

APPLYING LININGS TO CONCRETE SURFACES IN WATER AND WASTEWATER ENVIRONMENTS

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Abstract: The use of linings to rehabilitate concrete surfaces in water and wastewater environments has been increasing. This paper discusses the basics of concrete, concrete deterioration, and subsequent rehabilitation options, with an emphasis on coatings.

INTRODUCTION

A large portion of a concrete lining project is the assessment of the concrete surface and restoration of that surface such that it is suitable for lining application. The condition of the concrete surfaces can vary dramatically between projects, and even within the same structure. Since the true condition of the concrete will only be revealed during the execution of the project, some assumptions must be made during the design process. Ideally, a prototype repair system could be applied (i.e., test patch) to reduce the uncertainties, but it is not typically cost-effective to take a structure out of service for this level of design.

This paper discusses the concrete surface, deterioration mechanisms, and repair techniques.

BASICS OF CONCRETE

Concrete is a composite material that consists of a binding medium embedded with fine aggregate and coarse

aggregate. In hydraulic cement concrete, the binder is cement paste, a mixture of hydraulic cement, water, and possibly one or more admixtures.

Hydraulic cement is cement that sets and hardens by chemical reaction with water (hydration) and is capable of doing so under water (ACI 225R). The hydration reactions result in the formation of a hard solid mass. When hydraulic cement is mixed with water to form a paste, the phases of the cement react with the water (hydration) to form a slowly developing cementitious structure that adheres to and binds together the fine- and coarse-aggregate particles to form hardened concrete. The most abundant hydration product is calcium-silicate hydrate.

As long as moisture and unhydrated cement particles are present, the hydration products continue to form, increasing the strength of the concrete. The continued curing of concrete should not be neglected.

The most widely used hydraulic cement is portland cement. Other kinds of hydraulic cement include blended cements and ground granulated blast-furnace slag (ACI 233R). Pozzolans, both natural (ACI 232.1R) and artificial fly ash (ACI 232.2R), and silica fume, (ACI 234R) are often used as a cementitious ingredient of concrete.

CONCRETE CHARACTERISTICS

Understanding some of the characteristics of concrete can help when assessing aged structures. Following may be key issues:

- Local materials: concrete is made from local raw materials. This benefits delivery time but can result in variability of material quality.
- Compressive strength (crush resistance): concrete can be designed with very high compressive strength, which allows people to build structures that are both slender and very strong. However, poor workmanship can result in a product that doesn't meet design criteria.
- Fire resistance: concrete is naturally fire-resistant, which slows the spread of fire (flame propagation). However, high heat does degrade the concrete.
- Thermal insulation: concrete can absorb heat during daytime and to return it in the cool of the night. These thermodynamics must be considered when planning a coating project.
- Speed: techniques allow construction lead-time to be reduced (self-placing concrete, etc.). These can result in material durability changes.
- Workability: concrete can be pumped over long distances, horizontally and vertically, to its place of use. It can be fluidized (plasticized) sufficiently to make it flow easily. Conversely, it can be made compact, dense and thick. Understanding workability issues can help to identify weak point for concrete degradation.

- Process Flexibility: concrete is highly adaptable to the specific needs of different worksites. Again, adaptability can result in varied durability performance.

DURABILITY AND DEGRADATION OF CONCRETE IN WATER AND WASTEWATER ENVIRONMENT

American Concrete Institute has defined concrete durability as its resistance to weathering action, chemical attack, abrasion and other degradation processes. There is a heightened awareness that the quality of concrete is of utmost importance in determining the durability of concrete exposed to aggressive environment, such as water or wastewater immersion.

Concrete is a highly chemically reactive material, strongly alkaline, (its pH 12 to 13 when damp), and readily dissolved by acid solution (NACE 6G191). Although concrete is outwardly a dense material, it contains pores; and many of these pores are interconnected to form a network of channels that allows water and chemicals to permeate into the concrete.

A typical reaction of unprotected concrete exposed to water or wastewater immersion tends to break down the cement binder in the concrete. These, and potentially other mechanisms that chemically react with concrete and reduce the pH of the concrete, will result in a weakened and loosely adherent sand matrix at the surface of the concrete.

