep

Creep is a time dependent deformation. Under normal conditions it has the beneficial effect of causing a relaxation of stresses in a concrete section. However, restrained shrinkage builds up tension in repaired sections, which can cause cracking or failure in the repaired section. Little is known about creep of concrete in tension [1].
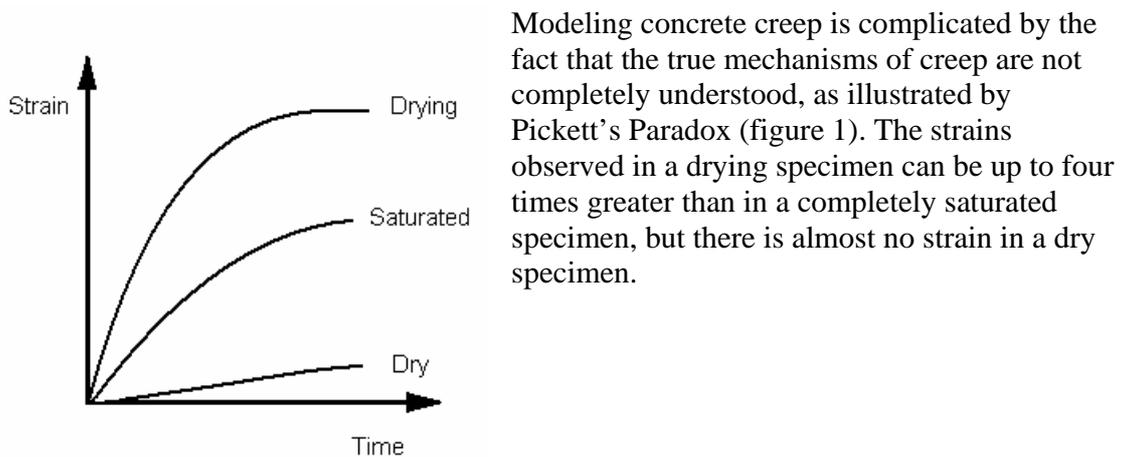
Figure 1: Pickett's Paradox

Modeling concrete creep is complicated by the fact that the true mechanisms of creep are not completely understood, as illustrated by Pickett's Paradox (figure 1). The strains observed in a drying specimen can be up to four times greater than in a completely saturated specimen, but there is almost no strain in a dry specimen.

Site Preparation

Industry practice for site preparation is to remove loose concrete, remove rust from the reinforcement, coat the rebar with a cement based corrosion inhibitors, and finally to roughen the rebars and concrete surface [17]. Research is still being done in order to determine the best way of accomplishing each step. Contrary to intuition leaving reinforcement in a corroded condition has some advantages. But assuming that the rebar is cleaned there are many ways of cleaning and protecting it to prevent further deterioration.

A slight amount of rust actually has some positive effects on the strength of the system. Steel that is already slightly rusted corrodes slower than clean steel [7]. As previously stated cleaning one area can cause areas on either side of the repair to corrode severely due to electrochemical effects [4]. In 1956 the Bureau of Reclamation stated that rust increases the holding capacity of bar because the rusted bar is rougher. However, Al-Duaijan [7] found that the pull-out strength of reinforced concrete is actually increased by rust. Almusallam [22] found that rusted rebars increased the bond strength by seventeen percent for bars less than four percent corroded. After four percent corrosion the bond strength dropped off quickly. Although bond strength seems to be increased, rust has a major disadvantage. It reduces the flexural strength of reinforced beams by as much as twenty-five percent [7].

The most common procedures used to clean reinforcement are sand blasting and manual and power wire brushing. Vassie found that only sand blasting was able to completely remove all rust and therefore prevent corrosion from resuming instantly after the repair was completed. If the steel is finely pitted then none of the methods are able to remove the rust completely [21]. A less common but innovative method of removing corrosion is acid etching. Not only does it remove rust but it also increases the roughness of the bars on a microscopic scale. As expected there is an optimal duration of application and an optimal percentage of acid solution to achieve the right amount of

roughness. Xiong et al found that a five percent solution of hydrochloric acid (HCl) applied for five minutes worked best [8]. That study also found that using a fly-ash mortar primer and acid etching was about ten percent better at preventing redevelopment of rust than primer alone.

Once the site has been cleaned corrosion inhibitors are applied to the reinforcement [15]. The greatest culprit in reinforcement corrosion is oxygen. Oxygen binds the electrons originally associated with the iron atoms and allows iron atoms to become ferrous ions and finally ferric oxides [9]. It is not possible to exclude oxygen from entering the concrete therefore inhibitors focus on protecting against the major catalyst on the reaction, chloride ions. Corrosion inhibitors have two goals. The first is to raise the level of chloride ions necessary to initiate corrosion. Secondly, reduce the rate of corrosion once it has begun. Additives that reduce permeability of concrete to chloride are not considered inhibitors although they do have the effect of decreasing corrosion [9].