As a general rule, reduced permeability leads to reduction in the conductivity of the concrete by reducing not only the amount of moisture intrusion but also the

amount of chloride ions carried by the moisture into the concrete.

There are several mechanisms for concrete degradation. Important degradation mechanisms in concrete structures include the following:

- Freeze-thaw damage (physical effects, weathering).
- Alkali-aggregate reactions (chemical effects).
- Sulfate attack (chemical effects).
- Microbiological induced attack (chemical effects).
- Corrosion of reinforcing steel embedded in concrete (chemical effects):
 - a) Carbonation of concrete
 - b) Chloride induced
- Abrasion (physical effects).
- Mechanical loads (physical effects).

In practice, several degradation mechanisms can act simultaneously with possible synergistic effects.

CONCRETE DEGRADATION IN WATER AND WASTEWATER ENVIRONMENT

Water is essential for most of the processes leading to concrete deterioration. Constant wetting and drying is more detrimental to concrete than submerged conditions. The concentration of aggressive substances in the pore structures increases as a result of cyclic wetting and drying leading to corrosion. The splash zone and tidal zone of water structures are more prone to corrosion than submerged zone.

There are numerous factors contributing to the breakdown of concrete in water and wastewater treatment facilities.

These include increased levels of corrosive chemicals (such as; hydrogen sulfide, carbon dioxide, and chloride), a variety of corrosive materials in the wastewater streams, constant abrasion from various media within the waste stream, variations in pH levels of the waste stream, utilization of new coagulants and disinfectants as well as carbonation and cavitation of the concrete .

Sulfide Attacks- Hydrogen sulfide (H₂S) generation in municipal wastewater treatment plants has always been present. Up until the late 1970s, H₂S levels stayed generally below 10 parts-per-million (ppm). During periods of low rain or high temperatures, however, levels could rise to 30-50 ppm, accelerating corrosion of concrete and causing depth losses of up to 3/4 of concrete a year.

Following the passage of the Clean Water Act in 1980, industrial pretreatment was mandated to reduce or eliminate the presence of heavy metals from wastewater discharges. These metals had been killing anaerobic bacteria found on concrete pipe and tank surfaces, and therefore dissolved sulfide concentrations were maintained at relatively low levels, hence reducing gaseous H₂S levels also. Because gaseous H₂S is equally as responsible for odors as it is for corrosion of concrete in wastewater treatment systems, both odor and corrosion problems have increased as a result of industrial pretreatment of heavy metals.

On the other hand, the building of larger regional treatment plants over the last two decades has resulted in longer travel distances and detention time for

wastewater. The pumping of wastewater through force mains means that pipes run full and slime layers cover the entire circumference of the pipes. Both factors have increased the sulfide production, subsequently increasing H₂S concentrations in aerated headspaces within wastewater systems.

In the collection systems for large domestic plants today, it is not uncommon to measure H₂S concentrations in headspaces as high as several hundred ppm. This general trend toward higher H₂S concentrations has promoted much higher concrete corrosion rates in domestic treatment plants (especially larger regional plants) than witnessed in the past. The corrosion rate of concrete has been as high as 1/2 to 3/4 per year, depending on concrete quality.

Sulfuric acid formation also is more constant due to the higher and more constant H₂S presence. As the pH levels have dropped below 2.0, the concentrations of sulfuric acid have risen from one to three percent to well above seven percent in some municipalities.

Moisture Penetration- Another common problem with reinforced concrete structures is deterioration brought about by the corrosion of reinforcing steel and the subsequent spalling of concrete. This is most often caused by moisture penetrating to the depth of the steel, where it reacts in the presence of oxygen and chloride to cause the steel to corrode. This process is aggravated by carbonation.

Carbonation- Carbon dioxide, CO₂, is a gas form in the atmosphere, it penetrates in the concrete pores. This penetration is

more fast when concrete is more porous. But, this gas can be dissolved in the water, which then react with cement and form carbonates. The result of the action of acidic environmental conditions bringing about a lowering of the alkalinity of the concrete from an initial pH of around 13 to around 9.5 over some years. At this stage the steel loses the passivating gamma-feric oxide layer, which becomes unstable at this level of pore water alkalinity and corrosive reactions start to become evident.

The depth or degree of carbonation can be determined by petrographic techniques (ASTM C 856) through the observation of calcium carbonate-the primary chemical product of carbonation. As the carbonation process effectively drops the pH of the concrete, a phenolphthalein color test can be used to estimate the depth of carbonation by testing the pH of concrete (carbonation reduces pH).

Chloride Attack- Another major problem with reinforced concrete is chloride attack. The porous nature of concrete allows chloride ions to percolate deep into structures, eventually reaching the reinforcing steel (rebar) and causing these structures to corrode.

Once chlorides attack a structure, they quickly eat away at the reinforcing steel, causing cracks to appear. If left untreated, these chloride ions can cause concrete spalls, expose steel reinforcement bars and eventually reduce the structural integrity of the structure to dangerous levels.

Concrete surfaces exposed to de-icing salt, such as drain system structures, transmission pipes, and

water/wastewater treatment facilities, are particularly vulnerable to its damaging effects. Even relatively new structures can exhibit rebar corrosion if chlorides are cast into them.

REPAIR METHODOLOGIES

A basic understanding of causes of concrete degradation is essential to performing a successful repair. If the cause of degradation is understood, it is much more likely that an appropriate repair system will be selected. Only after the cause(s) are known can informed repair techniques be used. After the underlying cause(s) have been determined, one or more of the following methods can be selected to repair the damaged concrete:

Concrete Replacement-The concrete replacement method consists of replacing defective concrete with concrete of suitable proportions and consistency, so that it will become integral with the base concrete.

Cathodic Protection (CP)- The corrosion process that takes place in concrete rebar is electrochemical in nature, very similar to a battery. Corrosion will result in the flow of electrons between anodic and cathodic sites on the rebar. Cathodic protection (CP) is the technology that has proven to stop corrosion in existing reinforced concrete structures. CP reduces corrosion by changing the thermodynamics of the steel, i.e., the chemical potential of the steel in contact with the concrete is changed to make it a cathode. It is well identified that the cathodic areas in an electrochemical cell do not corrode. The protection is done by forcing an electrical current at the steel/concrete interface. However, it

should be noted, *concrete cathodic protection systems are only designed to address corrosion problems in steel reinforced concrete* .

By definition, if all the steel rebar (anode sites) were forced to function as current-receiving cathodes, then the entire metallic structure would be a cathode and corrosion would be eliminated. Subsequently, the system will reduce or eliminate the corrosion by making the metal a cathode by impressing a direct current (DC), or by connecting it to a sacrificial or galvanic anode. There are two types of CP systems — sacrificial anode and impressed current.

Sacrificial Anode- In sacrificial anode systems, the current required for cathodic protection is supplied by the corrosion of a more reactive metal (sacrificial anode) such as zinc or aluminum-zinc-indium (Al-Zn-In), to create a current flow. Sacrificial anode systems are based on the principle of dissimilar metal corrosion and the relative position of different metals in the galvanic series. The direct current is generated by the potential difference between the anode and reinforcing steel when connected. The sacrificial anode will corrode during the process and is consumed. Current will flow from the anode, through the concrete, to the corroding reinforcing steel.

Impressed Current- As in galvanic anode systems, impressed current systems supply the protective current by a rectifier (or other DC power source) instead of by the natural potential difference of the anode to the structure. The potential difference between the anode and cathode is forced from a non-reactive anode by the action of

additional energy from a rectifier to force the electron flow that would be normally produced in the corrosion reaction. The energy for the electron supply action of the rectifier is provided by ordinary alternating current. The effect of these electrons at the structure being protected is the same as that derived from the sacrificial anode type of cathodic protection system.

Protective coating-Protective coatings are used to protect concrete from degradation by chemicals and subsequent loss of structural integrity, to prevent staining of concrete, or to protect liquids from being contaminated by the concrete.