There are three categories of inhibitors: anodic, cathodic, and a combination of the two. Anodic inhibitors primarily accept electrons thereby stopping the electrochemical reaction at the anode. They must be applied in high concentrations directly to the affected area. Anodic inhibition is an active process [9]. Cathodic inhibitors' function is to slow the cathodic reaction by accepting protons [4]. In other words they block cathode sites where oxygen picks up ferrous electrons to become hydroxyl ions [9]. The final category is a mix of the two. If done correctly they can protect against both chloride ions and microcell corrosion [4].

The first study of inhibitors occurred in 1957. It recommended the use of a strong oxidizing agent such as barium nitrite, potassium nitrite, and potassium chromate in order to prevent corrosion. That study found that sodium nitrite was the best inhibitor, but further tests uncovered that it increased the risk of alkali-aggregate reaction and caused the formation of salt deposits on the outside of specimens [4]. Although sodium benzoate and sodium chromate also work as inhibitors they cause a severe reduction in compressive strength.

Today the most common inhibitor admixture is calcium nitrite. It is the first inhibitor used commercially on a large scale. The first studies conducted on calcium nitrite found that it accelerates set time as well as increases the 28-day strength of concrete. The strength was found to be six percent for every percent per concrete weight of calcium nitrite added [9]. Later studies discovered that calcium nitrite also functions as an anodic inhibitor. It competes with chloride ions for ferrous ions produced in concrete [10]. The ferric ions then precipitate in the alkaline pH of concrete forming a passive film on the iron's surface [10]. As a result the mobility of the chloride ions is limited [9]. Calcium nitrite works particularly well in cement mixtures with a water-cement ratios of less than 0.5 [9].

The process of active anodic inhibition caused by calcium nitrite was displayed by a laboratory test in which a specimen was immersed in salt water. The reinforcement originally had a passive film coating. After a few weeks in the salt water bath the pH slowly dropped until it was "moderately active". It then began to rise until it was again passive and remained so for the rest of the test. At the end of the test the concrete was split open in order to examine the rebar. It was rust free except for a small one-millimeter diameter spot, which was adjacent to an air void. The air void was filled with

black powder. Gaidis hypothesizes that the air void caused an anode to form in the steel bar. After a week or so the calcium nitrite was able to diffuse into the site and oxidize and precipitate the ferrous ions [9]. This experiment demonstrates the active nature of anodic inhibitors. They invade anodic sites and steal electrons from chloride ions as they oxidize. This process forms a passive film around the reinforcement.

A second inhibitor that is gaining in popularity is aminoalcohols. Aminoalcohols are examples of cathodic inhibitors. Dimethylethanolamine is one kind of aminoalcohol, which inhibits corrosion by displacing chloride ions and forming a durable passive film. It adsorbs strongly and irreversibly into the iron oxide [9].

One example of a mixed inhibitor being investigated today is mix of esters and aminoalcohol. The aminoalcohol forms a passive film on the rebar while the organic ester reduces the permeability of the concrete by depositing insoluble calcium salts and fatty acids in concrete pores. This reduces the capillary absorption of the concrete [9].

Materials

Polymer Cement

The first patent for a polymer modified concrete was filed in 1923 for use in pavements. The next year the first patent for polymer concrete was filed for structural members [16]. In polymer concrete the organic polymer matrix mixes with the concrete gel matrix to form the material matrix [16]. Polymer resins improve the mechanical behavior of the concrete as well as improving the durability. Resins reduce the water and salt permeability and offer good corrosion protection. They also cure faster than traditional concrete, which is important to reduce the down time in service life of the structure [3].

There are three forms that polymer concrete comes in: polymer latex, liquid polymer, and water-soluble polymer. Polymer latex consists of very small polymer particles suspended in water by emulsion polymerization. Liquid polymers are made by adding viscous polymers with the hardener and accelerator during concrete mixing. Once very common repair material which is a liquid polymer is epoxy resins. The water-soluble polymer is made of cellulose derivatives or polyvinyl alcohol. It is mainly used to improve workability [16].