The proper use of protective coatings is the extremely effective means of preventing concrete deterioration and corrosion in water and wastewater applications. The function of a coating is to act as a barrier that prevents either chemical compounds or corrosion current from contacting a concrete substrate.

The coating's effectiveness of fulfilling this function depends on its degree of integrity (being a completely continuous film or freedom from imperfection or defects), its ability to bond to the concrete substrate, and its ability to insulate against the passage of corrosion current (dielectric strength) or chemical ions.

Corrosion protection by coatings for water and wastewater pipelines is the implementation of a well-balanced cycle of the following four equally important elements:

- a. Specifying and using a proper coating system
- b. Proper surface preparation for the coating system
- c. Proper application of the coating system
- d. Quality inspection of the coating system

When preparing a protective coating strategy it is usually necessary to differentiate between water and wastewater environment since the latter contains water that is usually much more aggressive in terms of water chemistry and its affect on concrete.

This paper will discuss the application of protective coating systems (Linings) to concrete surfaces in water and wastewater environment.

CONDITION ASSESSMENT OF CONCRETE FOR PROTECTIVE COATING APPLICATION

Because conventional sealers and paints are a comparatively thin and weak layer applied to the surface, they are wholly dependent upon the integrity of the concrete surface to maintain integrity of their protective film. In other words, paints and sealers are not structurally independent of the surface and, to be effective, must only be applied to a sound substrate. If the concrete has been in service without the benefit of protective coatings, the surface of the exposed concrete is likely deteriorated to some extent.

A detailed inspection of the surface conditions has to be performed during the design stage or provisions must be

made in the contract for varying conditions.

The recommended practice and procedure for assessing the condition of the concrete by the American Concrete Institute (ACI) include visual examination, nondestructive evaluation test (NDT), and destructive tests (ACI 364.1R).

a) *Visual examination*-The visual examination should be carried out to evaluate and document the extent and severity of any stress or deterioration, which could affect the service life of the structure. Cracks, spalls, corrosion of reinforcing steel, etc., should be identified as follows (ACI 364.1R):

- i) Cracks should be measured and recorded for width, depth, length, location, and type.
- ii) Spalling, scaling, honeycombing, efflorescence, and other surface defects should be measured and recorded.
- iii) Corrosion of reinforcing bars, including the extent and amount of loss cross section, should be measured and recorded.
- iv) Loose, corroded, or otherwise defective connectors for precast concrete elements, or ties to architectural elements or cladding should be noted.
- v) Deformations, whether permanent or transient under loads, out-of-plumb columns, and other misalignments, should be considered as appropriate.
- vi) Signs of foundation settlement or heave, and related stress, should be noted.
- vii) Water leakage, ponding areas, areas of poor drainage, or other indications of water problems should be noted.

viii) Evidence of aggressive chemical deterioration such as sulfide attack and acid attack should be noted.

b) *Nondestructive evaluation test (NDT) (ACI 228.2R)*-NDT is defined as testing that causes no structurally significant damage to concrete structures. NDT methods are applied for the investigation of concrete structures. It provides important information for the structural performance of the concrete, such as:

- Member dimensions,
- Location of cracking, delamination, and debonding,
- Degree of consolidation, and presence of voids and honeycomb,
- Steel reinforcement location and size,
- Corrosion active of reinforcement, and
- Extent of damage from freezing and thawing, fire, or chemical exposure.

Some of the common NDT methods are as follows:

- i) Ultrasonic pulse velocity
- ii) Ultrasonic-echo
- iii) Impact-echo
- iv) Radiography
- v) Half-cell potential
- vi) Polarization method
- vii) Infrared thermography
- viii) Carbonation depth and chemical test, such as pH, chloride, sulfide, etc.

c) *Destructive test (ACI 364.1R)*-Destructive tests provide a viable approach to estimation of concrete strength for a range of concretes. The disadvantage of this method is the damage to the concrete structures and limitation of data to the test location. Some of the common destructive methods are as follows:

- i) Standard test method for penetration resistance of hardened concrete.
- ii) Core sample extraction for petrography analysis, chloride diffusion, etc.
- iii) Dust samples

SURFACE PREPARATION FOR CONCRETE COATING

Since the adhesion of the coating will be limited by the strength of the surface, the deteriorated concrete must be removed to reveal a sound surface prior to application of any coating. Depending on the extent of deterioration, rebuilding of the surface with a mortar prior to coating application may also be necessary.

No general surface preparation standard exists for concrete however, most coating projects have unique conditions and special requirements that must be evaluated to determine which will best meet the engineerings and owners objectives. Some of the important factors for selection of surface preparation method(s) are:

- Substrate condition
- Owner requirements
- Material requirements
- Application conditions

Based on aforementioned factors one or more of the following method(s) can be used for concrete surface preparation:

Acid Etching-this method is commonly used to treat floors. This method is difficult to use on vertical surface. This method is described in ASTM D 4260 and NACE RP0892.

Abrasive blasting-This method may be used to clean concrete walls and floors.

Abrasive blasting removes loose, powdery concrete and laitance.

Impact-tool-These method may be used to remove existing coating, laitance, and weak concrete. These methods include scarifying, planning, scabbling, and rotary peeing, as described in ASTM D4259.

Power-tool-These methods may be used to remove existing coating, laitance, weak concrete, and protrusion in concrete. These methods include circular grinding, sanding, and wire brushing as described in ASTM D4259.

Flame Cleaning and Blasting-This method uses a propane torch or other heat source to extract organic contaminant from a concrete surface.

Hydroblasting-This method may be used to remove existing coating, contaminant, laitance, and weak concrete. This method is described in ASTM D4259.

Patching Material-Materials such as grouts, putties, and sealers are used to repair, patch, smooth, or seal the concrete surface to provide a substrate that is suitable for the coating system to be applied.

CONCRETE SURFACE PREPARATION FOR IMMERSION SERVICES

According to the American Concrete Institute (ACI), poured concrete should be cured for a minimum of 28 days at temperatures of over 70F (temperature and humidity control the cure time).

To provide an acceptable concrete surface for lining system for immersion

services the following procedures should be followed:

- *Condition Assessment*-Concrete shall be inspected prior to surface preparation to determine the condition of the concrete.

- *Surface Preparation*- Hydroblasting is one of the most efficient methods to be used to remove deteriorated concrete surface. This method prepares the surface by removing the deteriorated and soft concrete and leaving the strong and intact concrete. At the same time it removes the surface contaminant without spreading them on adjacent areas. Ideally, the surface preparation will reveal a surface to be coated that has a cohesive strength of approximately 300 psi, or 10 percent of the compressive strength of the concrete, whichever is greater (concrete tensile strength -NACE 6G191).

- *Concrete Repair*-Concrete that has been damaged due to physical or chemical forces should be repaired. A typical deteriorated concrete surface could easily vary by more than a 1/2" in profile due to these forces and other surface irregularities inherent to a deteriorated concrete surface. These areas should be repaired to the level required by the coating system in the immersed service condition. However patching materials are available in a range of consistencies for this application by variety of methods.

There is a repair technique to repair the concrete surface by using microsilica cement as follows: Microsilica cement mortar should be applied to the damaged concrete. Immediately after forming, while the mortar is in a plastic state the patched areas should be sealed with a

100% solids, low viscosity penetrating type epoxy primer.

In order for an epoxy to bond to plastic concrete, it should exhibit the following characteristics:

- Be capable of forming an emulsion with the concrete paste (cement and water). An epoxy product that kicks out of solution or coagulates when mixed with cement paste would not be expected to work well.
- Be low in viscosity and exhibit good wetting and penetrating characteristics
- Contain no solvents (100% solids product) to eliminate the possibility of solvent entrapment.

- *Concrete Cracks*- Elastomeric lining generally has sufficient thickness and flexibility to bridge narrow cracks even if the crack width fluctuates. However, cracks wider than 10-15 mils should be routed and sealed prior to application of elastomeric membrane. A bond breaker, such as polyethylene strip, should be provided at the bottom of the groove to allow the elastomeric membrane to change shape without the concentration of the stress on the bottom.