Drying shrinkage becomes constant by the end of the curing period of twenty-eight days and can achieve a final value that can be either higher or lower than regular cement. It is important that the shrinkage be lower or similar to the concrete that is in place as a study by Shambira determined. While testing repaired columns in axial compression the study found the polymer repair mortars with high shrinkage values lost structural effectiveness after only a few weeks [19]. The creep coefficient of polymer cement is much lower than normal concrete [16]. The coefficient of thermal expansion is nearly the same [16]. That is important because when repaired members subjected to hot temperatures or direct sunlight both the original concrete and the repair material will expand at the same time, reducing the amount of strain developed along the interface. Polymers attract moisture during curing giving them low permeability, an order of magnitude less than concrete, and low chloride diffusion [4]. The polymers also bridge

the micro-cracks preventing crack propagation. On the down side the modulus of elasticity ranges from 0.001 to 10 GPa while regular cement ranges from 10 to 30 GPa [16]. As previously stated, the modulus of elasticity of the repair material should closely match the modulus of the in-situ concrete.

Epoxy resins are one of the most commonly used polymers. They offer the same benefits as general polymers do namely good adhesion strength, chemical resistance, low shrinkage, moisture resistance, and rapid hardening [14]. Polymer resins are not cheap however. Therefore, a lot of work has gone into studying the optimum ratio of resin to aggregate, which has been found to be from 1:7 to 1:12 [2]. Any less than 1:12 causes a drastic reduction in strength.

Magnesia-Phosphate Cement Composites

In 1947 Every formulated the idea for a rapid setting cement containing a mixture of a dry mixture of inert filler, a solid inorganic base, and a soluble inorganic acid salt. He recommended a dead-burned magnesite as the base material [18]. Today magnesia-phosphate composites (MPB) are made with magnesia (M_gO), mono-ammonium ($NH_4H_2PO_4$), borax ($Na_2B_4O_7*10H_2O$), water, and fibers [12]. Magnesia-phosphate sets extremely fast achieving similar strength an ordinary concrete would achieve in twenty-eight days in only three hours [11]. Fast setting materials are generally brittle. Fibers are added to magnesia-phosphate composites in order to uncrease the ductility of the system [11]. A study conducted by Pera found that polypropylene and metallic fibers showed stable behavior under wet-dry cycles. They also displayed elastic-plastic and strain-hardening behavior respectively. Polyester and polyamide fibers however still displayed brittle behavior [11].

MPB hydrates exothermically meaning that smaller thicknesses generate less heat and acquire their final strength more slowly than thick sections. High curing temperatures lead to higher final strengths [12]. The most attractive feature of MPB is the fact that it sets extremely rapidly. It withstood being covered by polluted water an hour after application to a concrete river embankment in Shanghai, China [12].

Conclusions

This paper began as an attempt to fit repair materials to different conditions. However, as the literature was thoroughly investigated it became obvious that there is a lack of information on repair materials in general and no studies investigating the big picture. Most research studies conducted on repair materials focus on very specific properties of the material. For example, Emmanuel Soudée and Jean Péra [23] wrote an article entitled "Influence of magnesia surface on the setting time of magnesia-phosphate cement". It details the effect of surface roughness on wetting magnesia-phosphate specimens. Studies like this detail specific characteristics of a material, which is fine when a material has already be selected. With information like that a contractor can optimize the productivity of the repair. However, studies like that do not help people select which material is best suited to each situation.

The first step in material selection is to identify the behaviors of concrete, which may affect the interaction between the new material and the in-situ concrete. Concrete can be an expensive process and it is not economically feasible to repair concrete components if the repair fails after only a few years. Failures may occur because of stresses and strains developed along the interface due to concrete creep and shrinkage as well as the effects of weather. Corrosion protection is much more important in environments likely to lead to high chloride concentrations, such as costal structures, than in the Midwestern America. It is also important to identify the priority of the structure being repaired. For example, a structure such as the Harvard Bridge near MIT could not be shut down for twenty-eight days to allow concrete to cure. For important bridges or other such structures limiting downtime is essential, therefore rapid curing materials are essential.

The next step is to identify the optimum method of preparing the site for repair. Improper preparation can reduce the durability and service life of a repair. There is some debate in the literature about the best method for preparing the reinforcement for repair. Studies have shown that rate of corrosion in slightly corroded steel is less than that of steel just as corrosion begins. Rust also increases the pullout strength of a specimen but it reduces the flexure strength. Therefore, it is best to clean the reinforcement.

Polymer concrete has a lot of the properties that make it a good repair material, which may be why it is why it is so popular. The only property it is lacking is compatibility in modulus of elasticity. Polymer concrete can attain a modulus of less than one third that of ordinary concrete. Magnesia-phosphate composites set extremely fast, within three hours. However, there is little information about the use of each material for specific conditions. This should be the turn that future research should take.

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