Epoxy injection has been successfully used in the repair of structural cracks. However, unless the cause of cracking has not been corrected, cracking will probably recur near original crack. If the cause of the cracks cannot be removed, then two options are available. One is to route and treating it by using elastomeric membrane and bond breaker.

CONCRETE COATING

Protective coatings play a critical role in extending the service life of concrete surfaces in harsh environments. When subjected to the harsh conditions inherent in water and wastewater treatment facilities, the role of the coating system in protection of concrete surfaces is particularly important for a number of reasons:

- The coating system must protect the concrete from chemical attack and deterioration by hydrogen sulfide, carbon dioxide, and chloride attacks.
- The coating system must protect the concrete from microbiological attack. Microorganisms, which cause the breakdown of organic matter also, can cause deterioration of concrete (through the formation of hydrogen sulfide), resulting in spalling and sloughing.
- The coating system must protect the concrete from spalling and cracking caused by moisture penetration. Moisture enters the concrete and is drawn inside by capillary action. In cold temperatures the moisture freezes in the pores, swells, and causes spalling.

Prior to the late 1980s, relatively thin film coatings based on coal tar epoxy and amine cured epoxy formulations provided effective corrosion protection of concrete for up to 10-12 years.

However, as a result of government-mandated industrial pretreatment, construction of large regional treatment plants with longer wastewater detention times, recent air quality regulations and other factors, concrete structures in wastewater treatment systems are typically exposed to more corrosive conditions today than in the past.

In recent years, these same coating materials have failed prematurely (within six months to two years) and severely. These failures were caused by both insufficient acid resistance and inadequate resistance to permeation by wastewater gases.

Another factor for increasing failure of protective coatings are new methods of odor control, such as covered headspaces. Enclosed headspaces created by covers such as over clarifiers combined with higher concentrations of H₂S have led to an increase in the volume of gases to which the coatings are exposed on a routine basis.

Coatings should measure up to standards higher than ever before in the areas of: improved sulfuric acid resistance (note: some municipalities are regularly testing products with a 10% sulfuric acid solution), lower permeability, increased film thickness, resistance to bacterial action, successful field performance history and optimum adhesion.

A typical coating might, for example, be only 12 mils (.012) thick; it would seem impractical to provide sufficient protection for the concrete structures. In contrast, to a typical sealer and paint approach, a polymer lining has sufficient cohesive strength to provide substantial film integrity independent of the substrate. It will also provide a cost-effective method to deal with an irregular concrete surface that has resulted from deterioration. This approach is contingent upon the assumption that not more than 1/3 of the concrete surface has been deteriorated, and major rebuilding of the concrete surface will not be required.

A structural polymer lining using a mesh backing embedded within the film to bridge bugholes and other defects and to form a continuous lining that is approximately 60-80 mils in thickness. Where greater integrity of the liner is required, glass reinforced epoxy may be used.

A typical lining system specified for concrete in water and wastewater environments are high-build and high solid polymeric lining applied in two or three coats to 18-20 mils of DFT or more on the concrete surface.

Due to today's higher solids and higher viscosity materials, some of the protective coatings do not penetrate within the concrete sufficiently to achieve the best possible adhesion. Therefore, the application of a sealer on the concrete surface should be considered to enhance the adhesion.

The purpose of this sealer coat is to penetrate the concrete, satisfy the porosity and tie down any residual dusting. The depth of penetration of sealer in the concrete is determined by the viscosity of the sealer and the porosity of the concrete.

For the immersed service condition the concrete surface should be sealed with 100% solids, low viscosity penetrating type epoxy primer to reduce porosity, strengthen the surface, and promote mechanical adhesion.

Finally, to achieve and maintain the design service life, the protective coating system requires a regularly scheduled program of inspection, touch-up, and maintenance. The system should be inspected at six-month intervals for severe exposure, and 12- to 18-month intervals for more moderate exposure.

